PSA of Si signals: what we have learnt within the FAZIA collaboration

G. Pasquali
pasquali@fi.infn.it
University of Florence & INFN-Sezione di Firenze

Outline

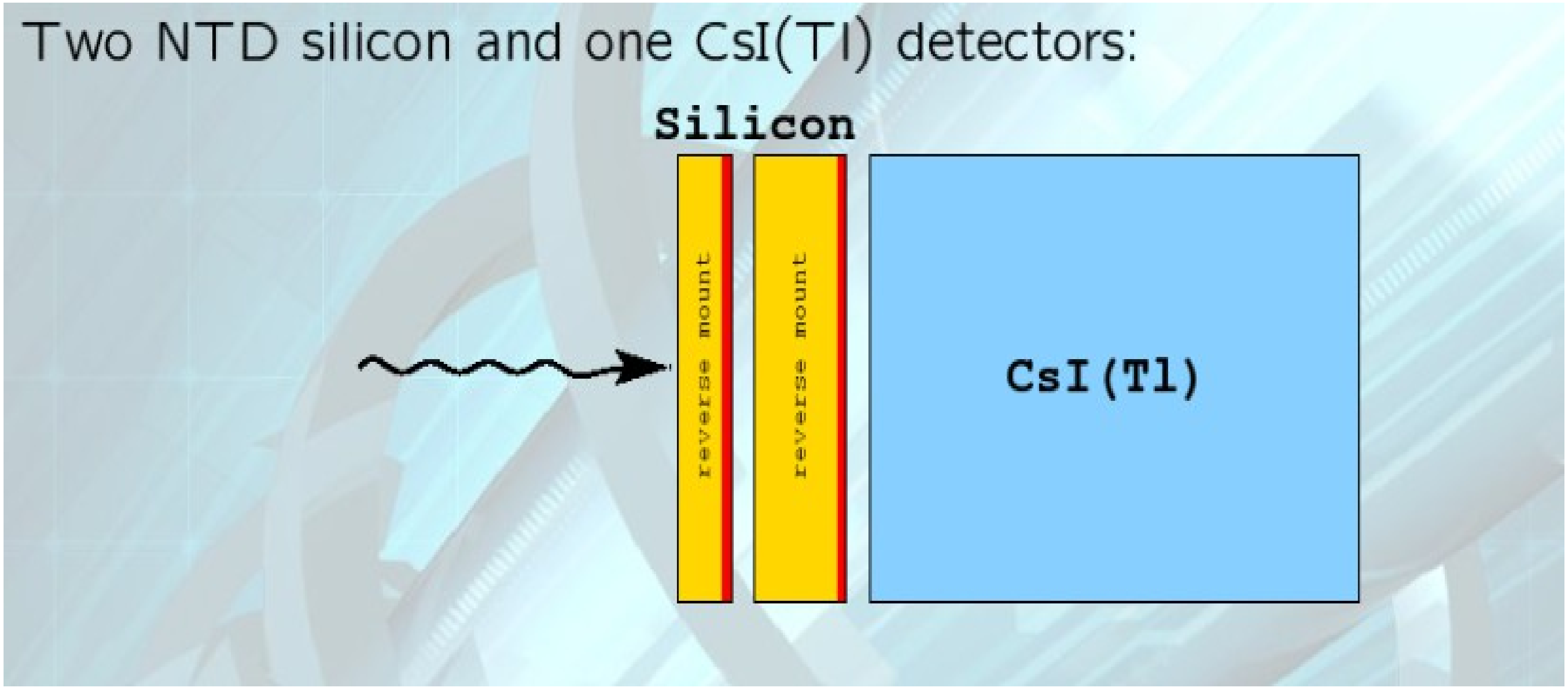
- **Introduction: The FAZIA collaboration**
- **The physical process and PSA basics**
  - **Energy deposition, Signal Formation and treatment**
  - **PSA basics: front (junction side) or rear (ohmic side) injection?**
  - **PS identification methods: "E vs Charge signal risetime" and "E vs Max I"**
- **Effects spoiling pulse shape**
  - **Straggling and channeling**
  - **Doping non-uniformity and changing bias voltage**
  - **Radiation Damage (Recombination and trapping)**
  - **Sheet resistance (when no Al layer on surface)**
- **Front End Electronics**
  - **Fidelity related issues (PA response, minimizing pick up noise and cross talk, anti-alias response etc.)**
  - **ADC noise (ENOB), ADC optimal resolution and sampling rate.**
- **FAZIA demonstrator**
- **Conclusions**

The FAZIA collaboration

- **Established in 2006 (FAZIA= "Four π A and Z Identification Array")**
  Members' nations: France, Italy, Poland, Spain, Rumania (+Canada, India and US)
- **Started as an R&D project to improve PSA and ΔE-E**
- **Goal: to design and build a new-generation detector for charged particles, suited for Isospin Physics to be done at Radioactive Beam Facilities like Spiral2, SPES and FAIR. The main partners are INFN and CNRS (~90 members)**
- **Experiments performed: CIME'06, LNL'07, LNS'09, GANIL'10, LNS'11**

FAZIA basic cell

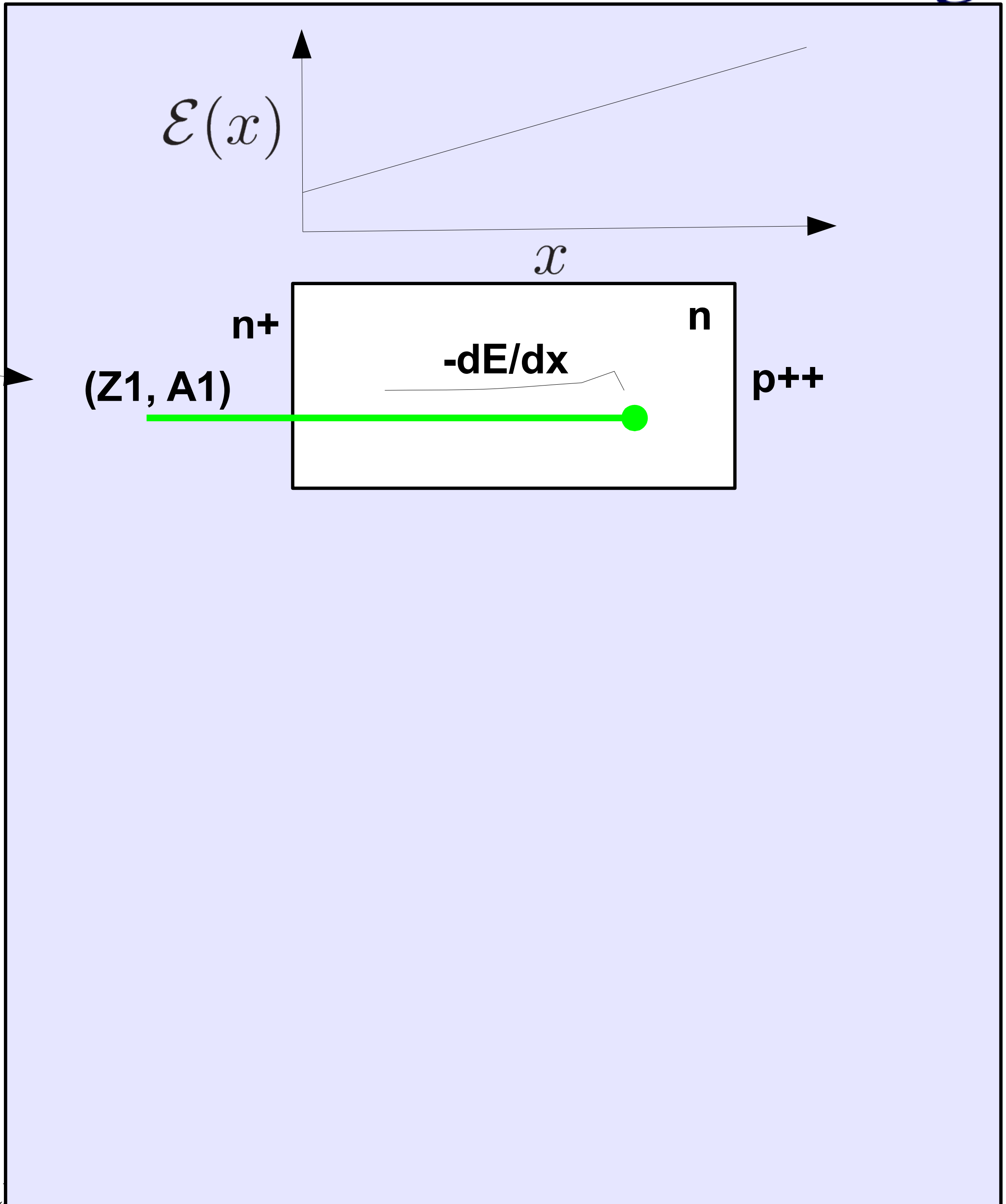
- **Basic cell: triple telescope Si(300um)-Si(500um)-CsI(10cm)**
- **Silicon are nTD, reverse mounted, 20x20mm^2, bulk ρ~3-5 kΩcm**
- **CsI is read out by a photodiode or by second Si (Single-Chip Telescope)**



Signal formation and treatment

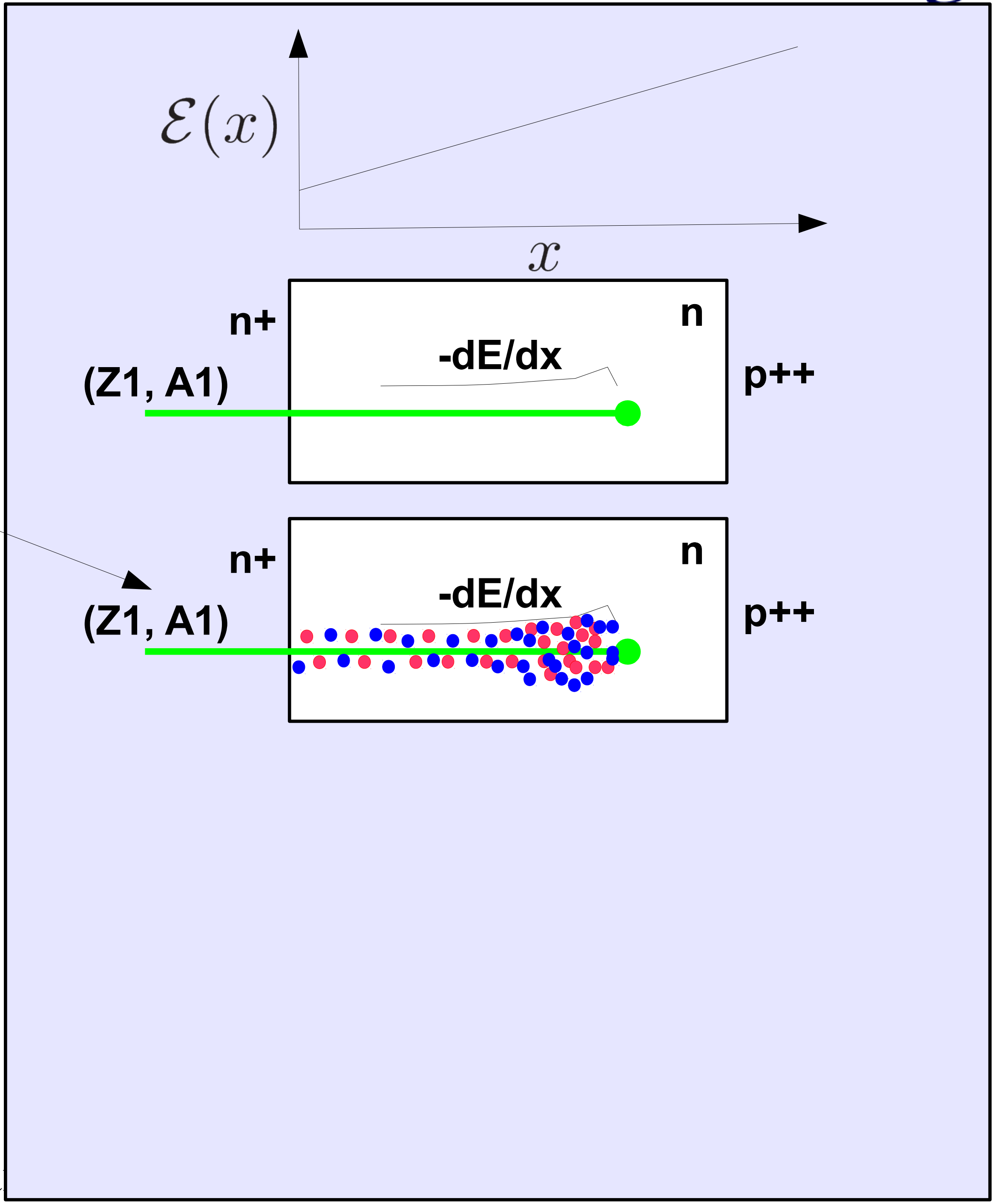
Signal formation and treatment

- **Ion stopped in Si: energy deposition in bulk**



Signal formation and treatment

- Ion stopped in Si: energy deposition in bulk
- From energy to e-h pairs. High dE/dx =>high e-h density => carrier plasma



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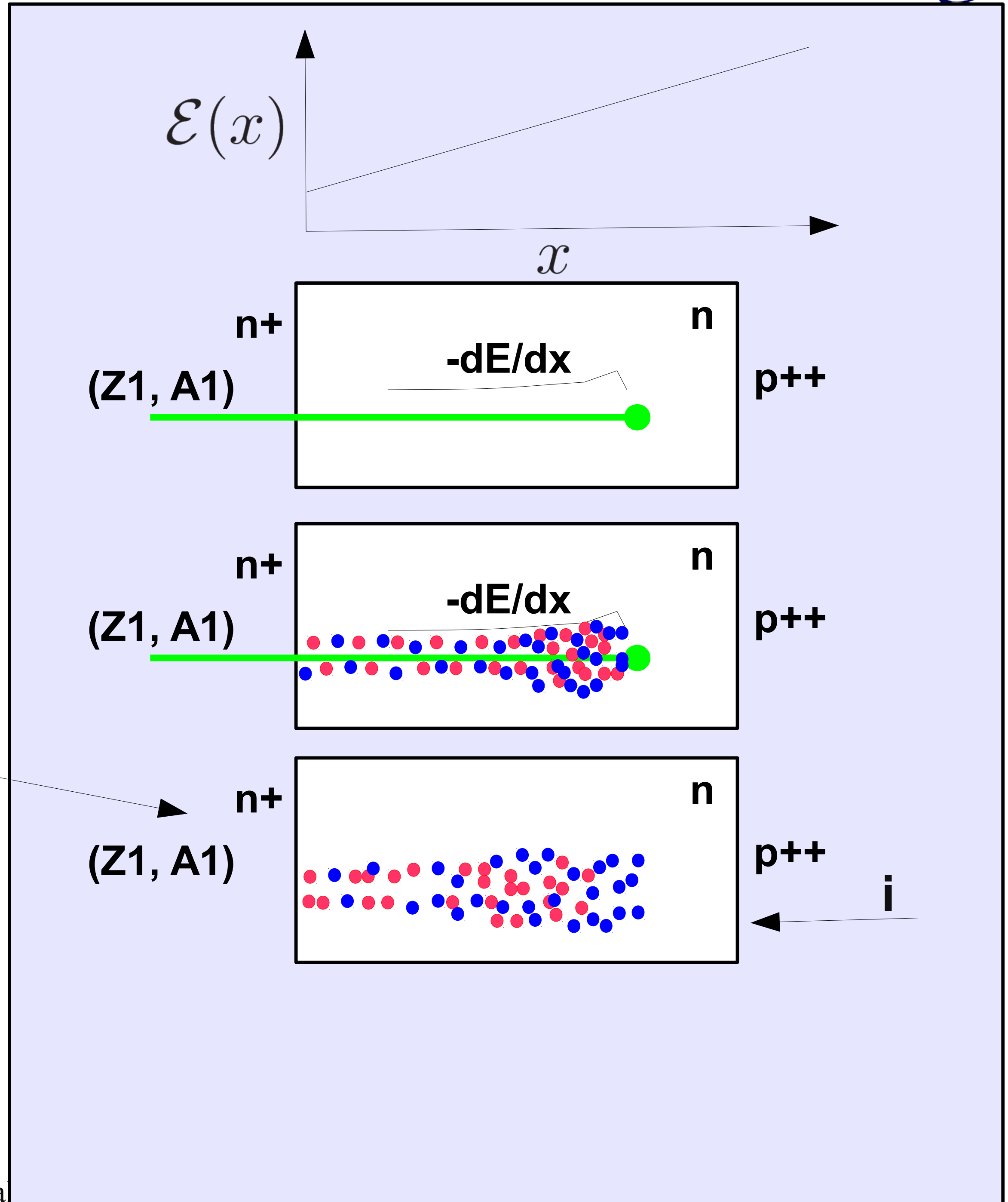
- Plasma erosion time+ e-h drift to electrodes: current induction on electrodes.



Signal formation and treatment

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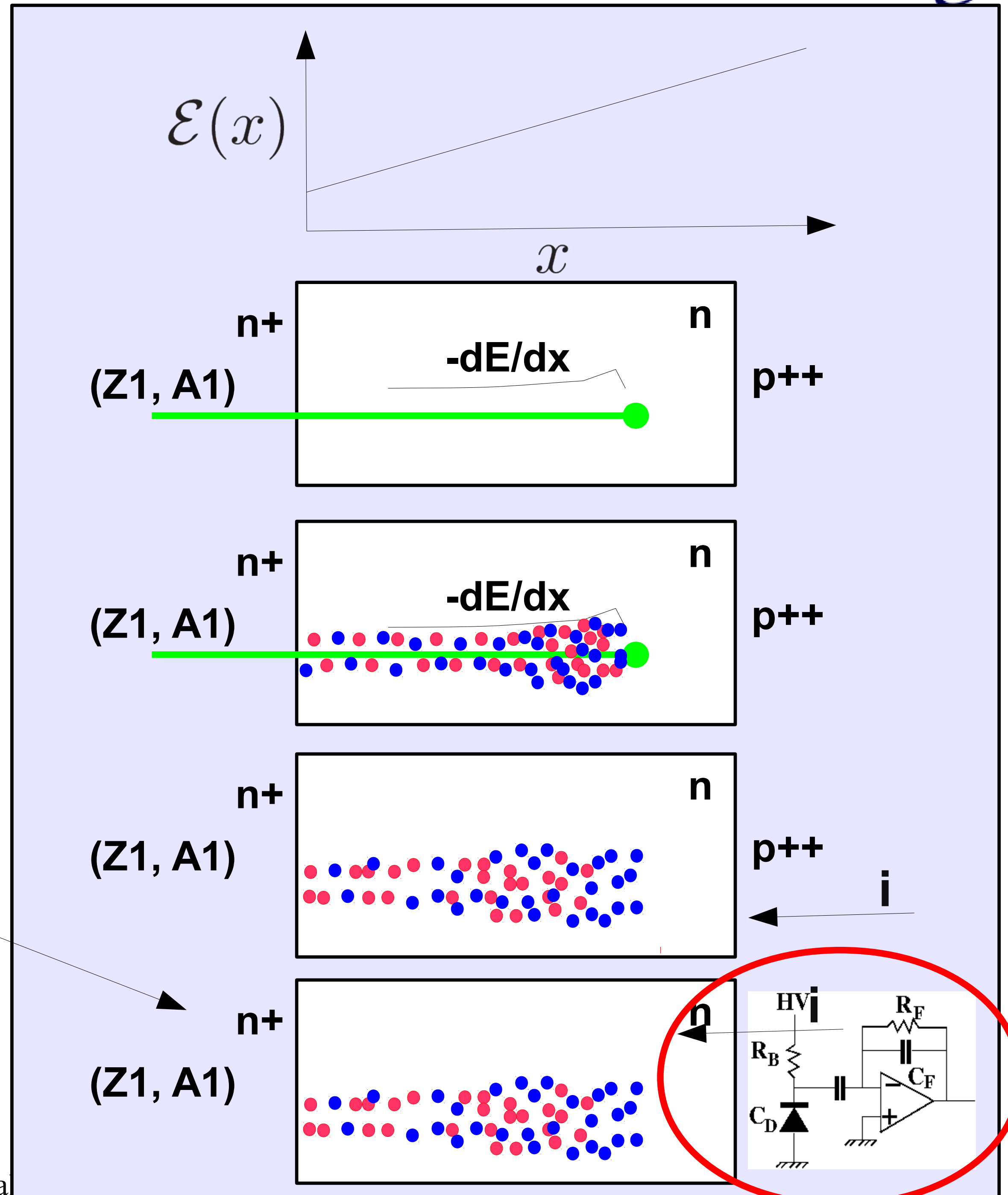
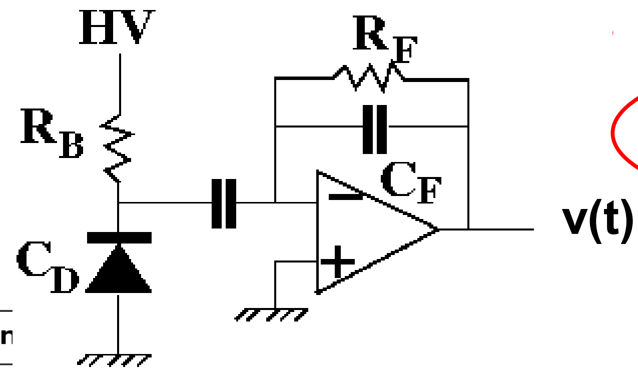
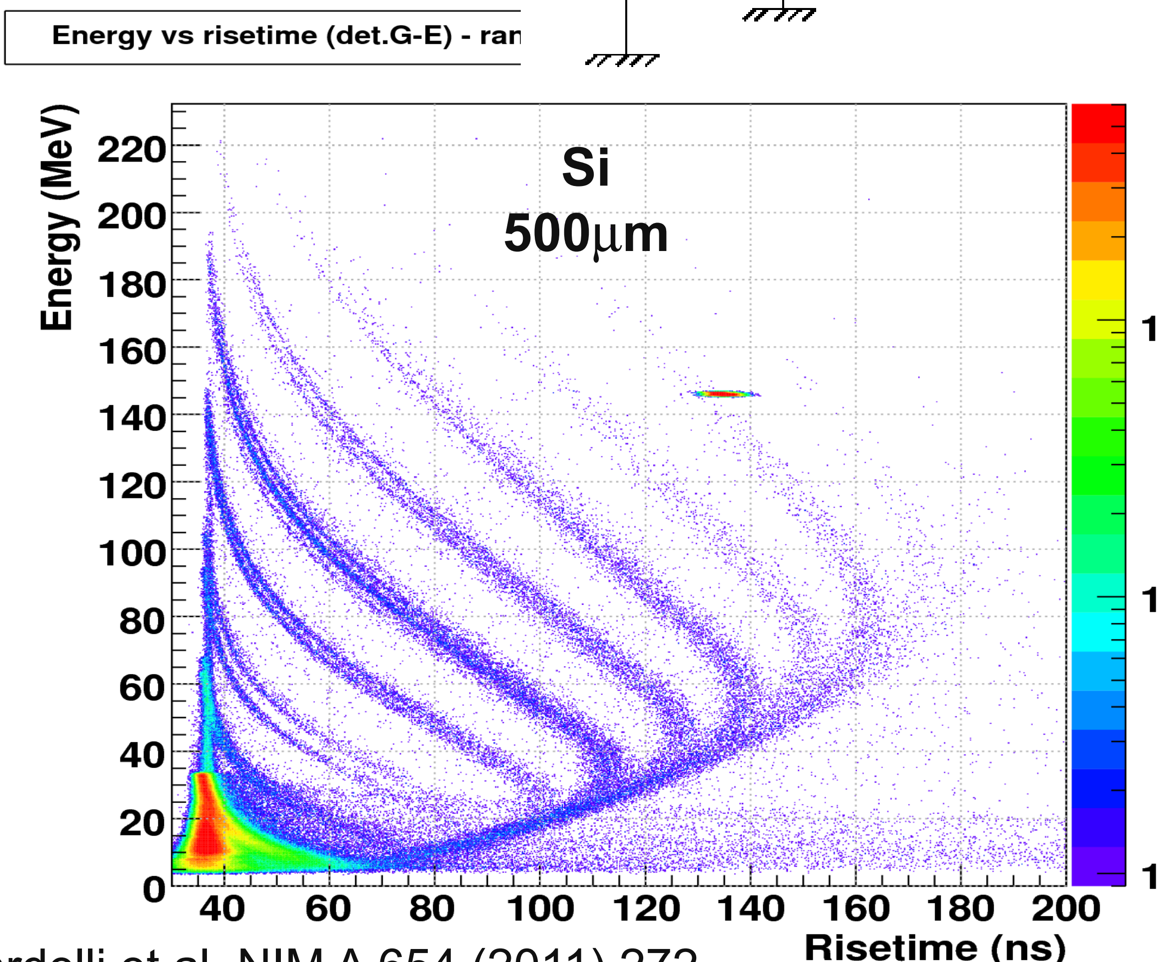
- Signal treatment in FEE

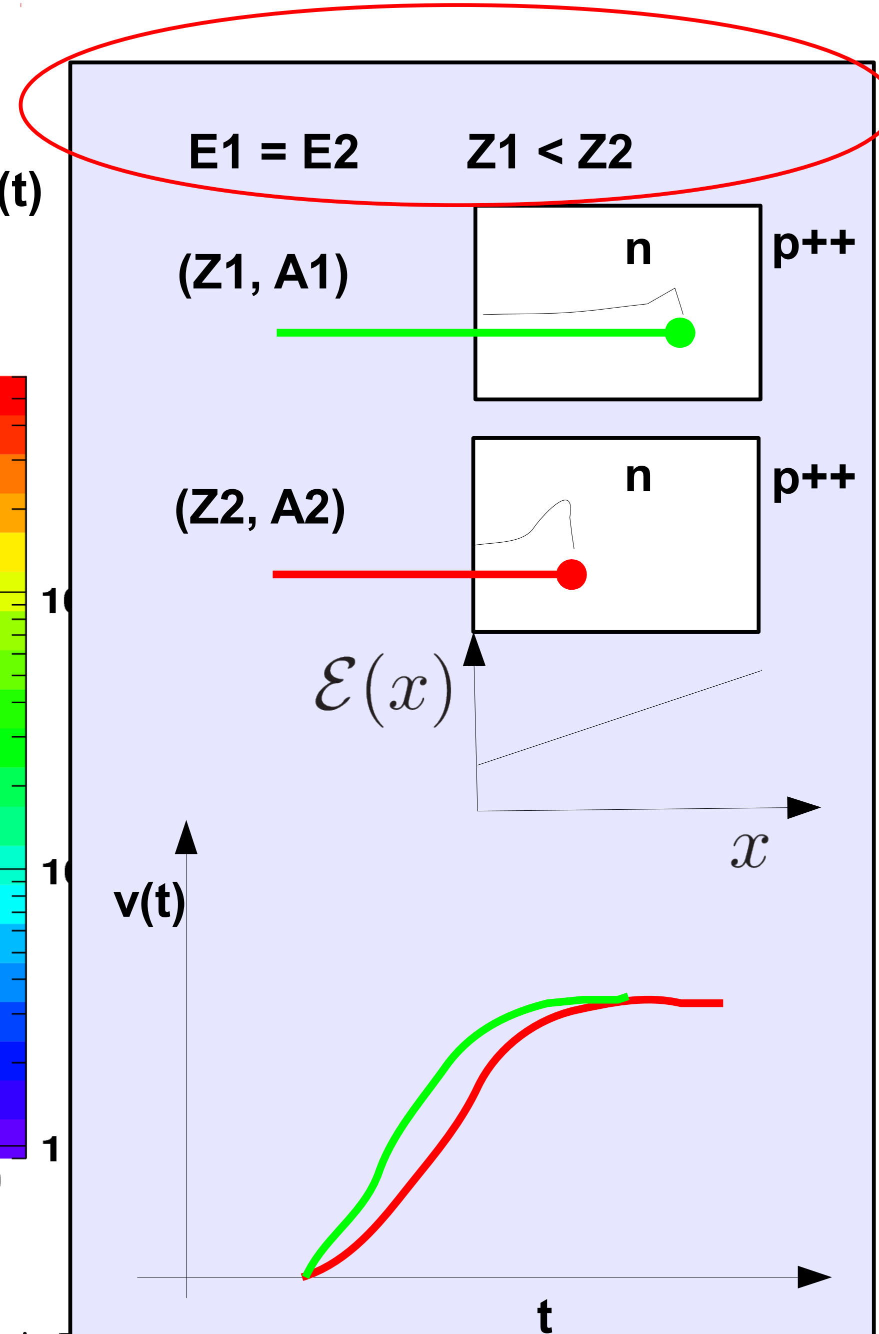


PSA in Silicon: Energy vs Rise-Time

N.B. Particles entering from ohmic side.







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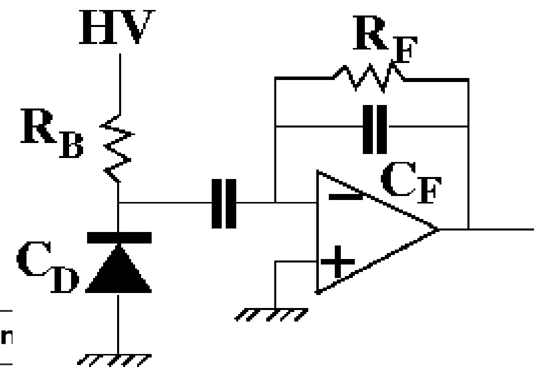

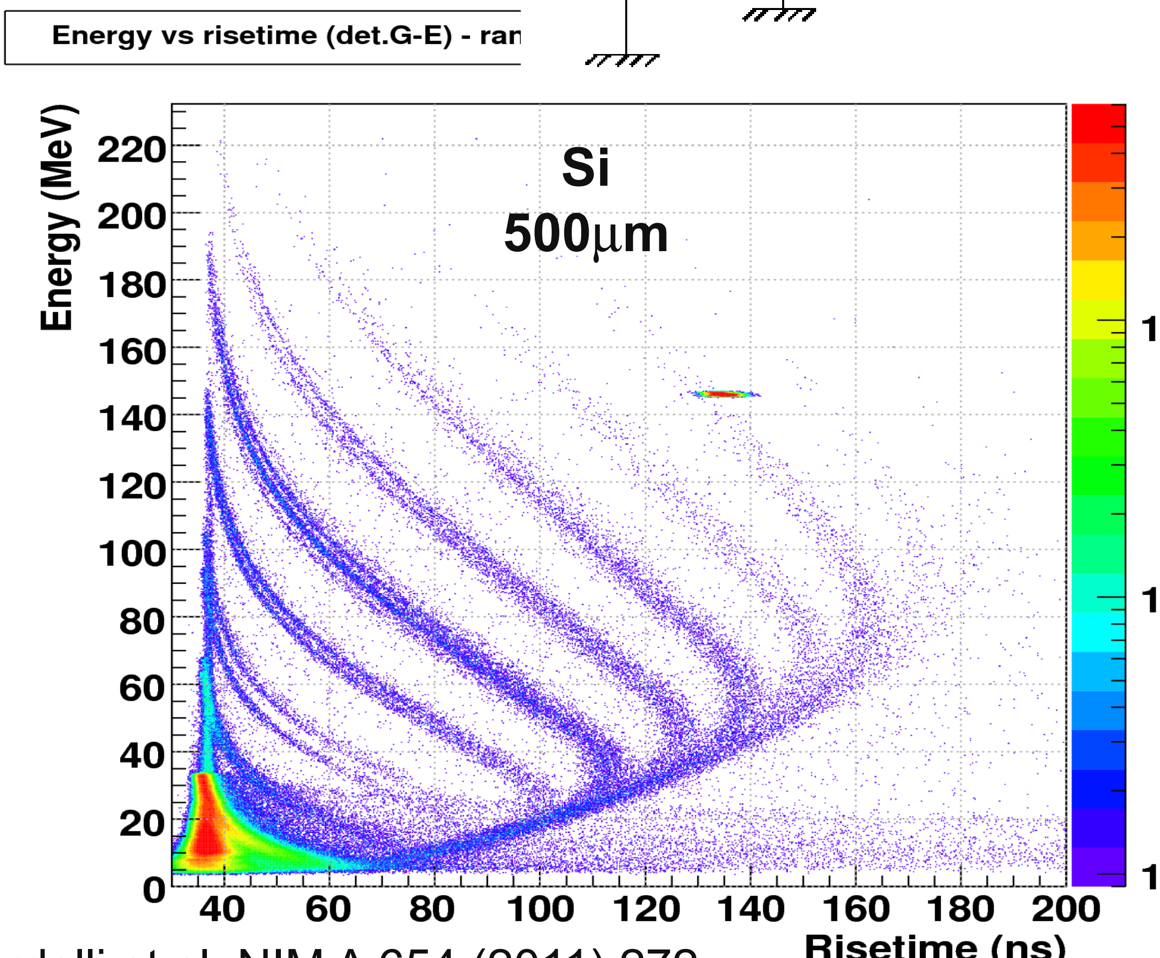

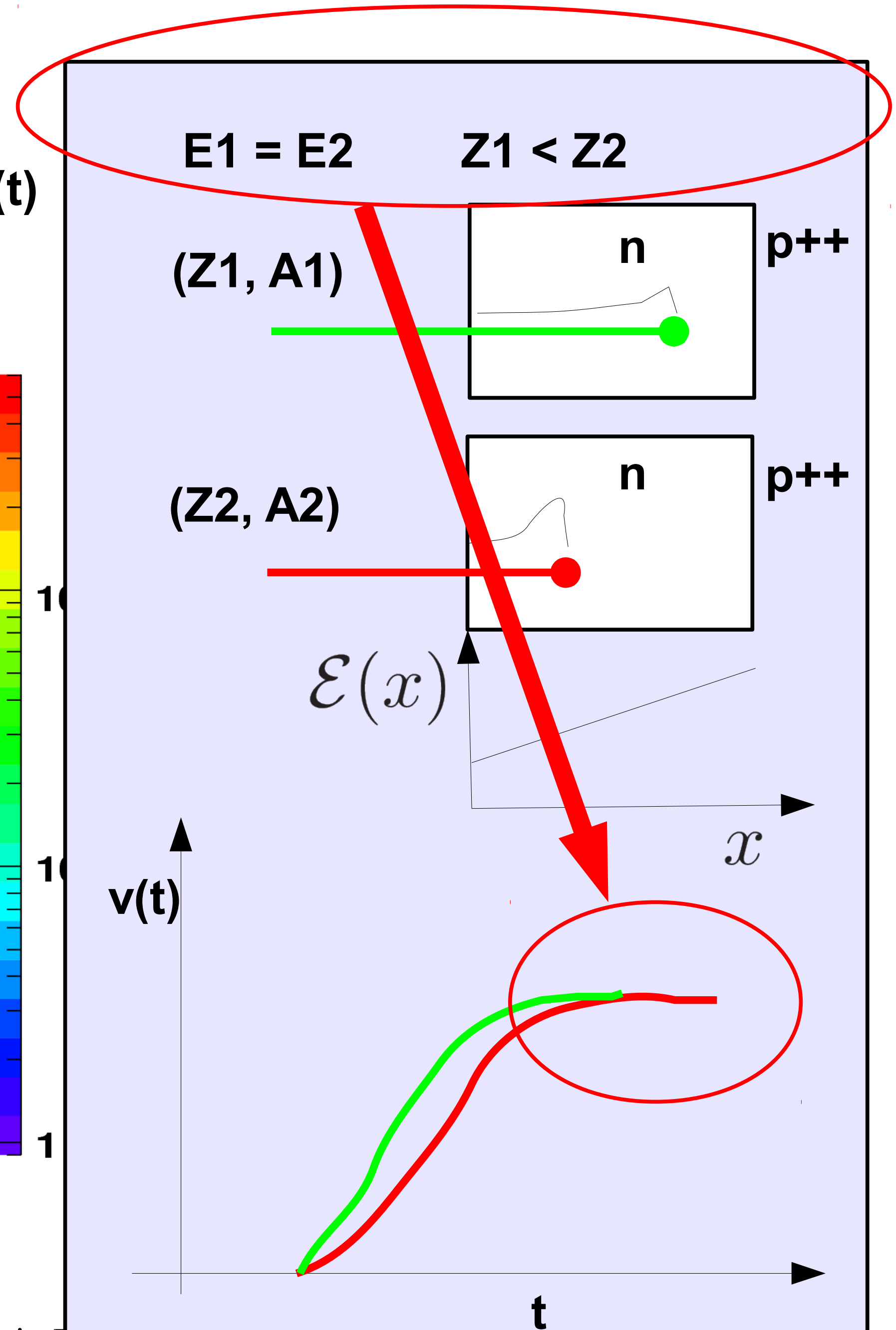

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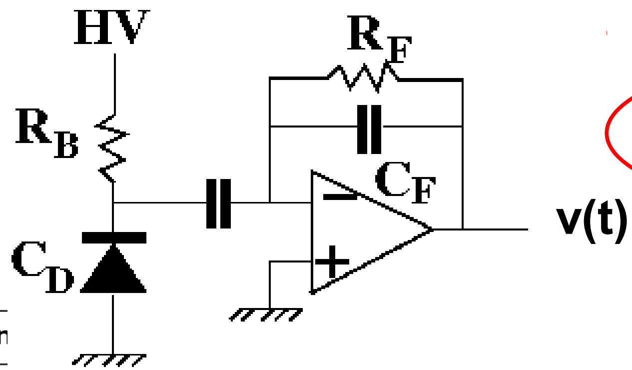

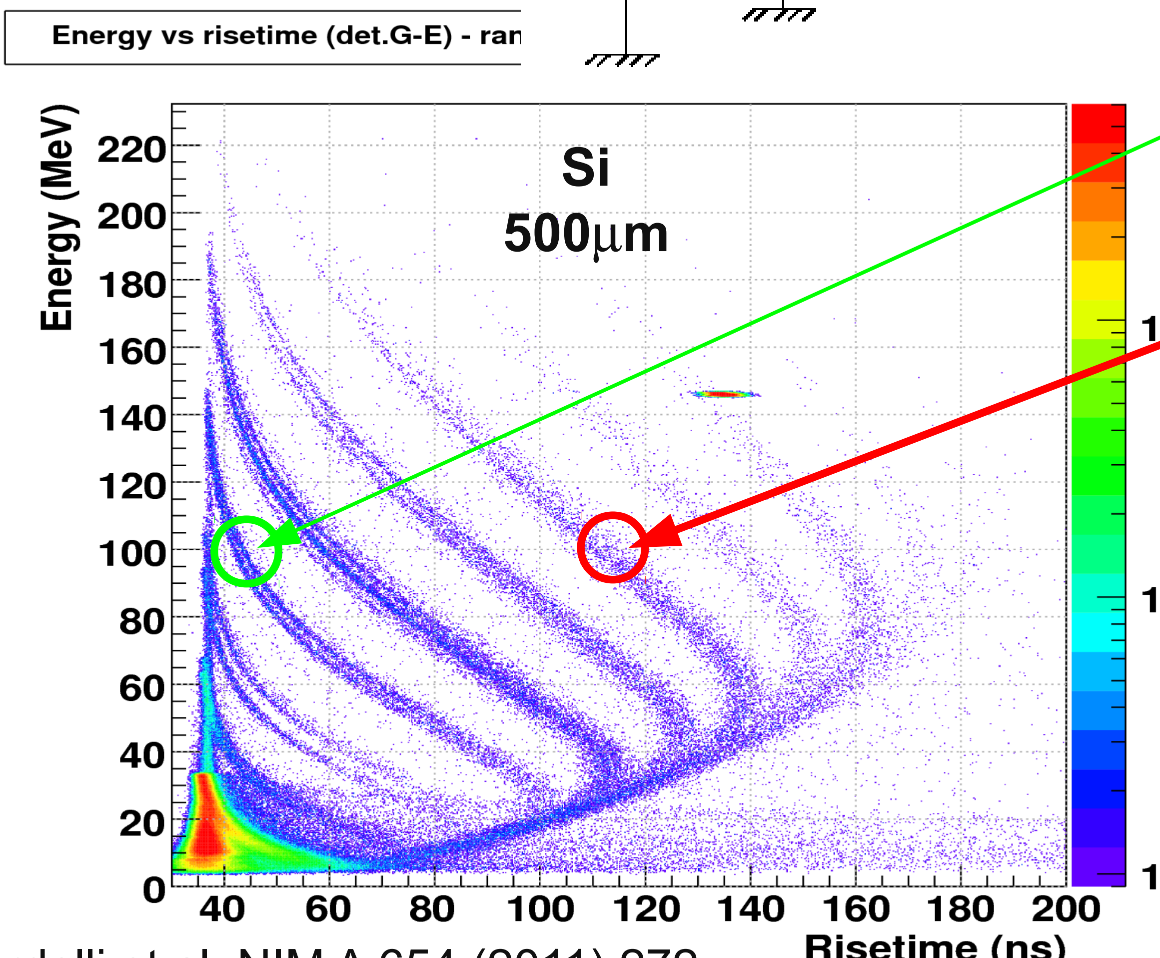

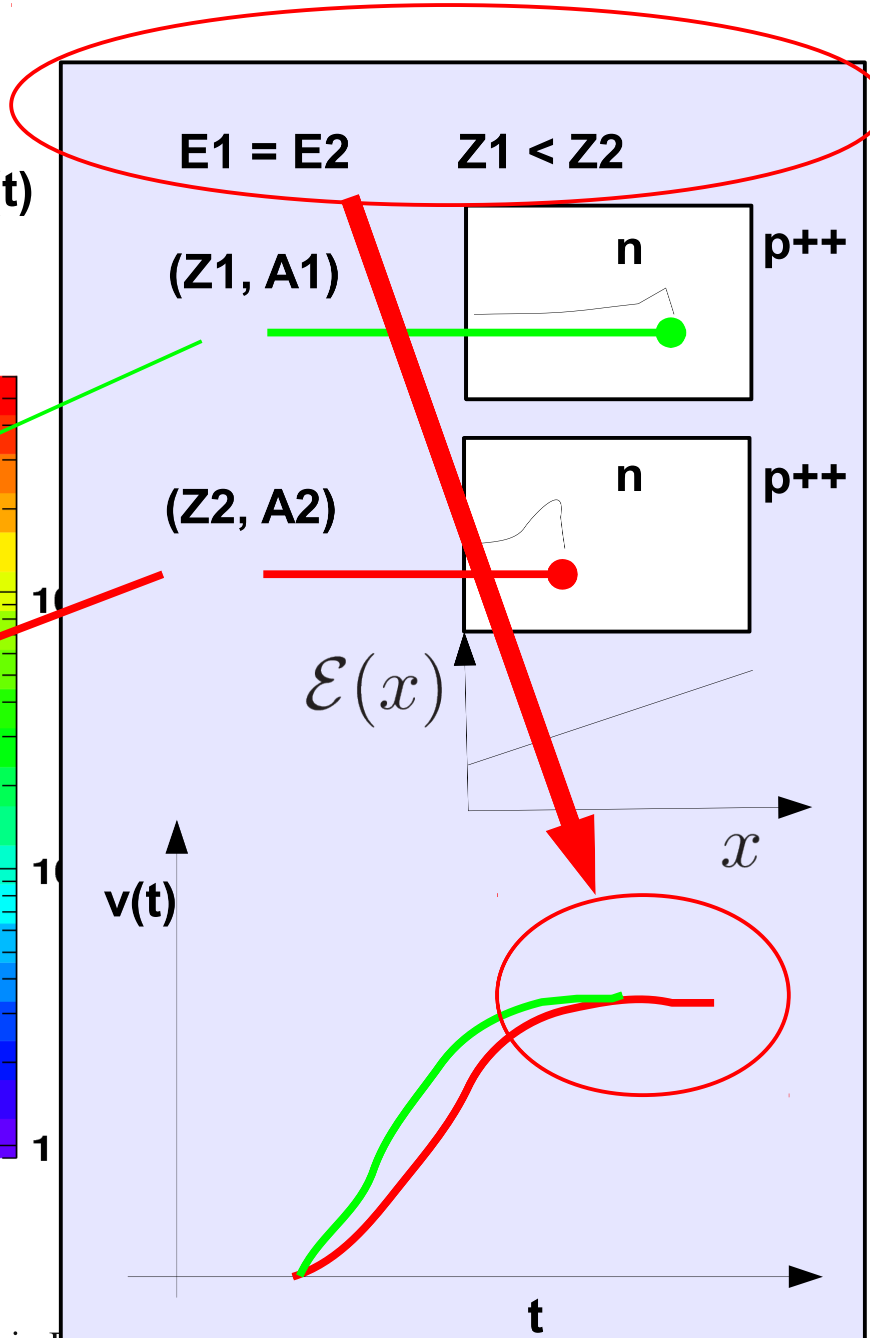

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PSA in Silicon: Energy vs Current Max

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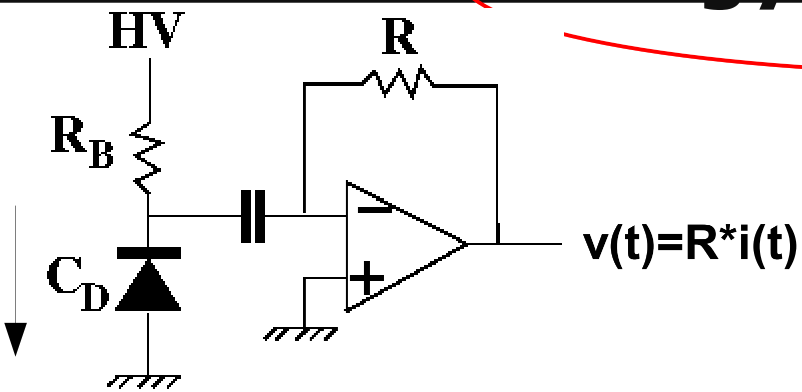

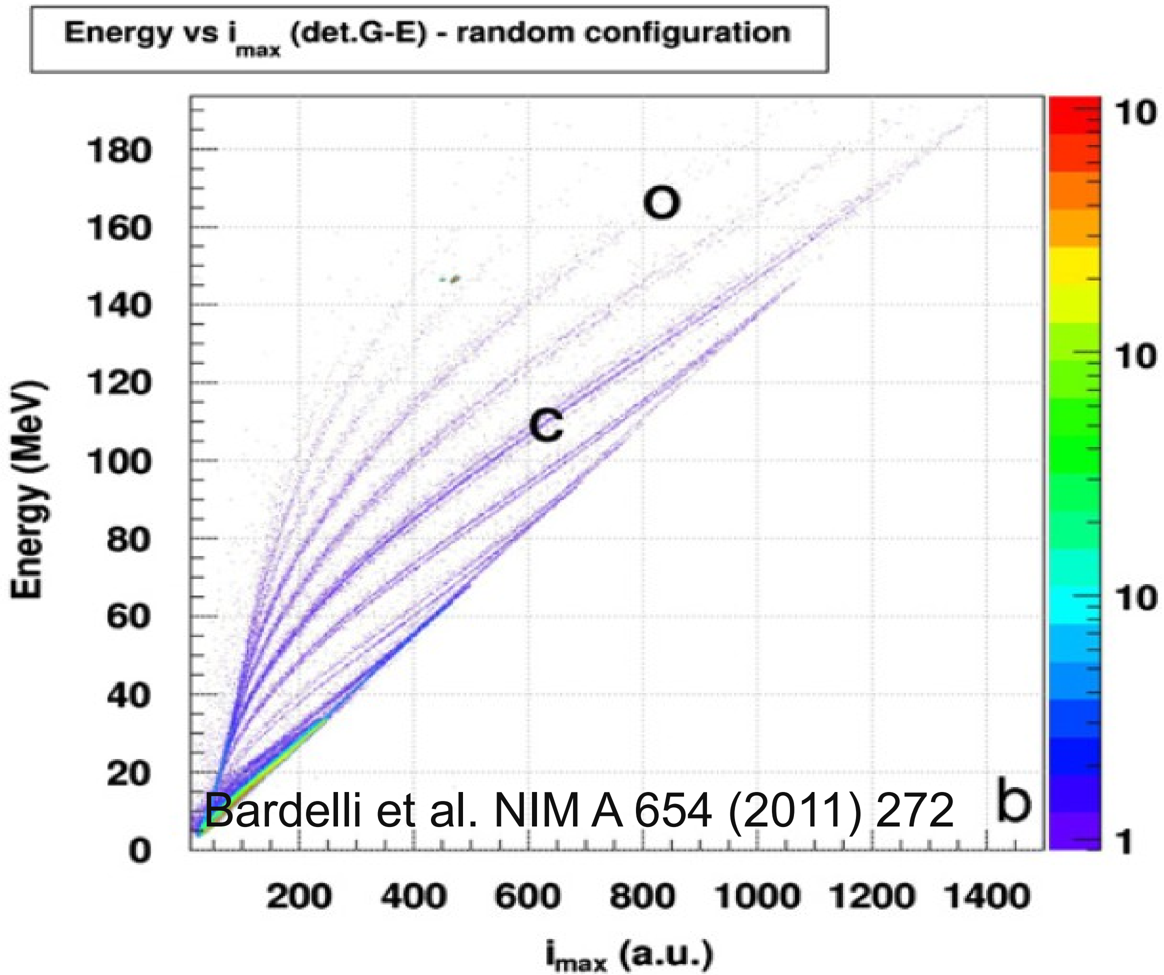

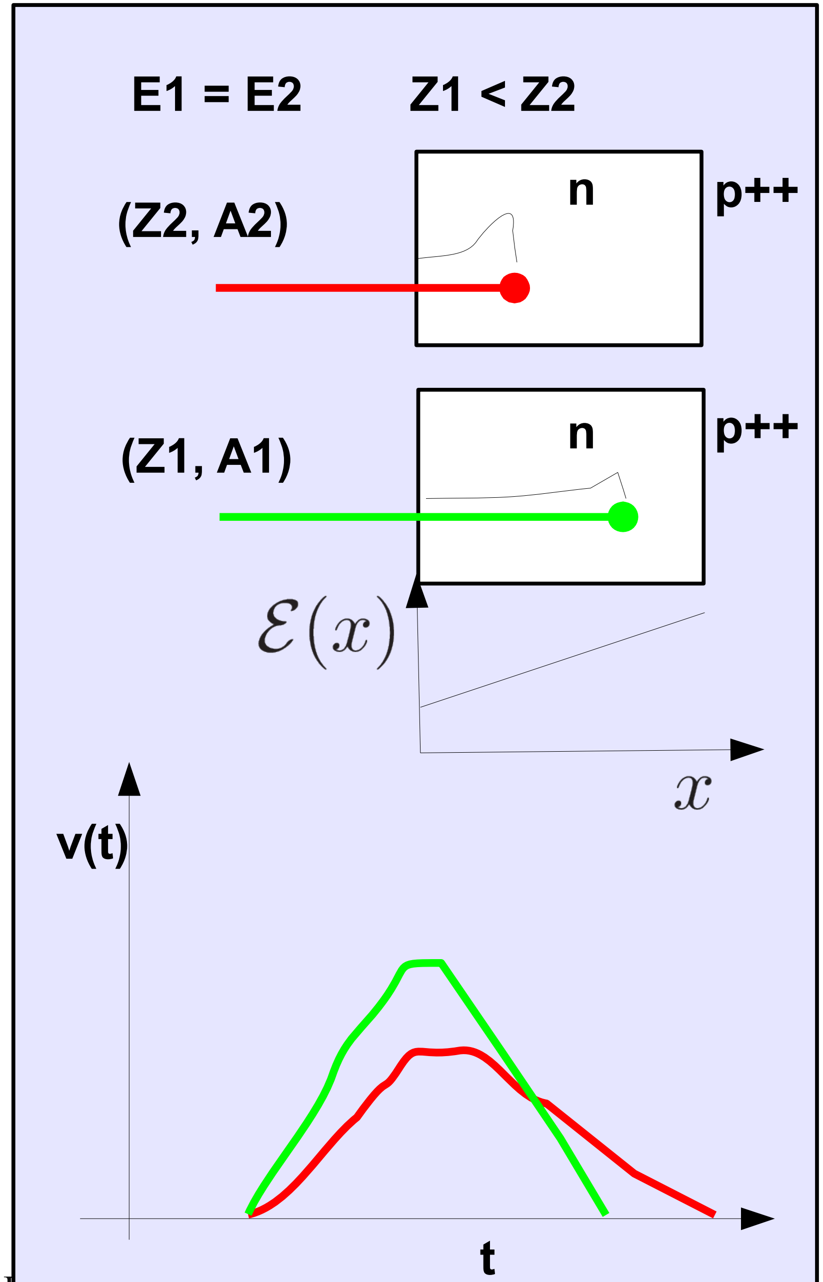

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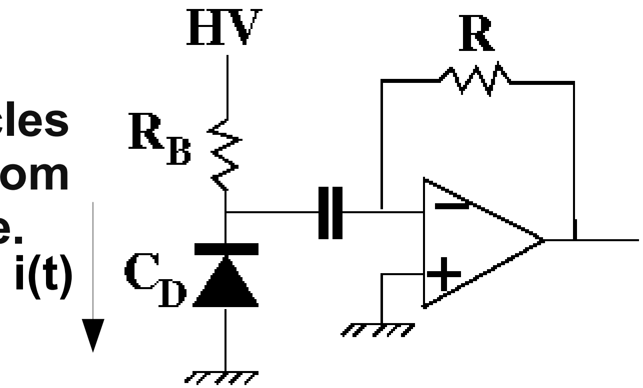
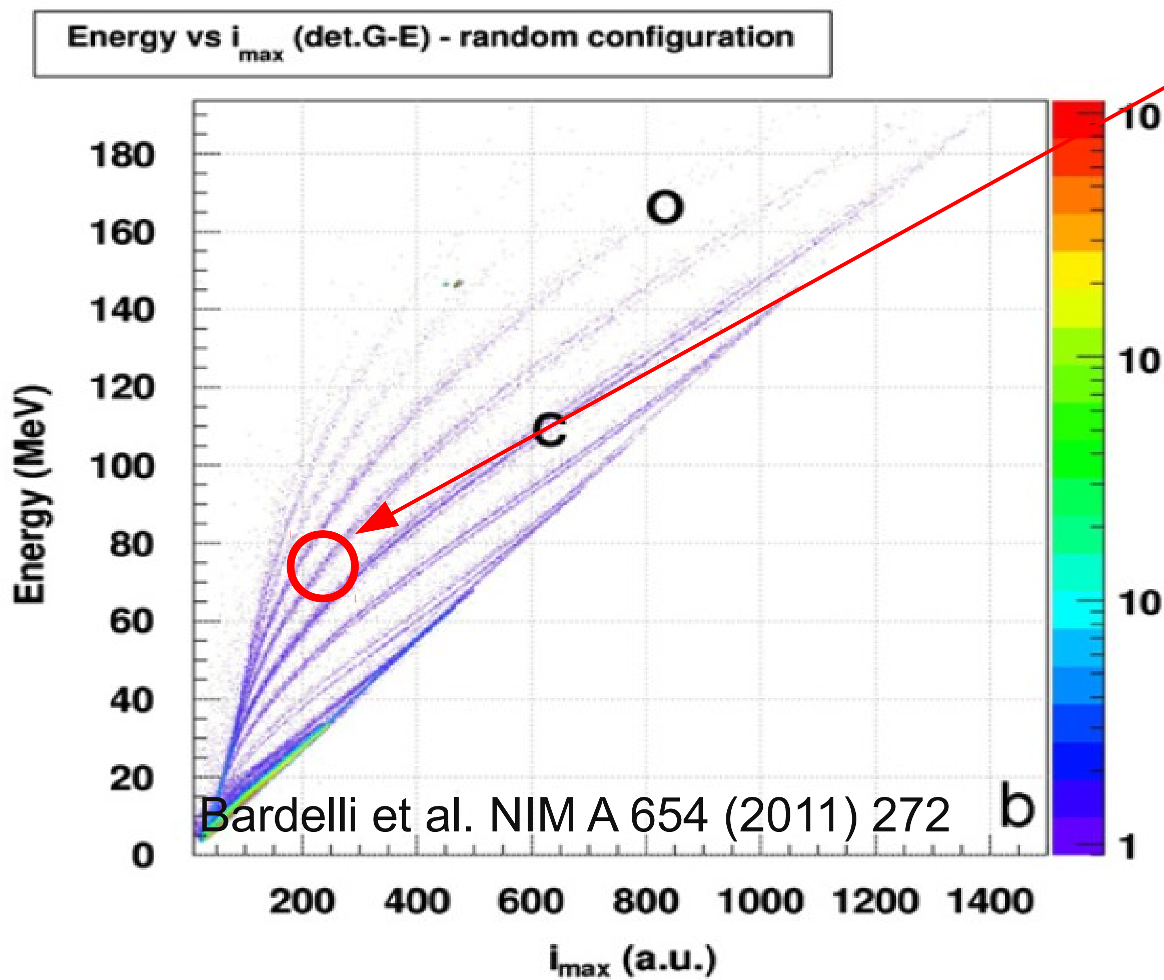
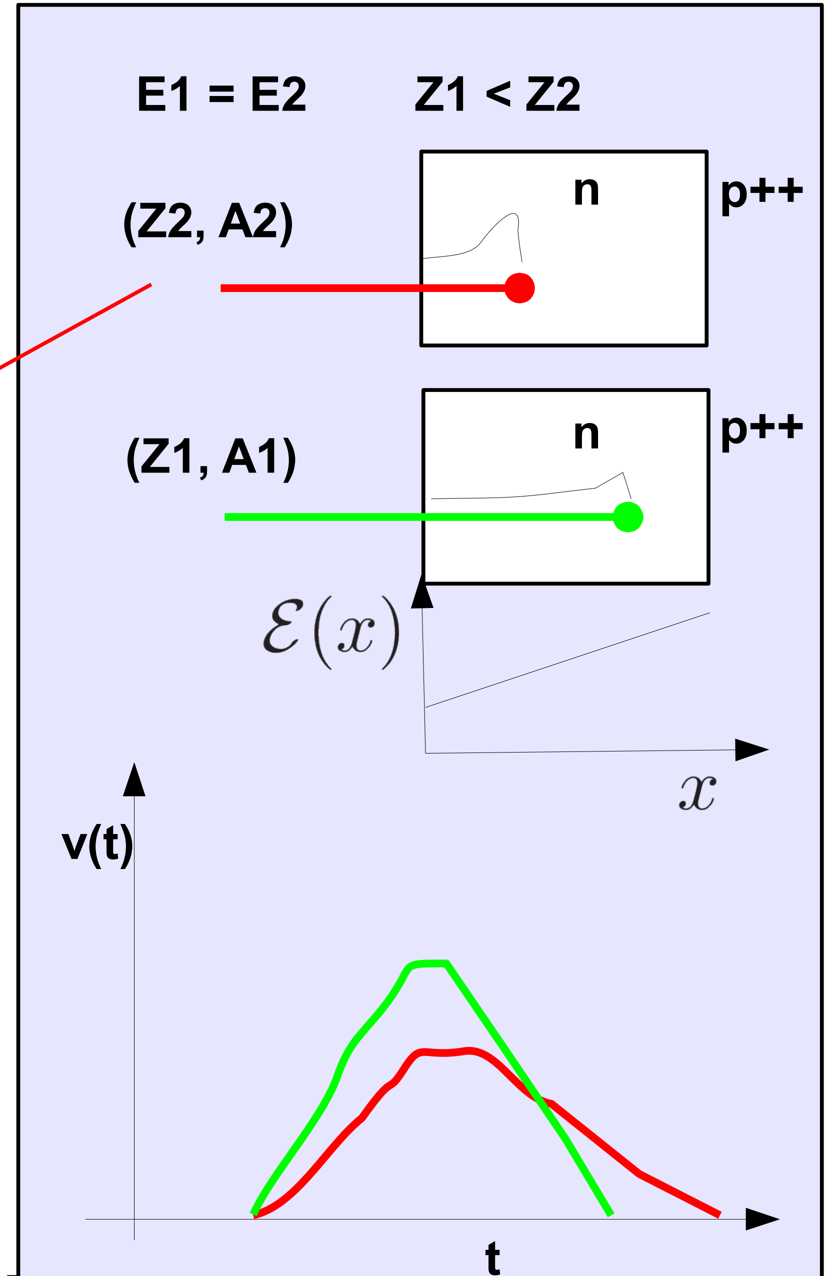


v(t)=R*i(t)





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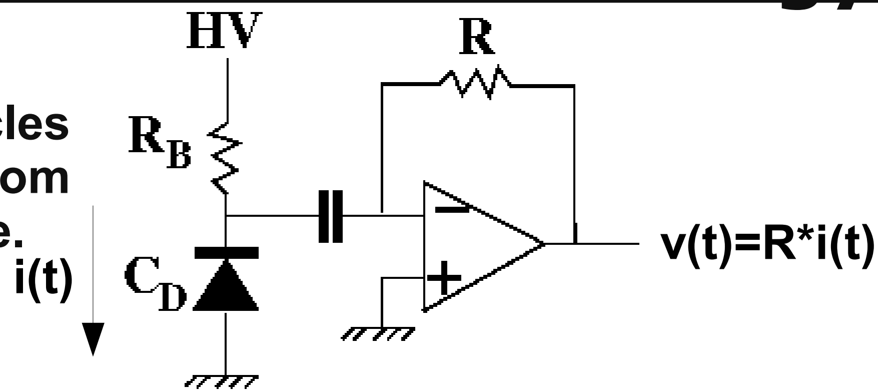

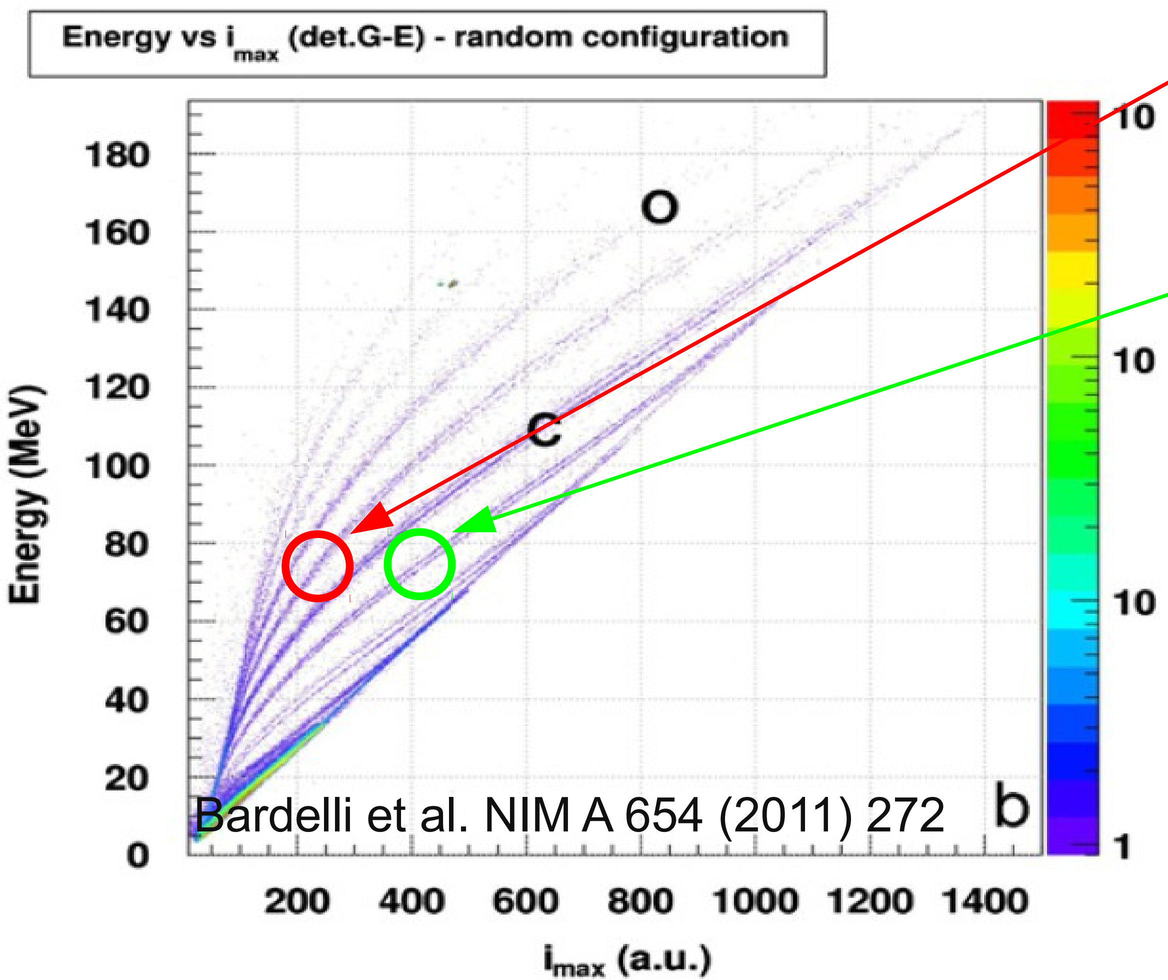

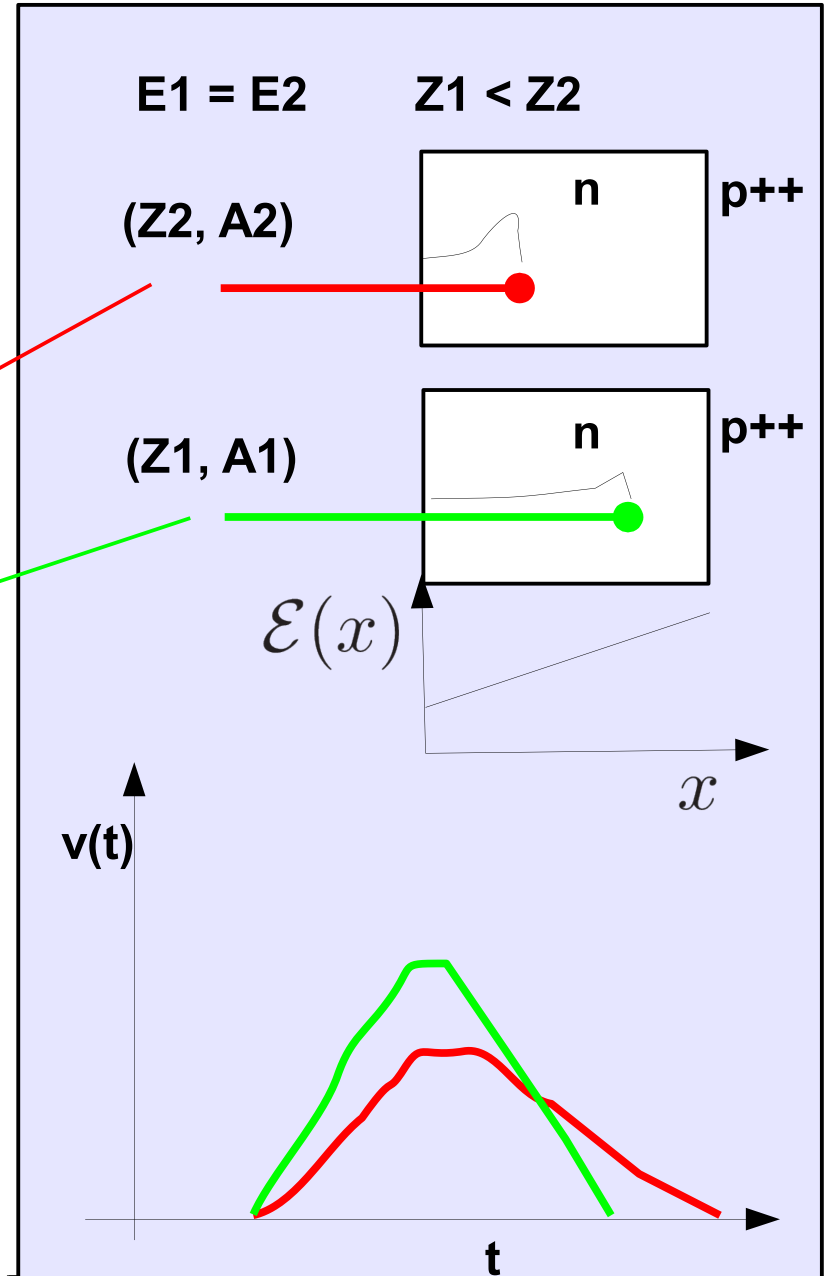

PSA in Silicon: Rise Time or max{I}?

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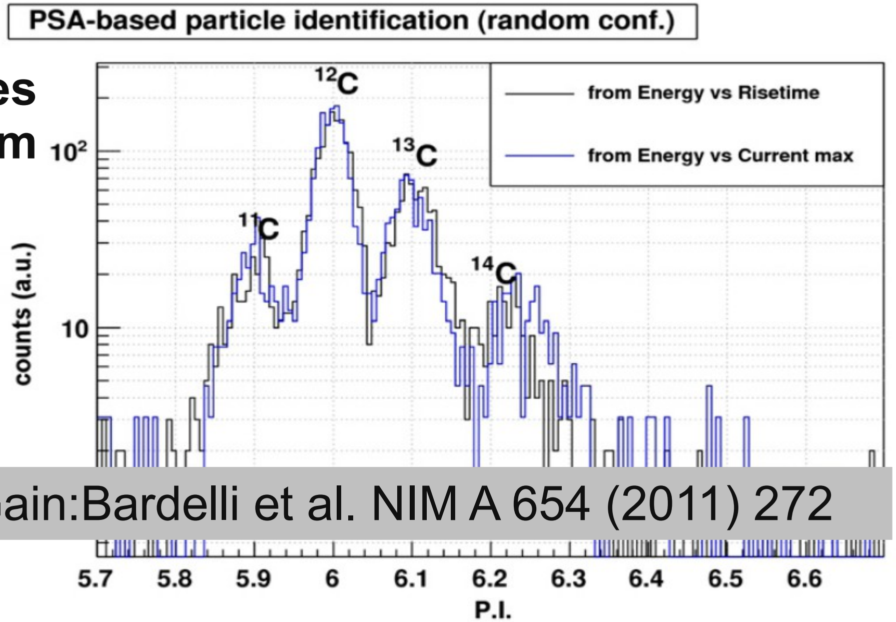
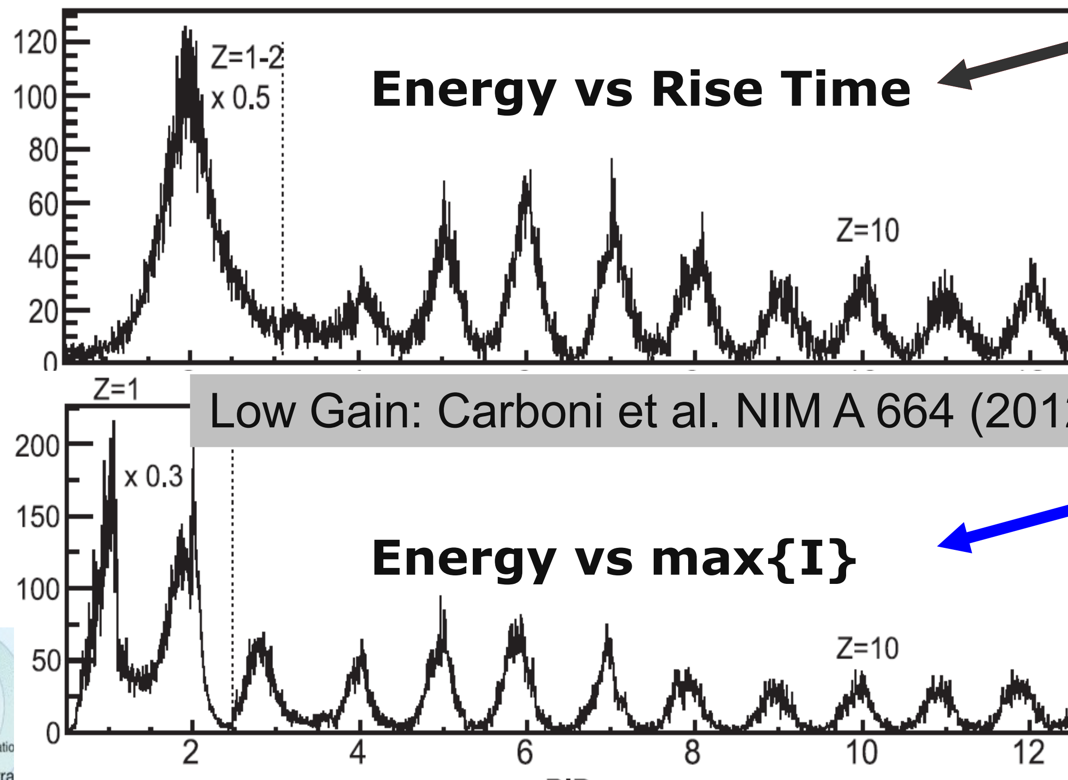
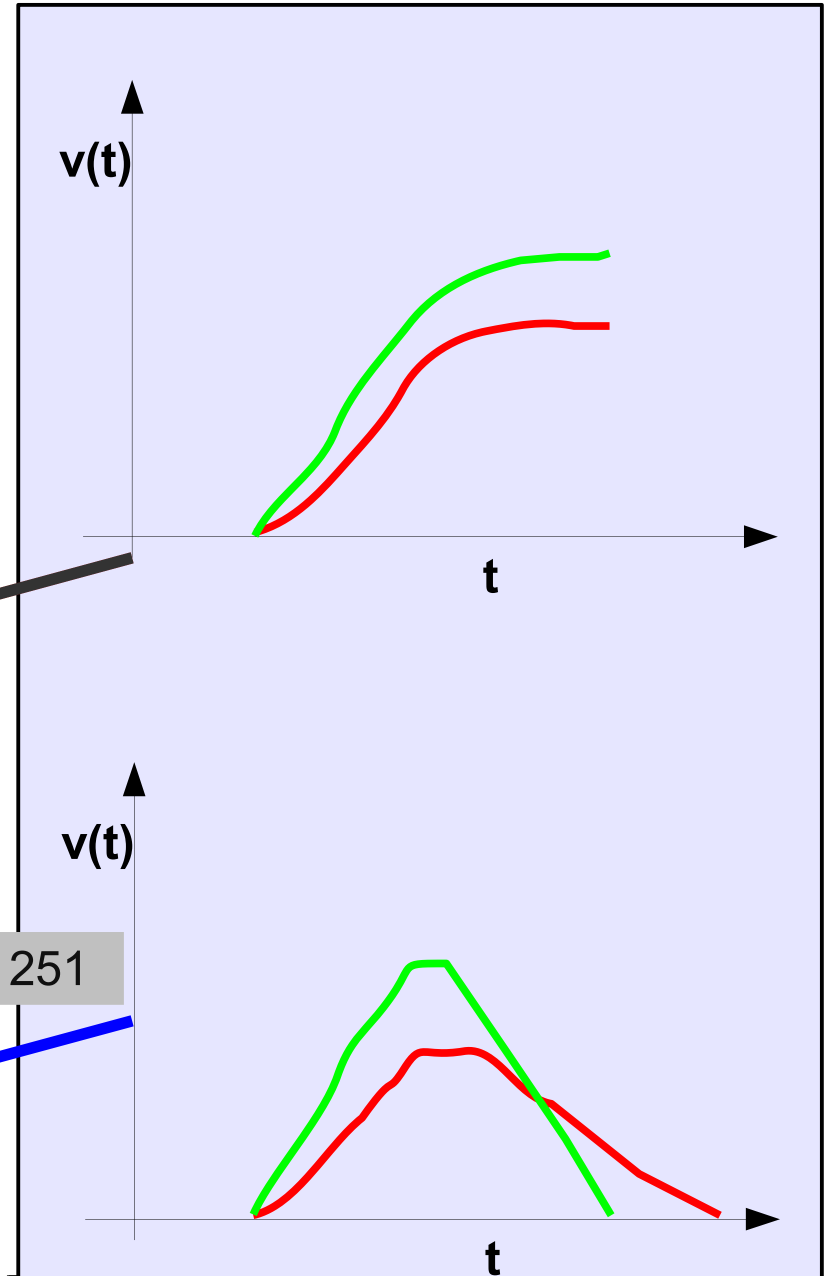


High Gain: Bardelli et al. NIM A 654 (2011) 272



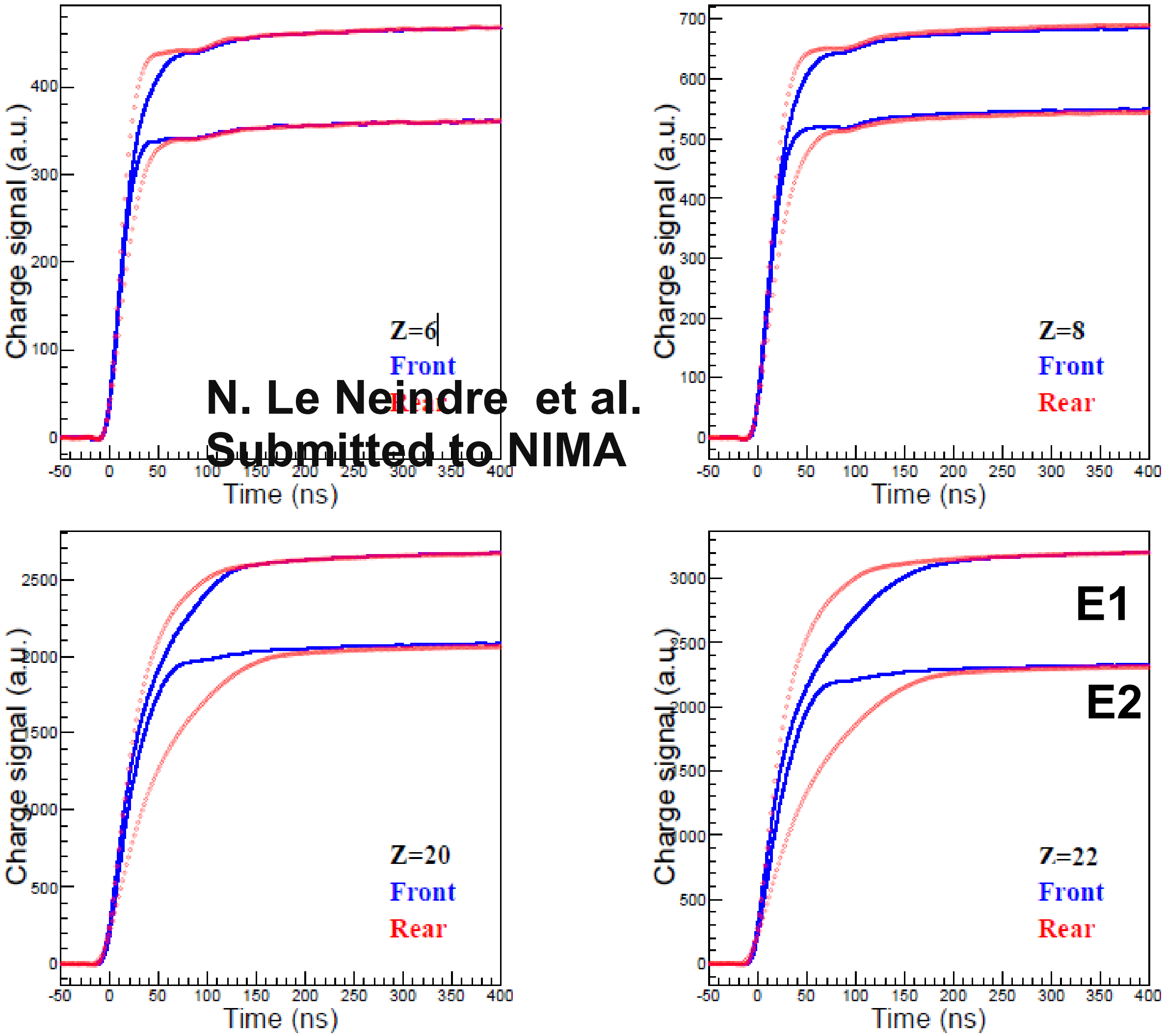
Low Gain: Carboni et al. NIM A 664 (2012) 251



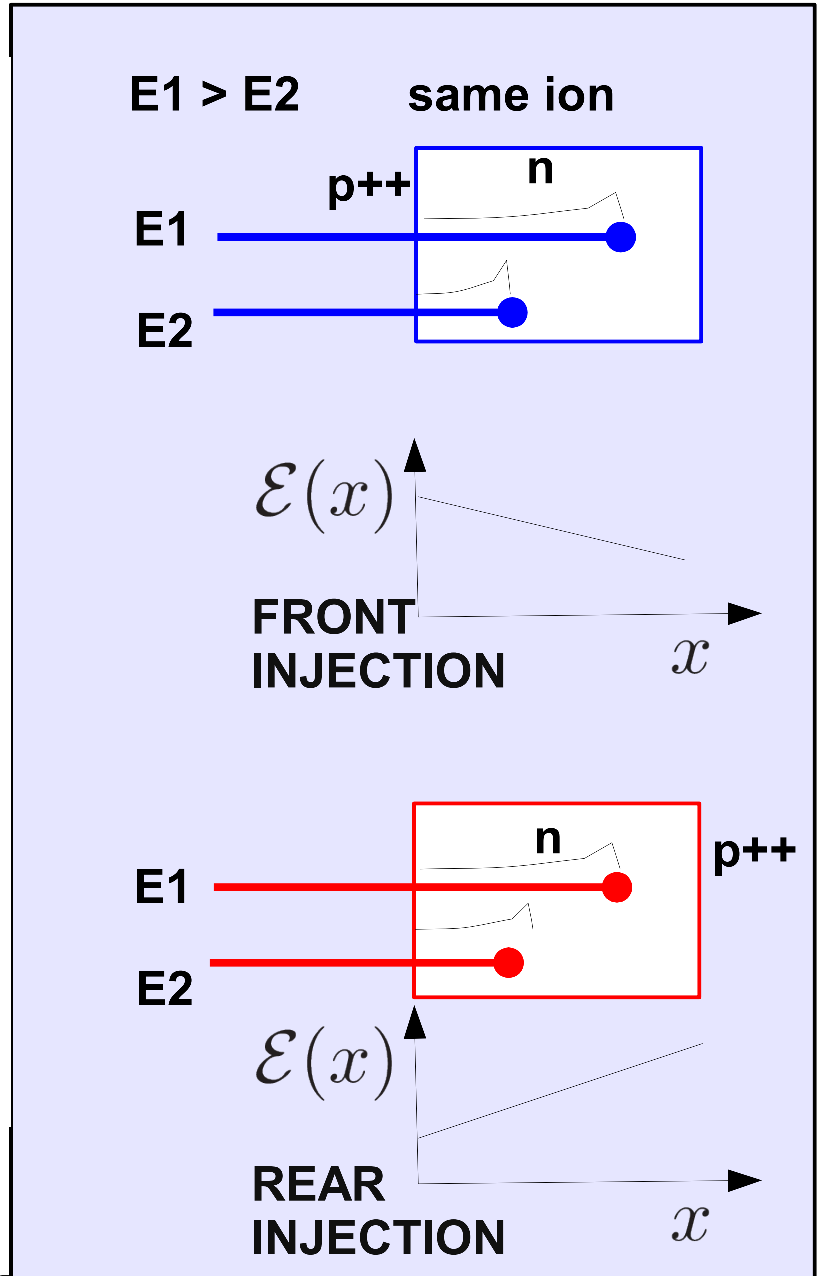
in FAZIA

PSA basics + Front/Rear injection

Plasma erosion and e-h transit time affected by charge density and penetration depth.



N. Le Neindre et al.
Submitted to NIMA



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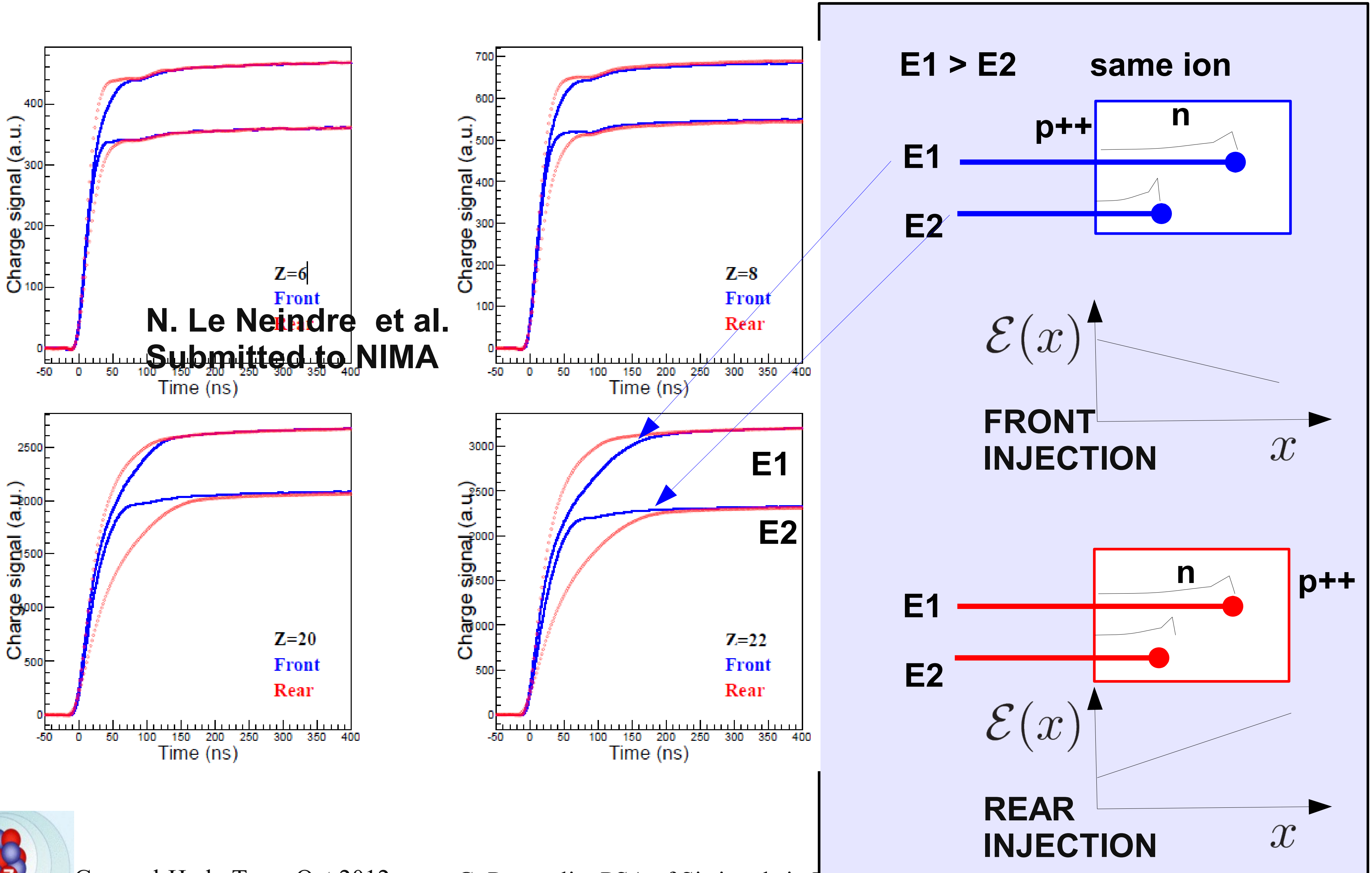

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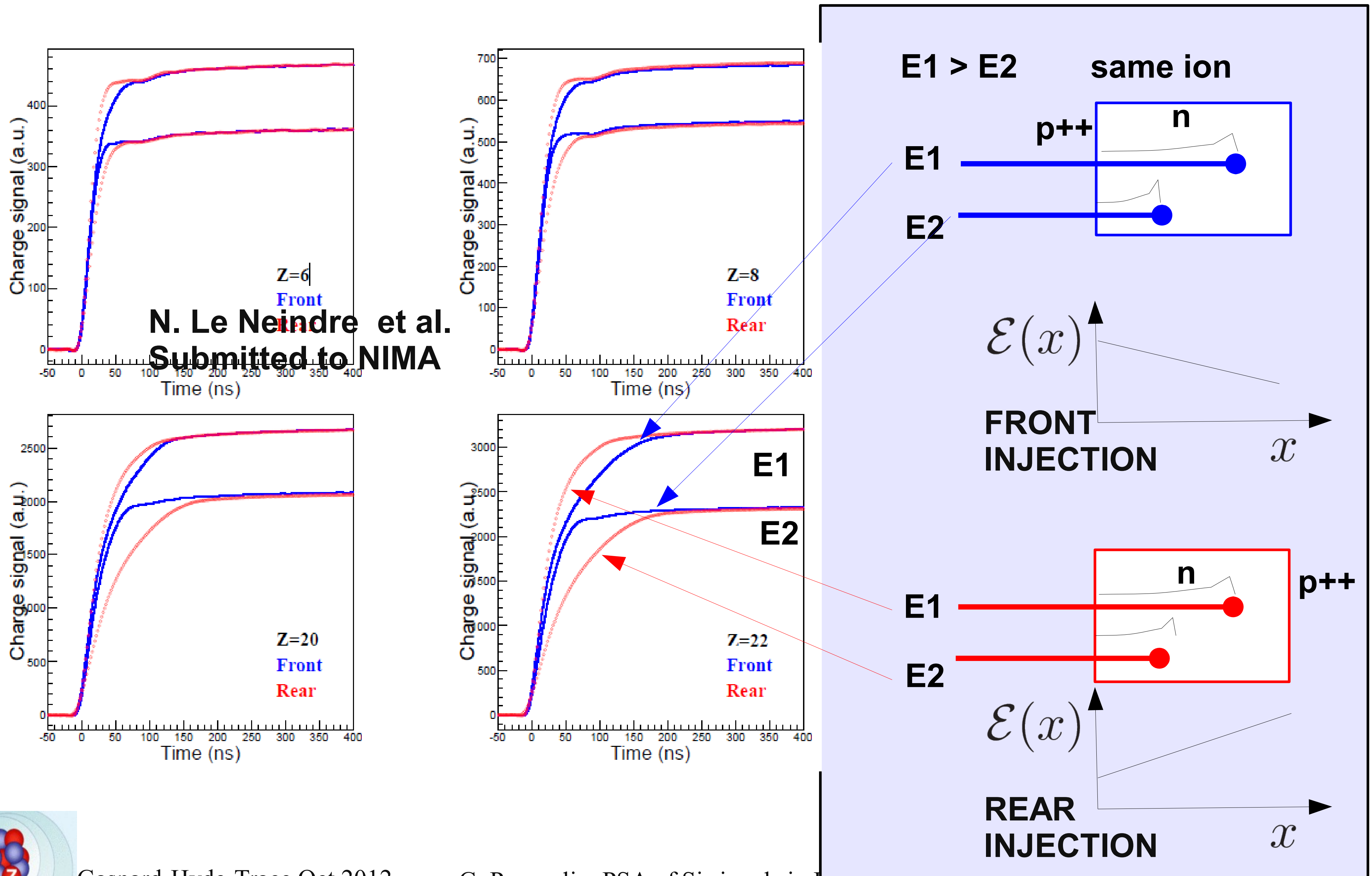
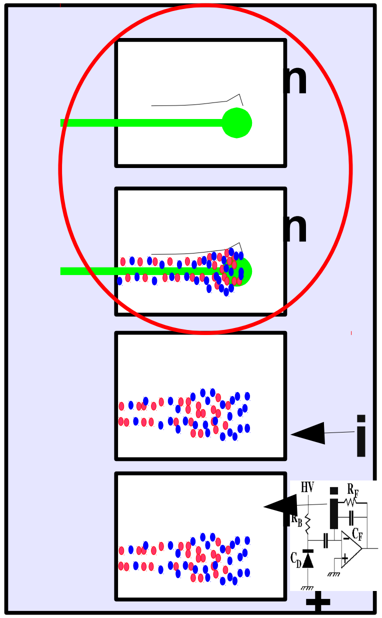
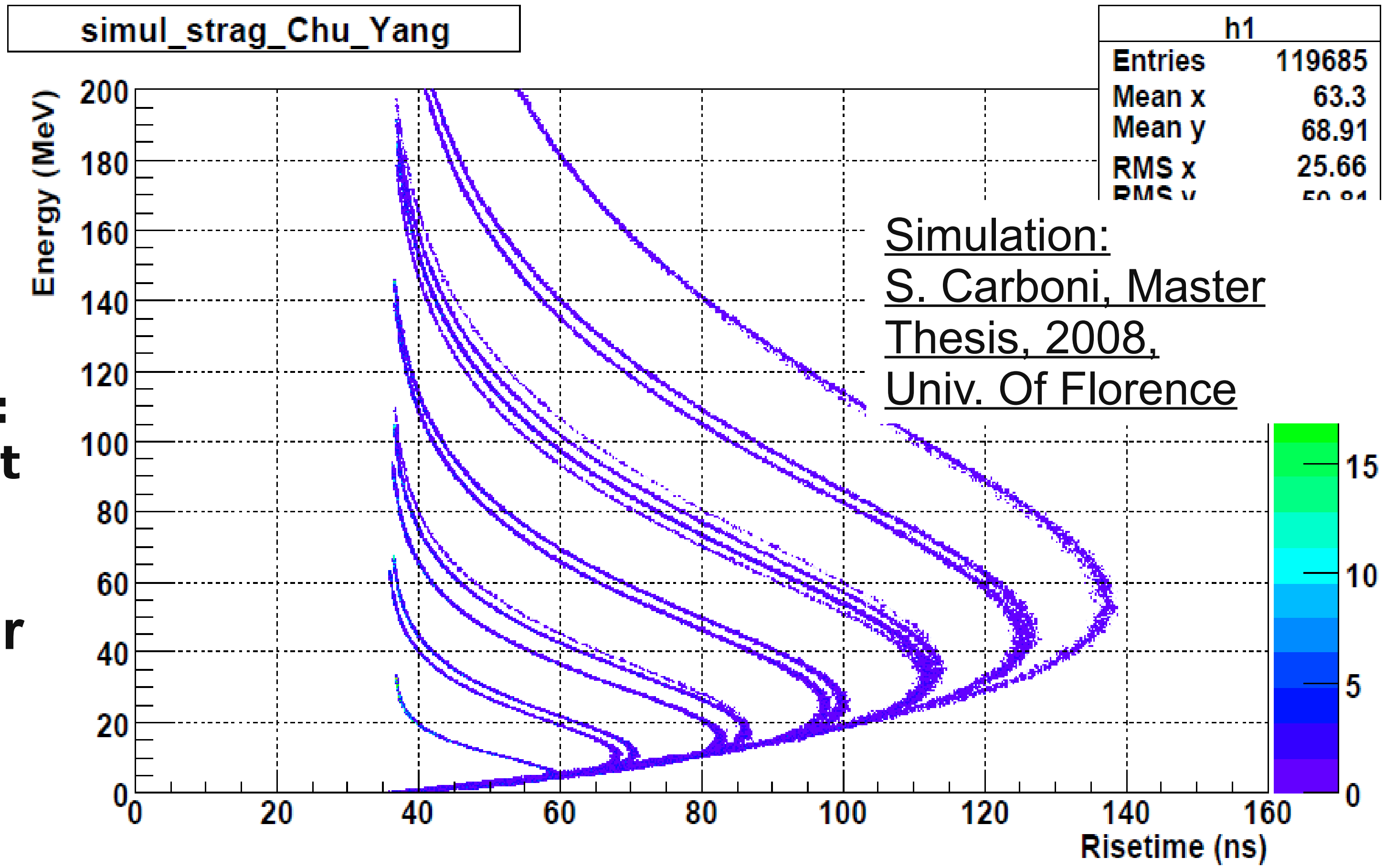


Effects spoiling PSA

Spoiling PSA: Range straggling



- Ion stopped in Si: energy deposition in bulk
- Longitudinal straggling => carrier density fluctuates



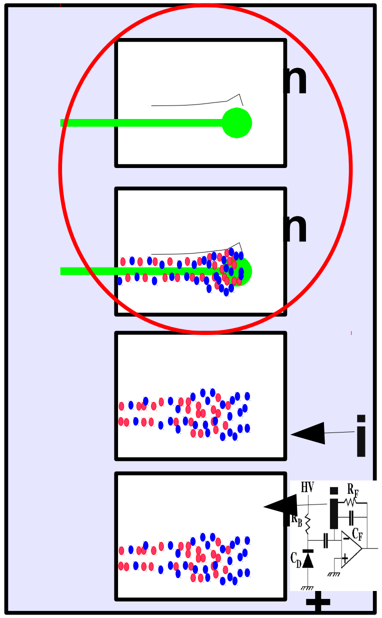
AVERAGE VALUES:

- **From experiment**

FLUCTUATIONS:

- **"Corrected" Bohr straggling**
- **Seibt et al. Rise time parameter.**

Spoiling PSA: Range straggling



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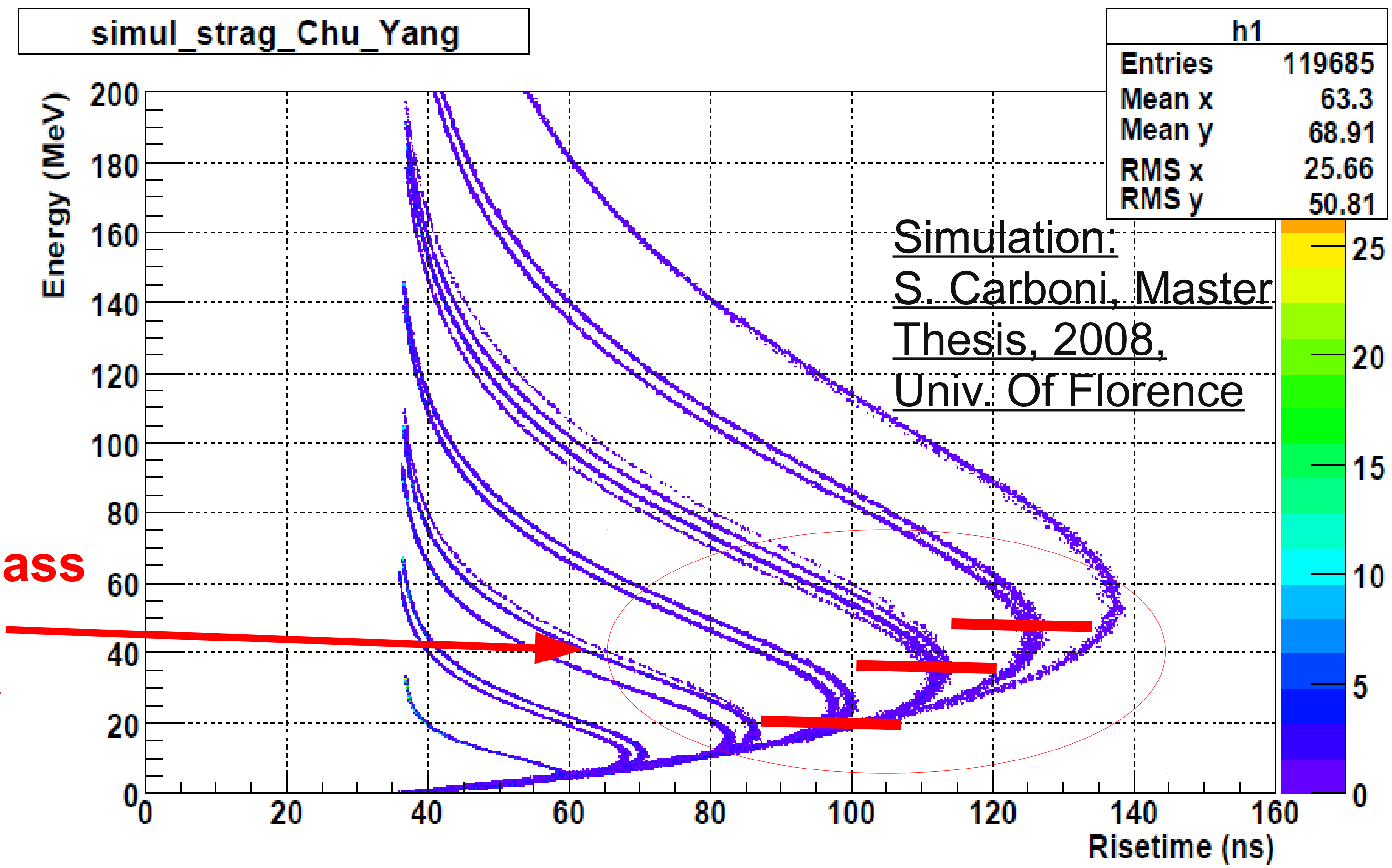
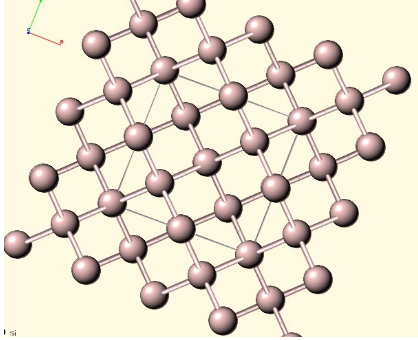
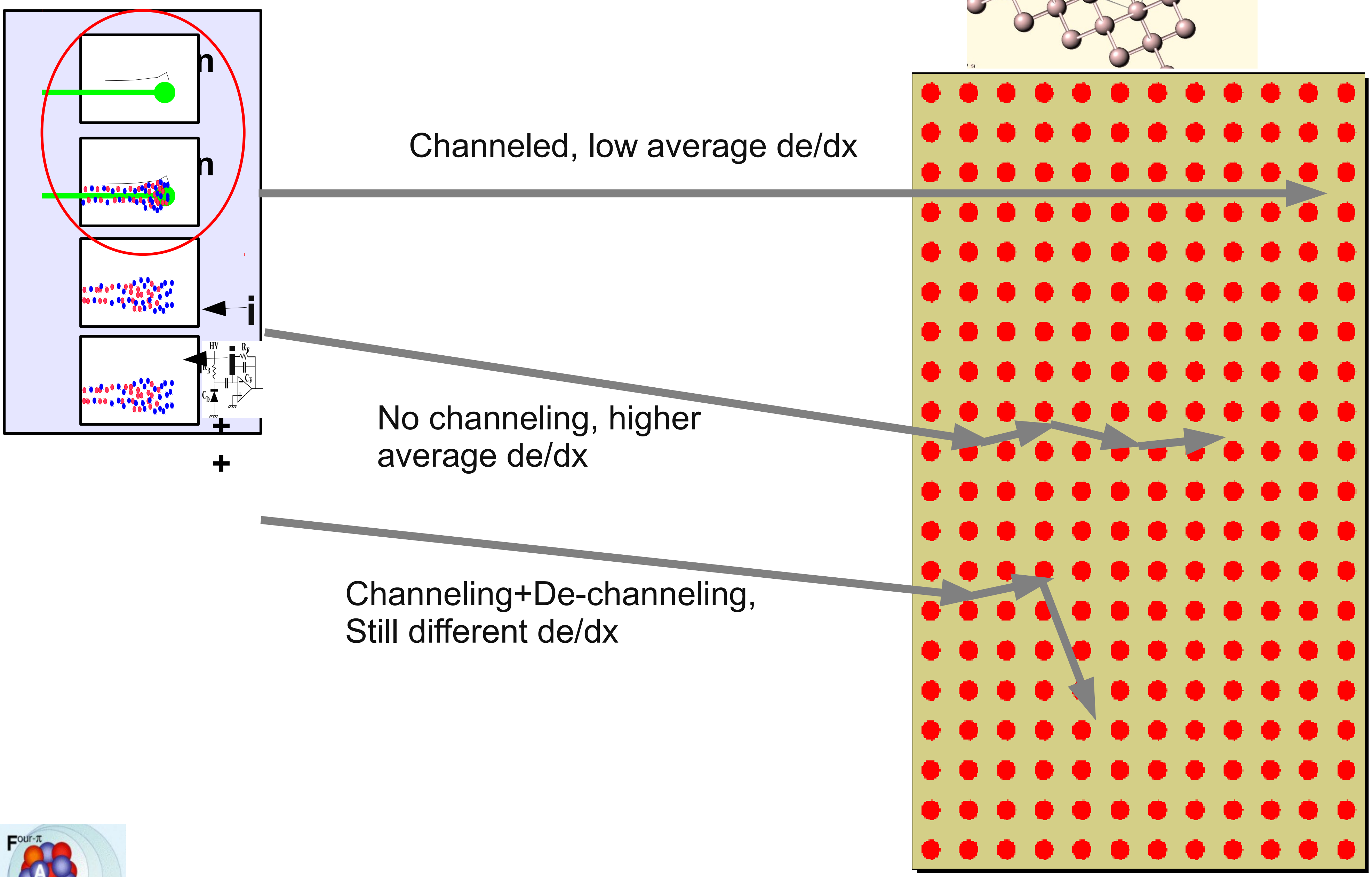


Low energy threshold for mass identification. Increase with A

Spoiling PSA: Channeling





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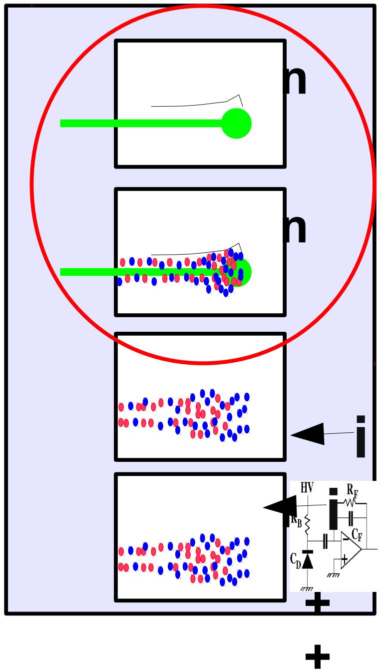

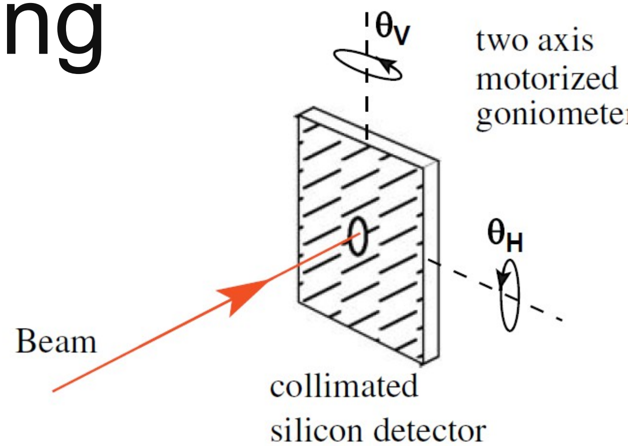

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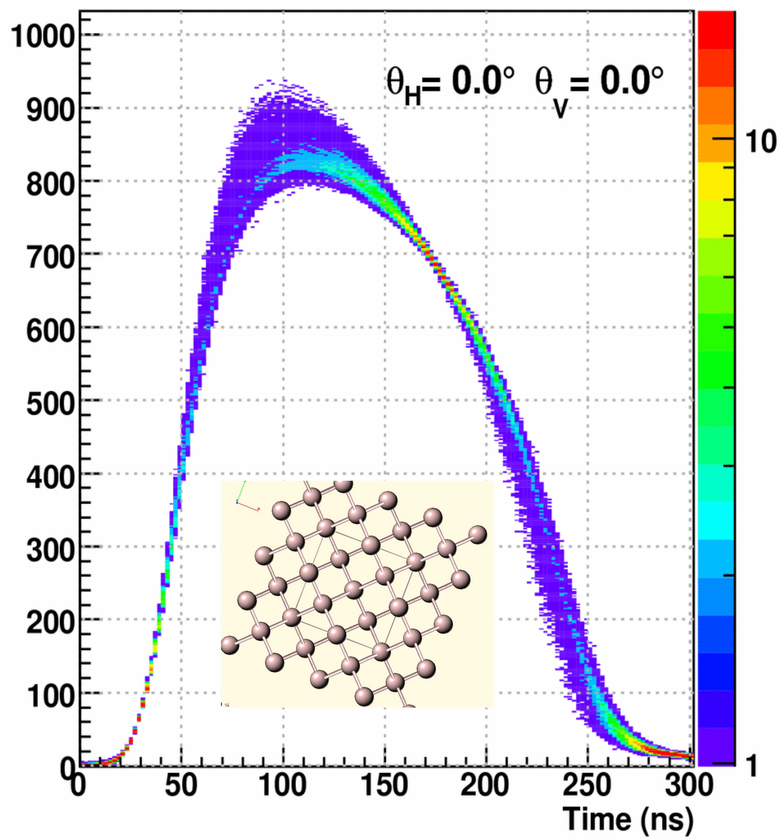
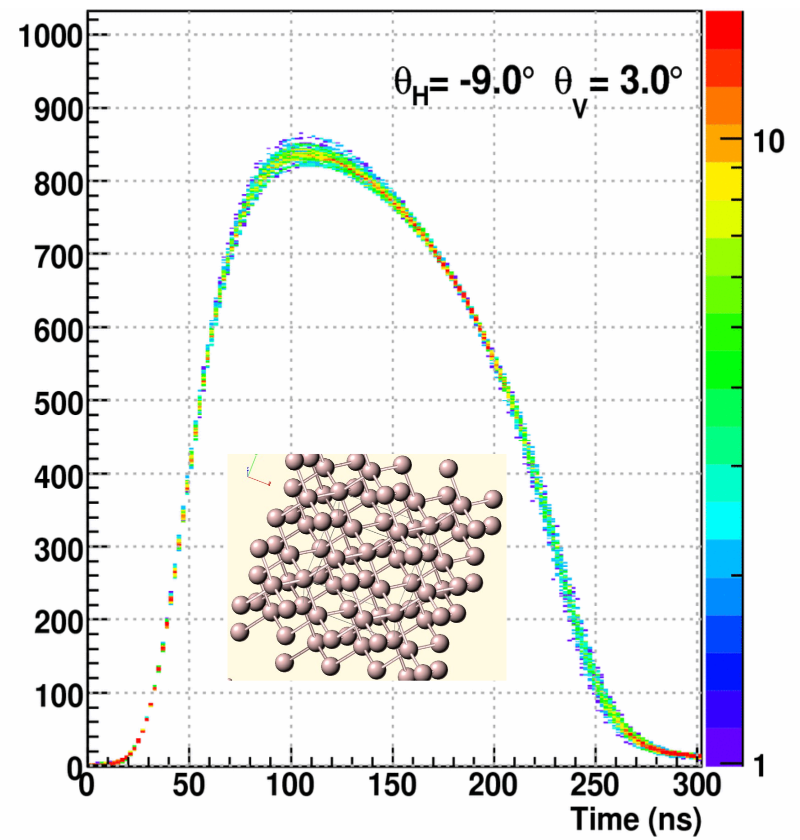
Current signals for a ^{80}Se @ 410MeV, <100> detector, 1000 events:





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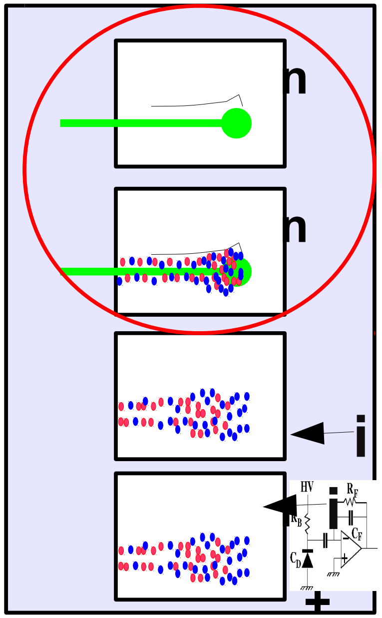

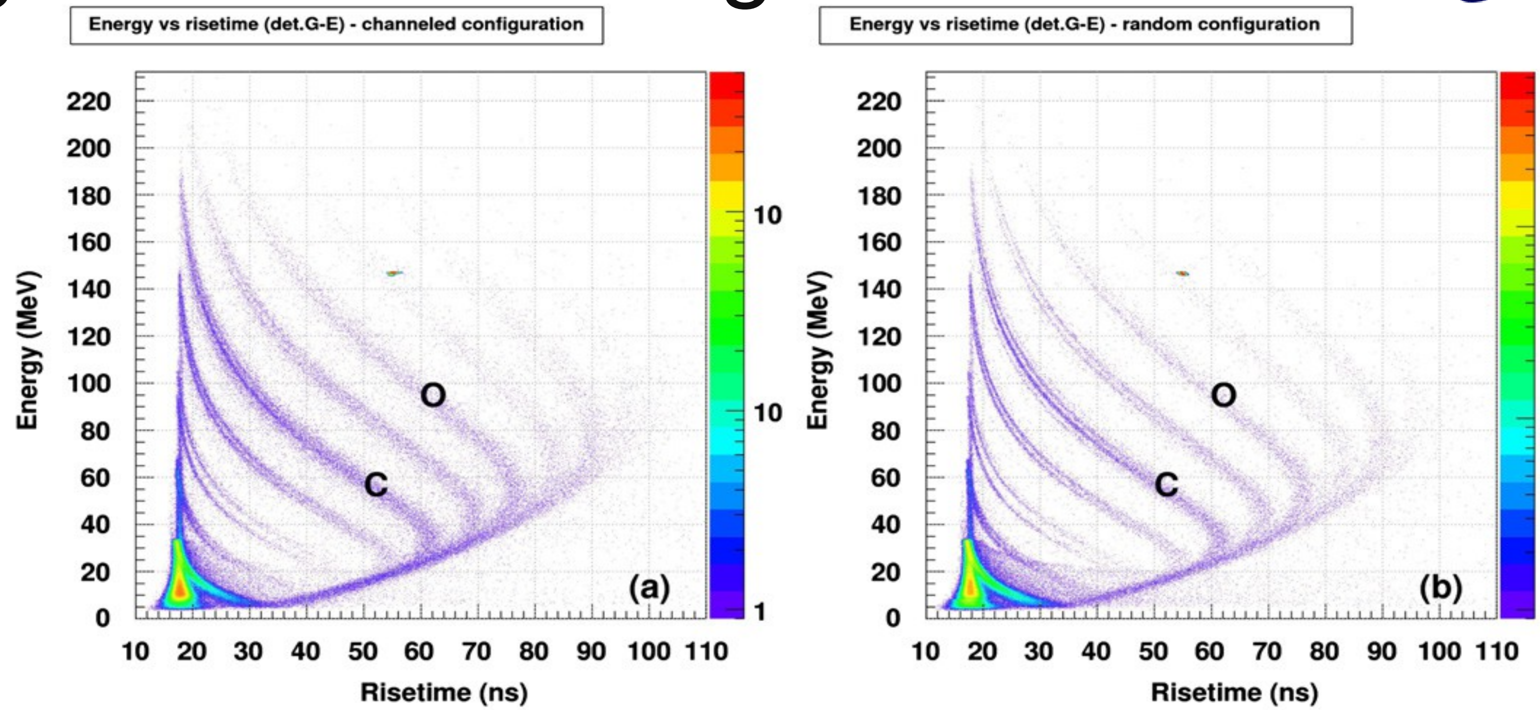

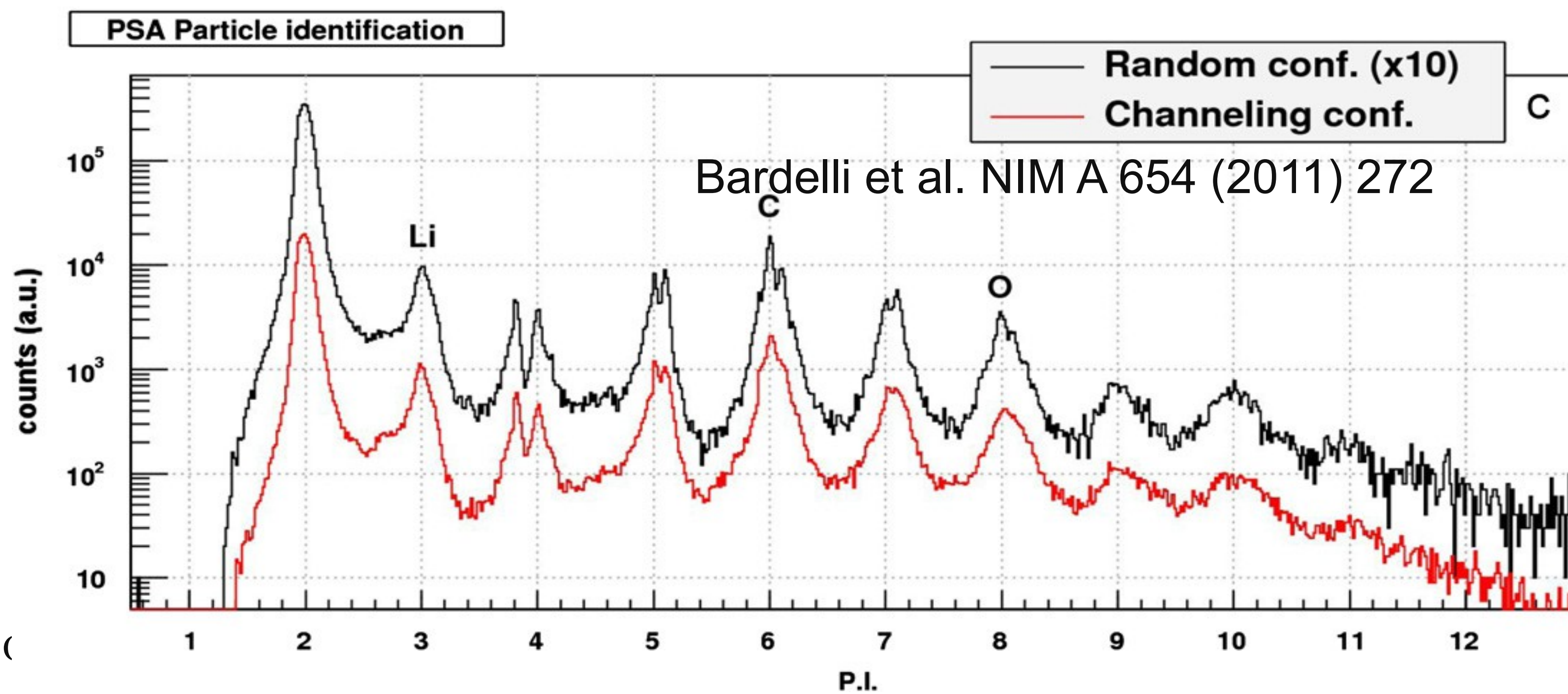

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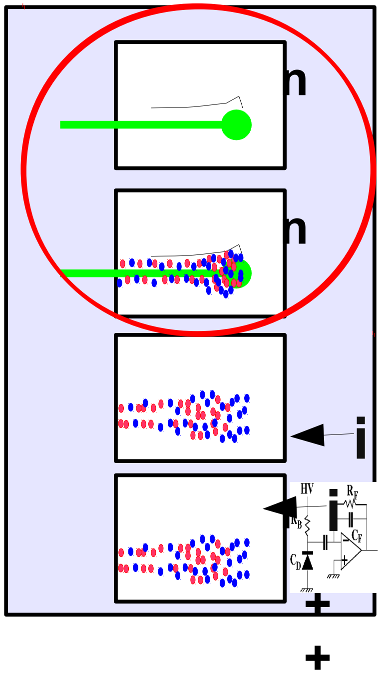

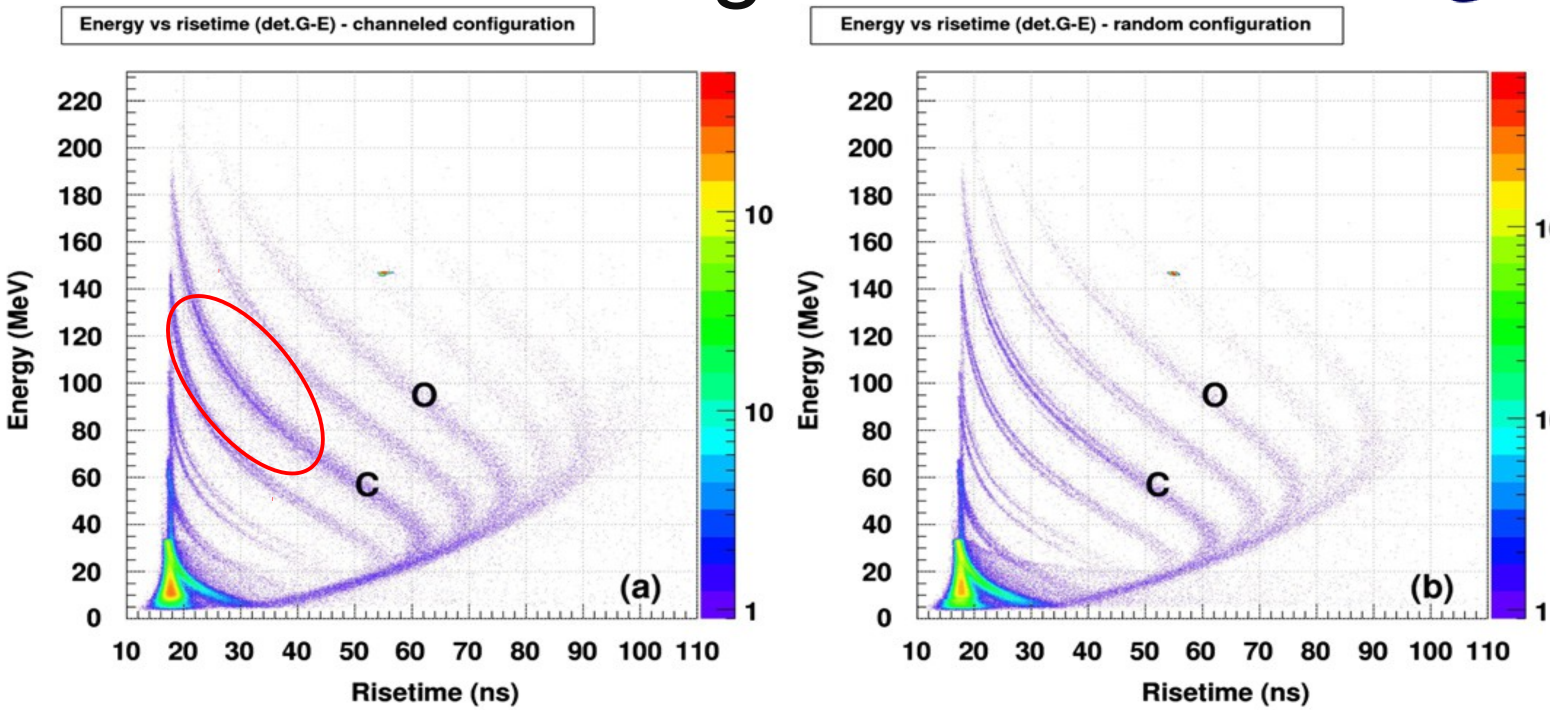

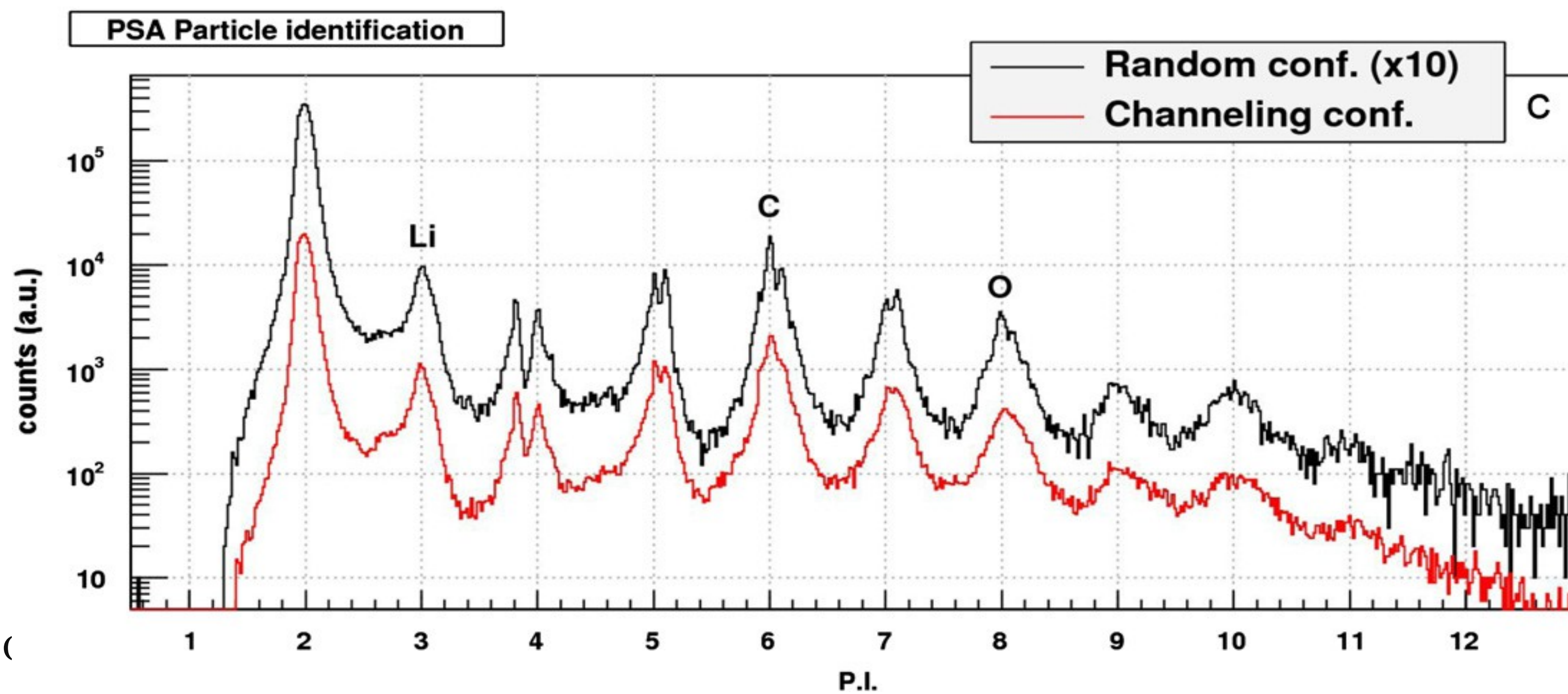

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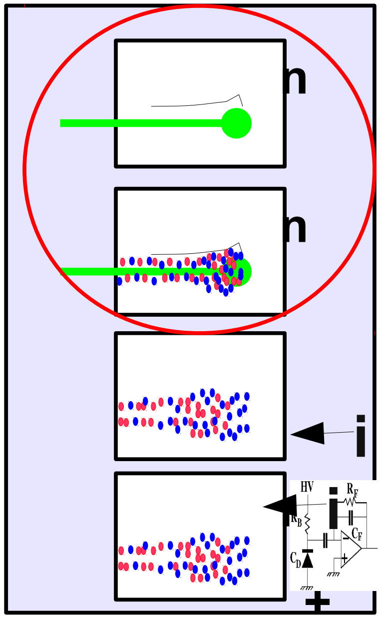

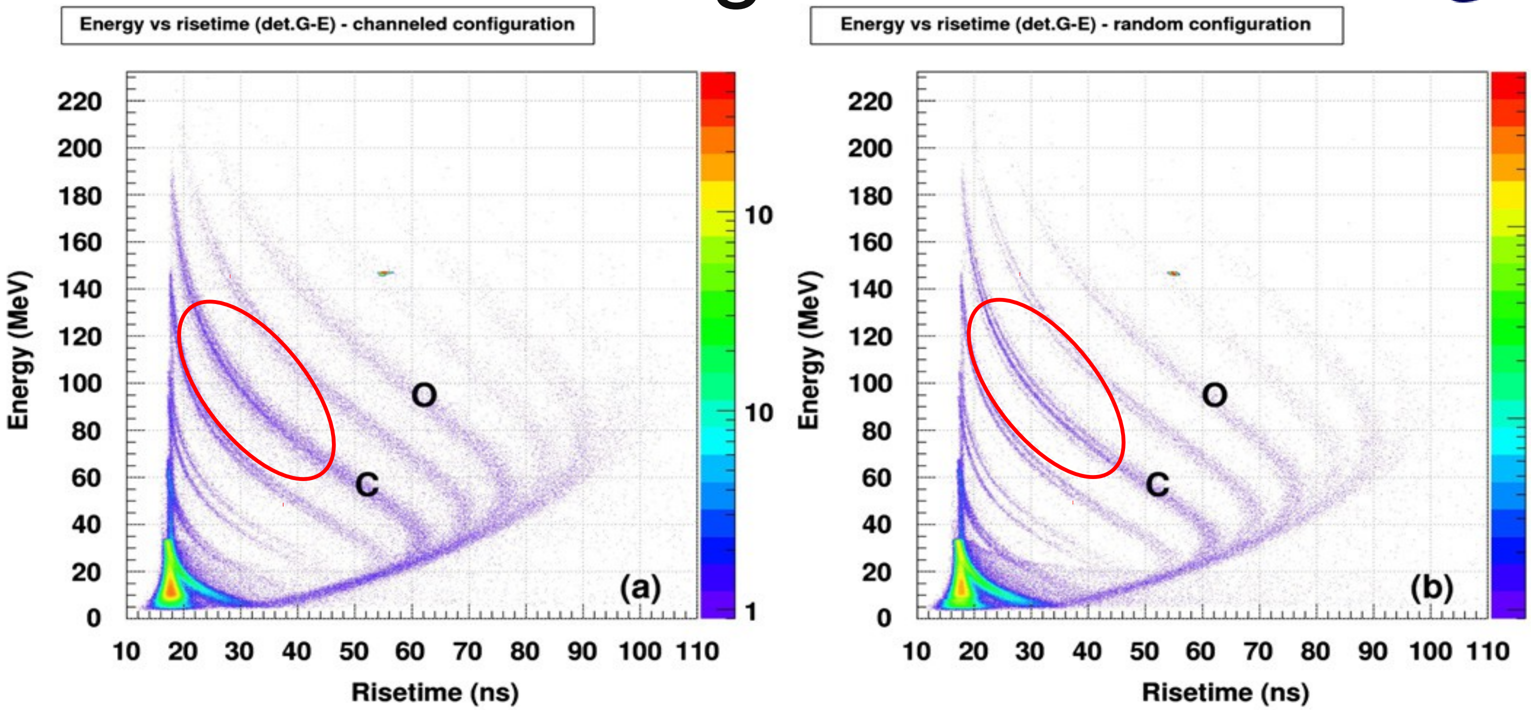

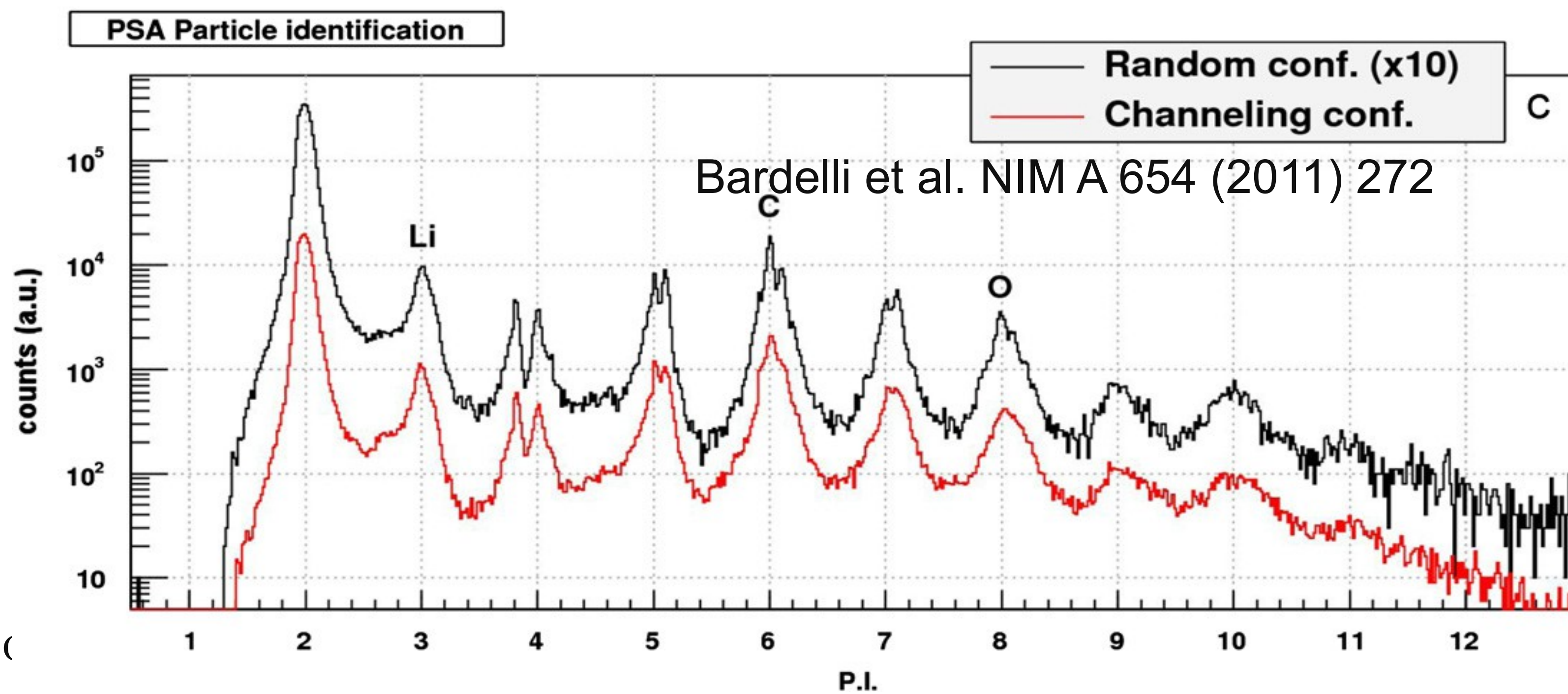

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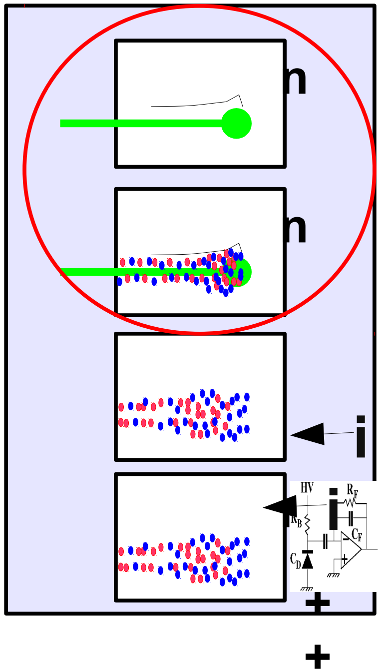

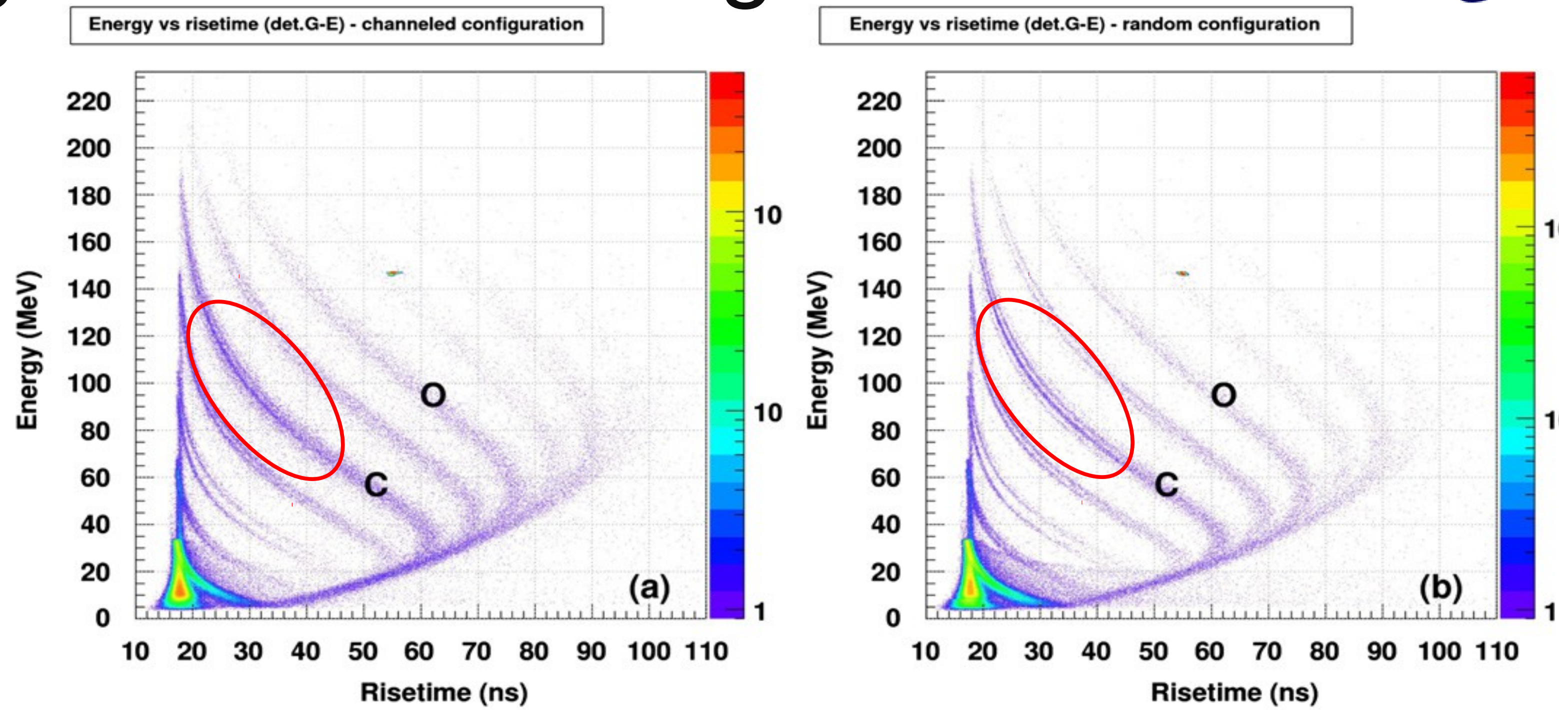

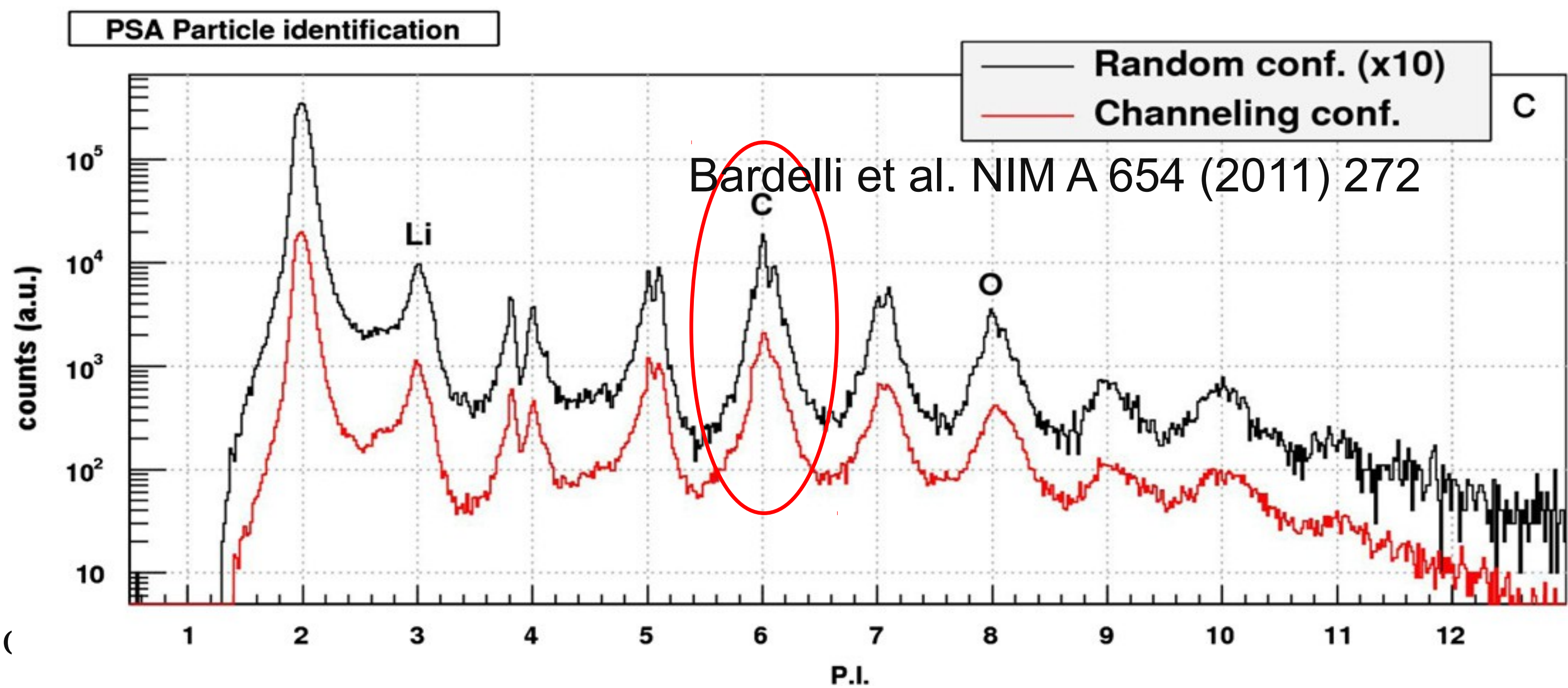

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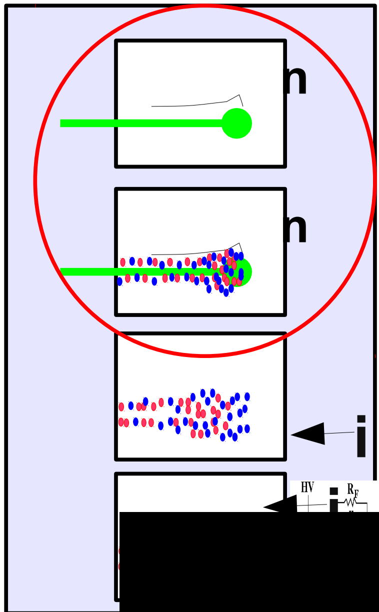
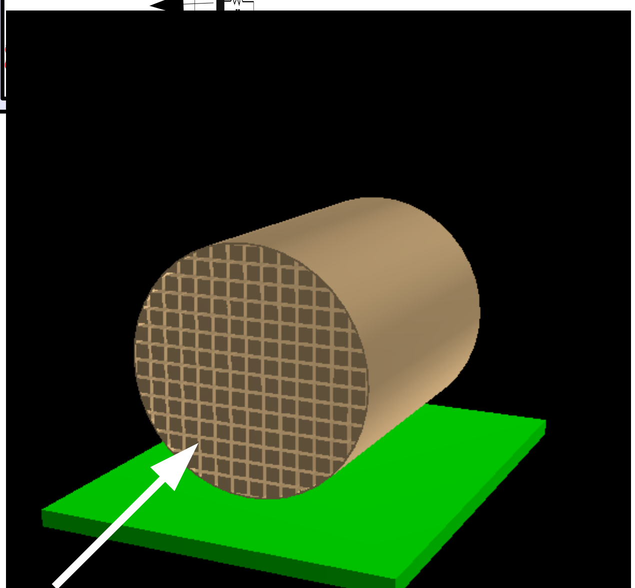
Spoiling PSA: Avoiding Channeling



Silicon wafers can be cut from silicon ingots with a special cut: in order to recover the “best” experimental configuration, two angles are needed: for <100> θ_{off}=8°, φ=13°

Maximum angular detector coverage: ±2°

start from a silicon ingot (i.e. <100>)...



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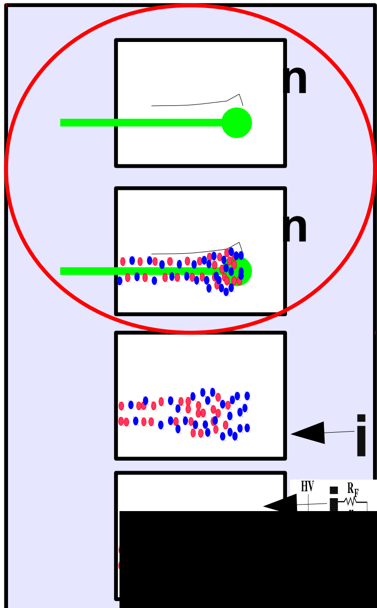

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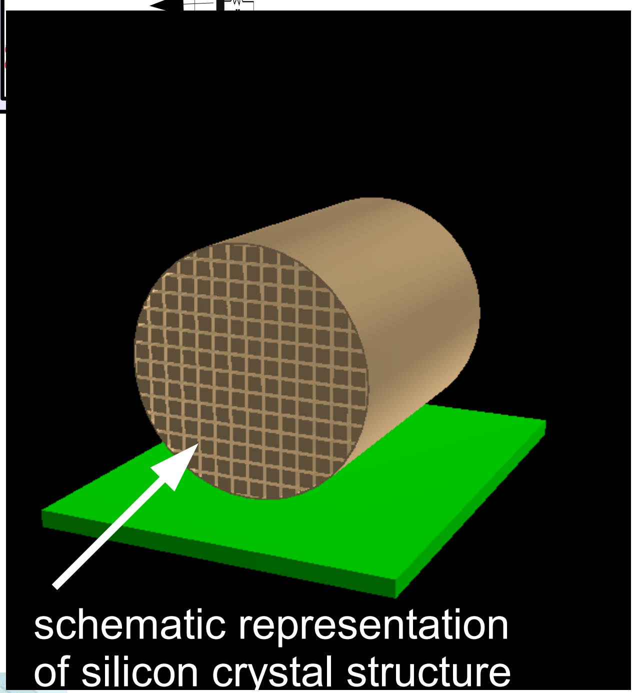
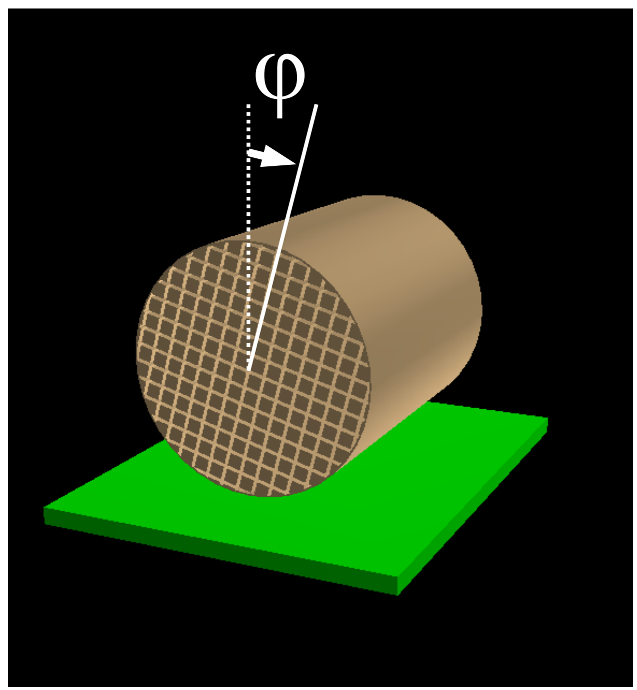


...rotate along the symmetry axis...



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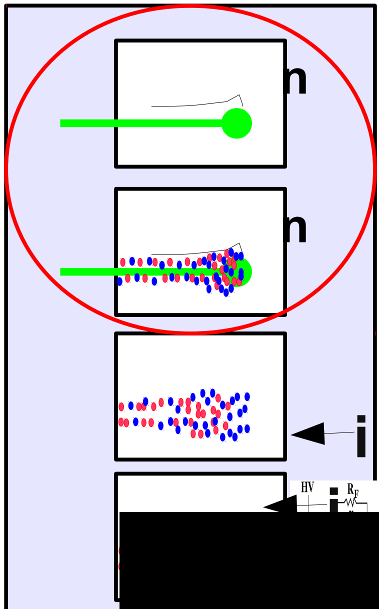

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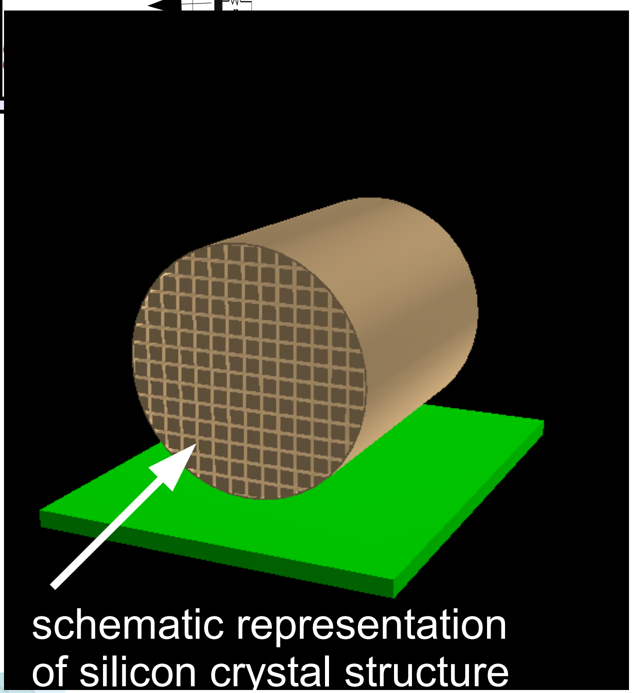

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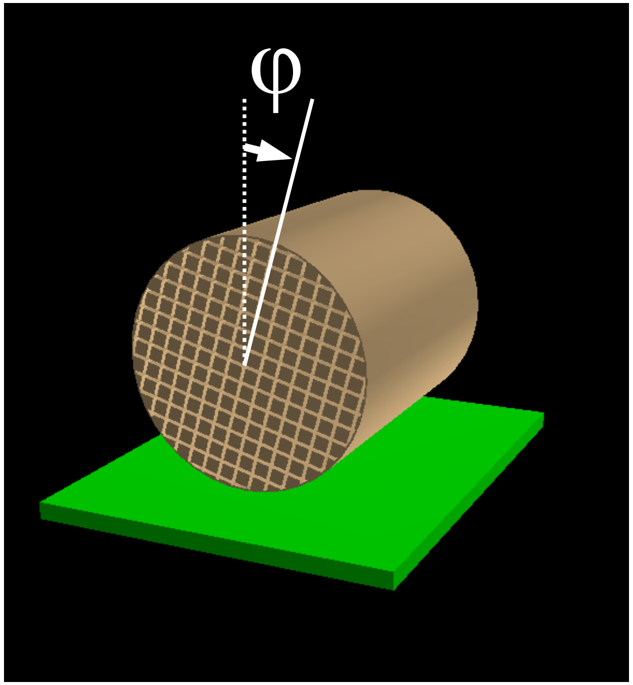
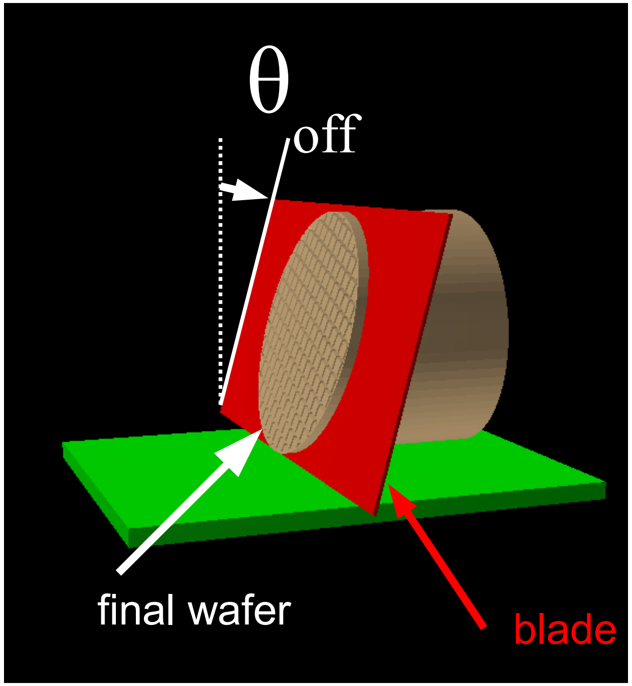
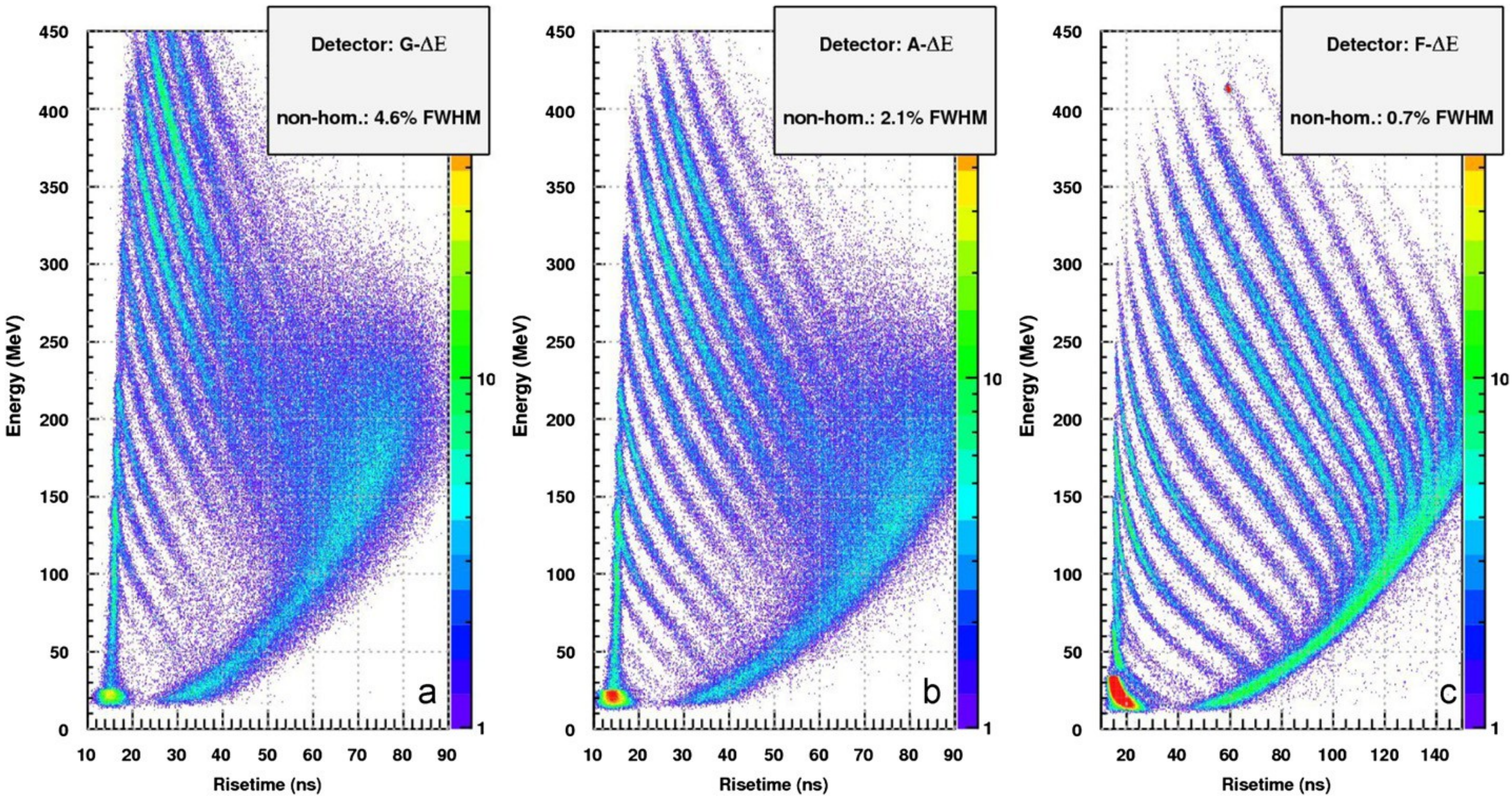


...perform an off-axis wafer cut.



Spoiling PSA: Non uniform doping

All detectors nTD Si => standard nTD uniformity not enough



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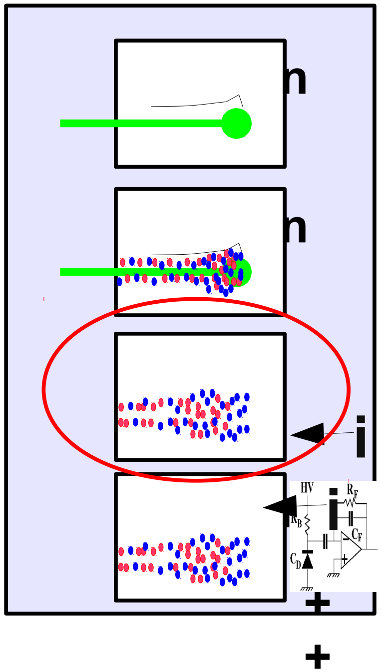
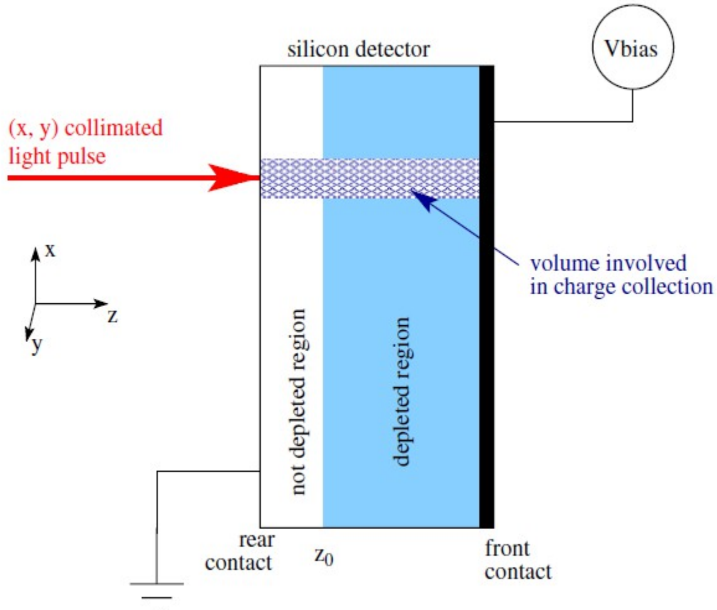
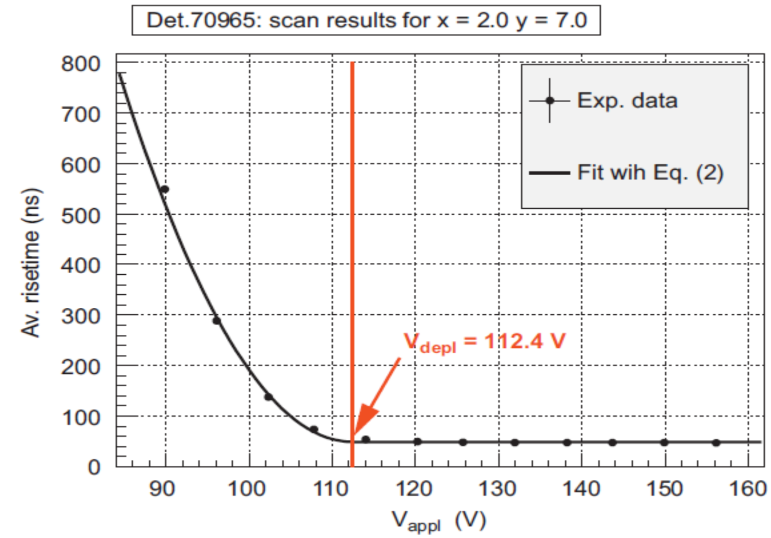
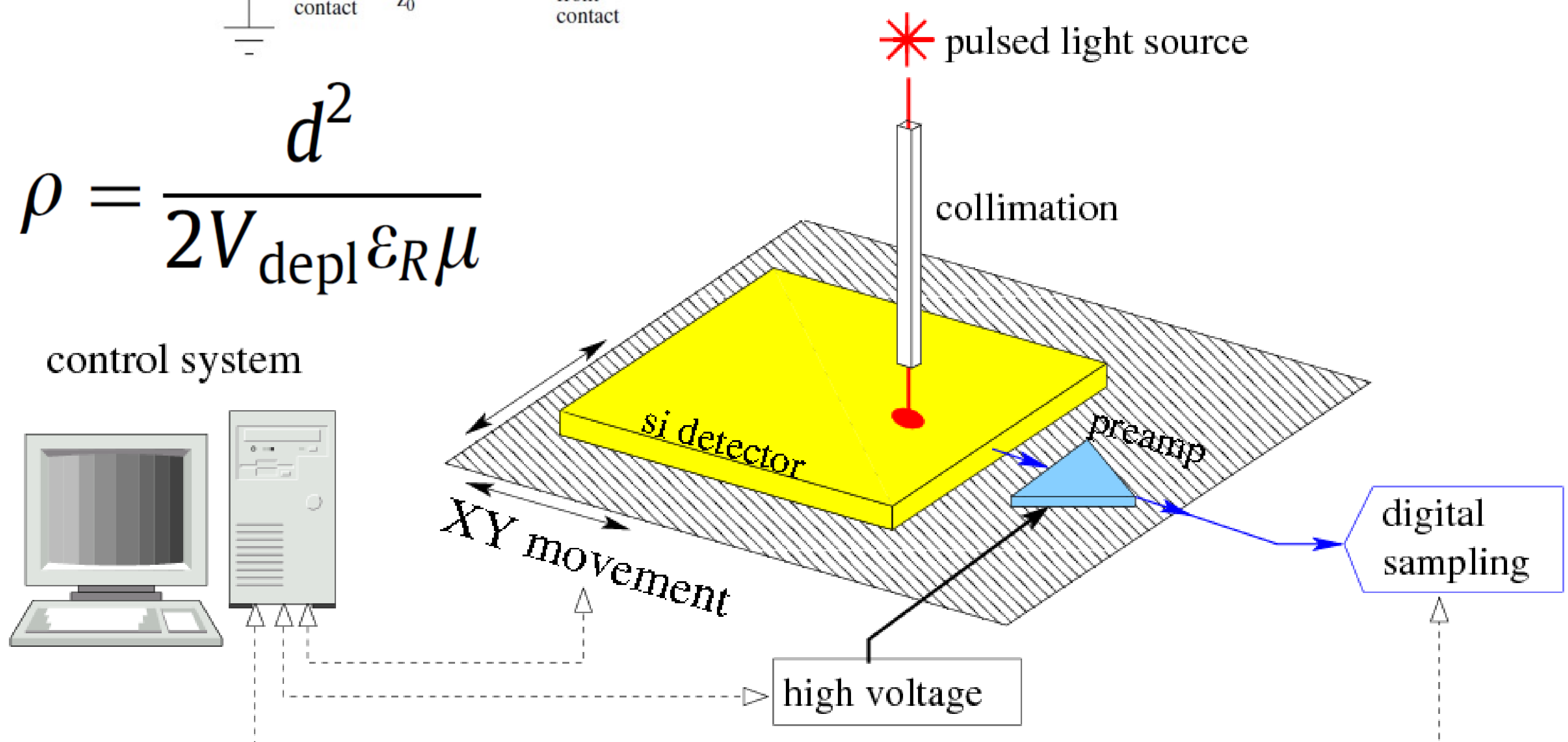
Spoiling PSA: Non uniform doping







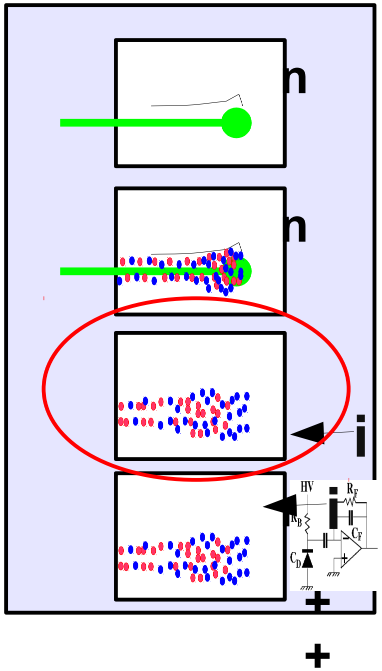
$$\rho = \frac{d^2}{2V_{\mathrm{depl}}\varepsilon_R\mu}$$



Gaspard-Hyde-T

Bardelli et al. NIM A 602 (2009) 501

Spoiling PSA: Non uniform doping

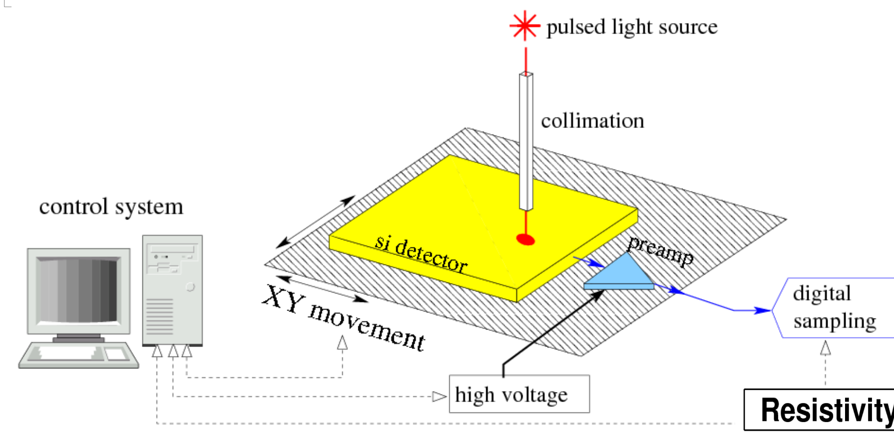


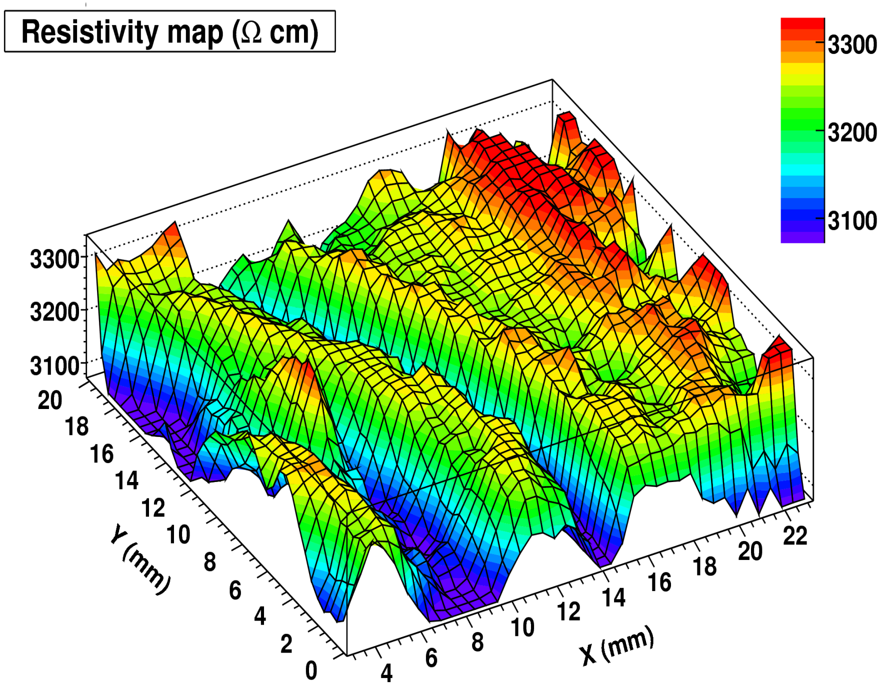
The detector is mounted on a XY movement.

A point-like light pulse irradiates the ohmic side

Shapes are collected with a digitizer

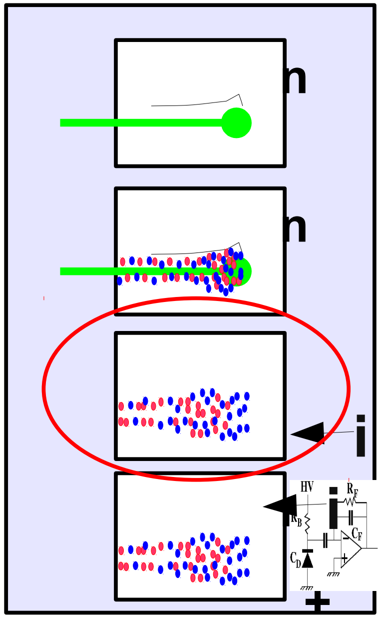
Both the XY support and the HV are computer controlled.





Bardelli et al. NIM A 602 (2009) 501

Spoiling PSA: Non uniform doping



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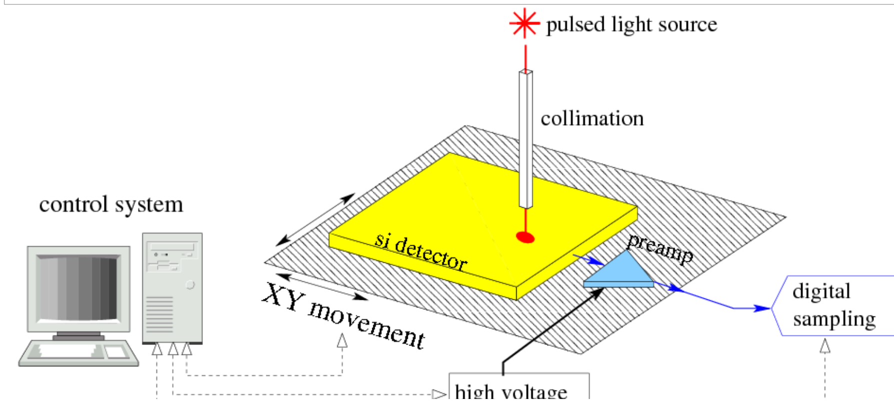
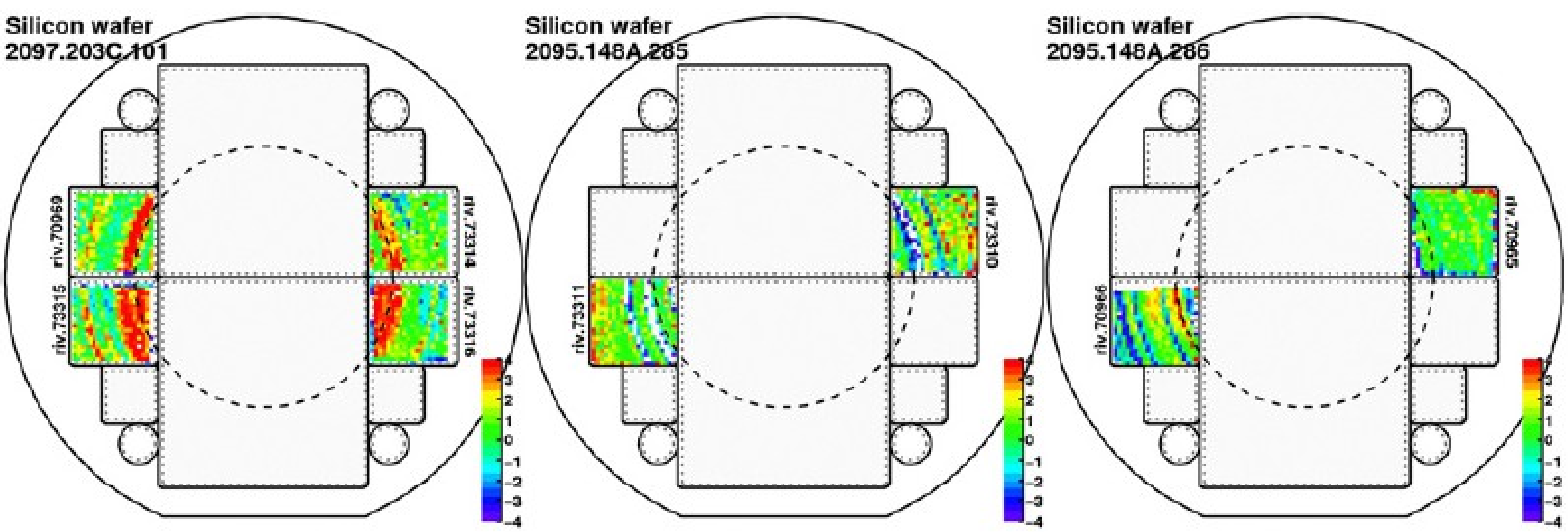
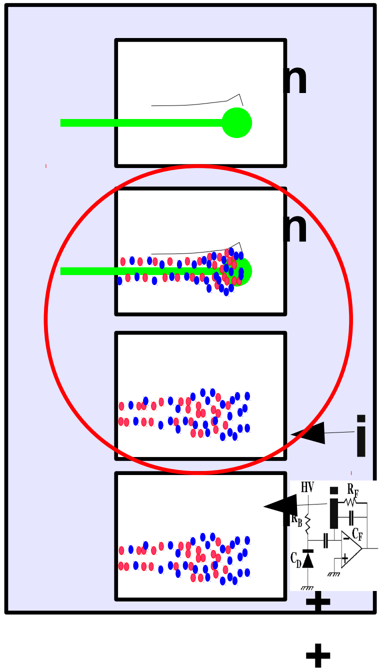




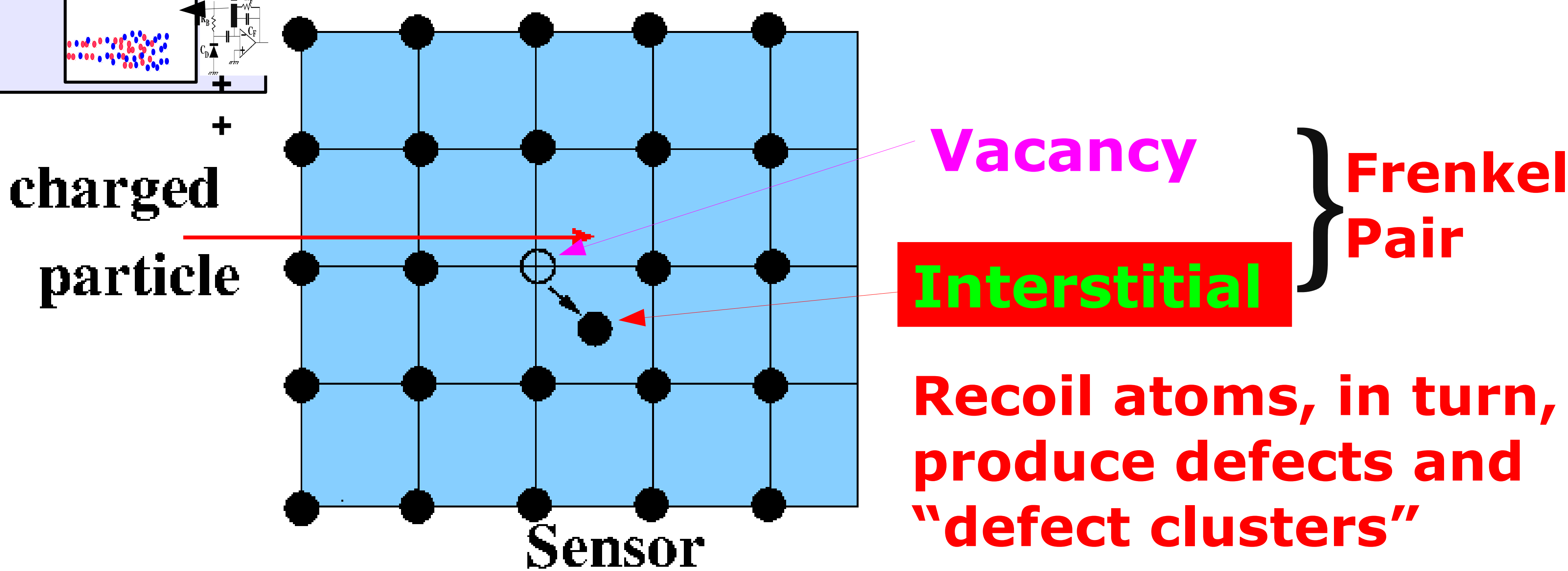
Bardelli et al. NIM A 602 (2009) 501

Spoiling PSA: Radiation Damage



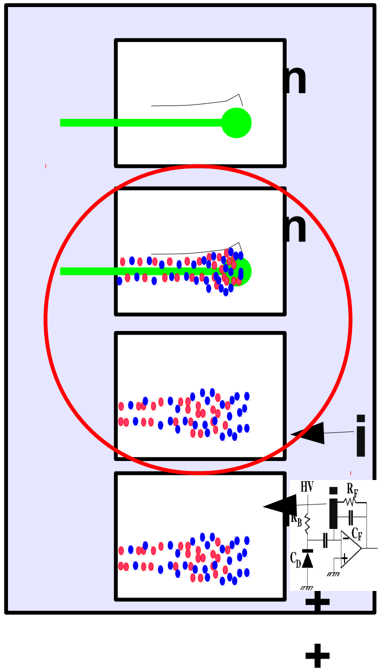
Non Ionizing Energy Loss (NIEL) also possible:

- **Rutherford scattering with atomic nuclei**
- **Nuclear reactions with atomic nuclei**

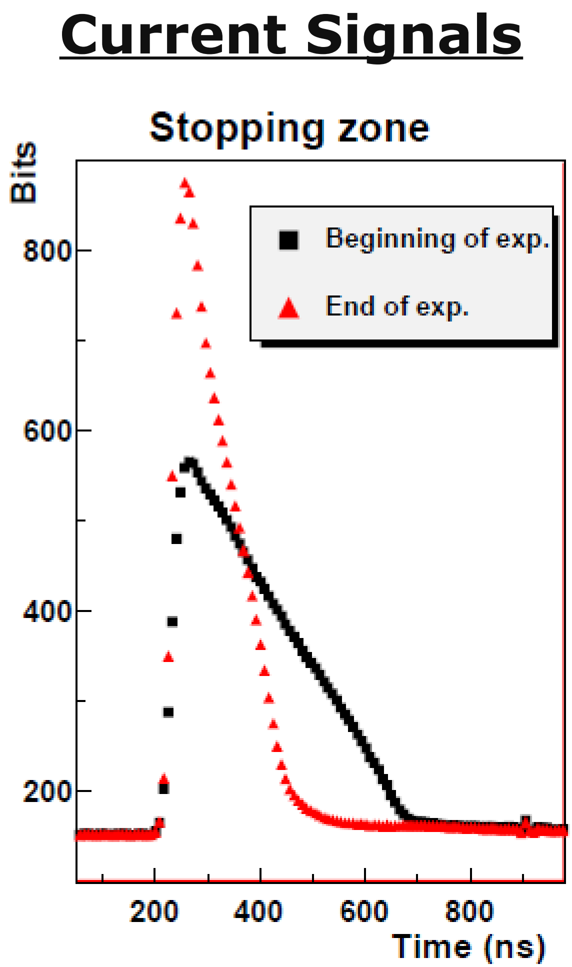


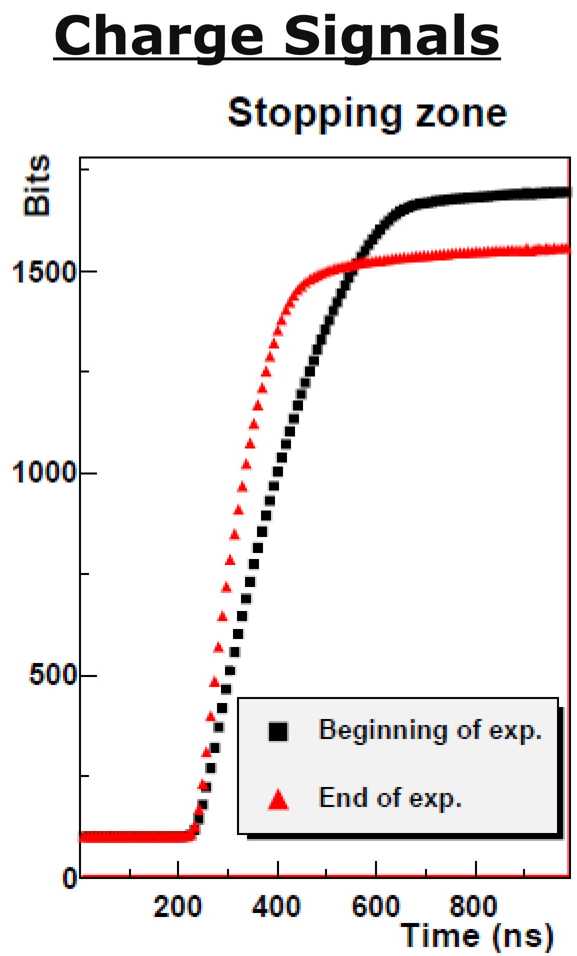
Recoil atoms, in turn, produce defects and "defect clusters"

Spoiling PSA: Radiation Damage



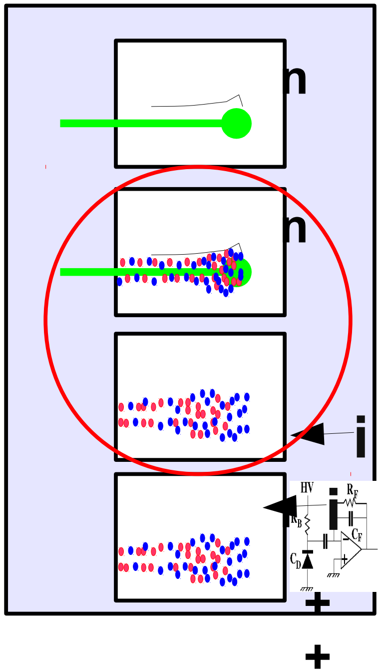
Elastically scattered Xe ions @35MeV/n (range 140μm after 300um Si absorber)



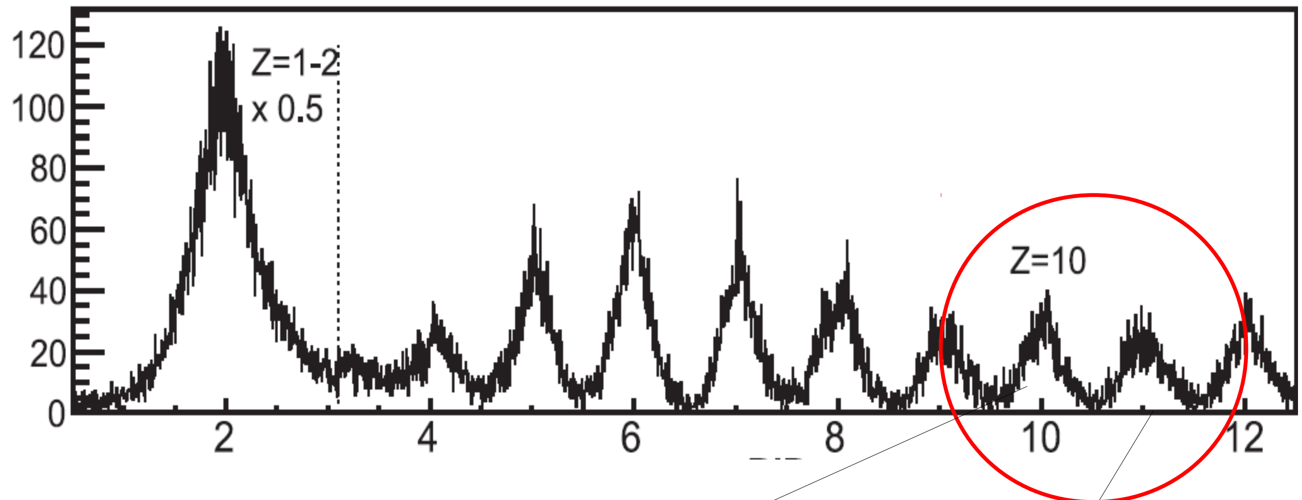


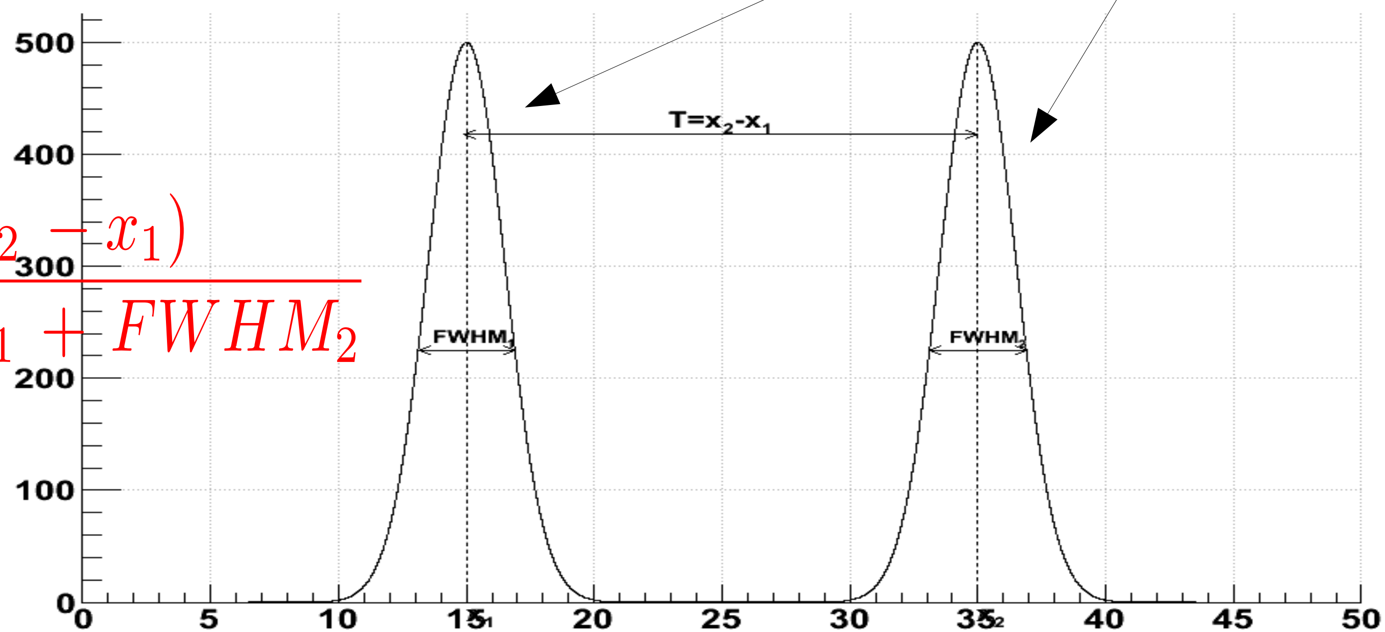
Barlini et al. Submitted to NIM A

Spoiling PSA: Radiation Damage



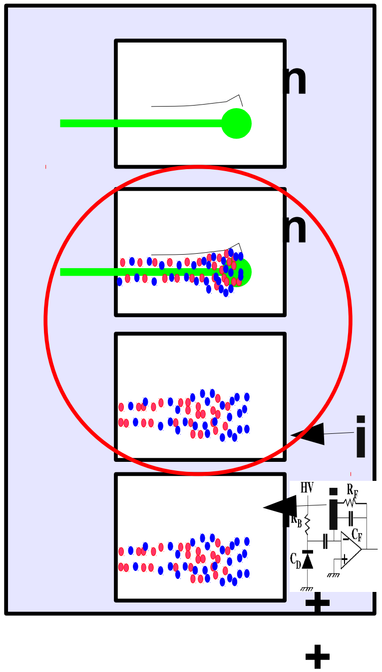
Quantitative estimate of Z identification..

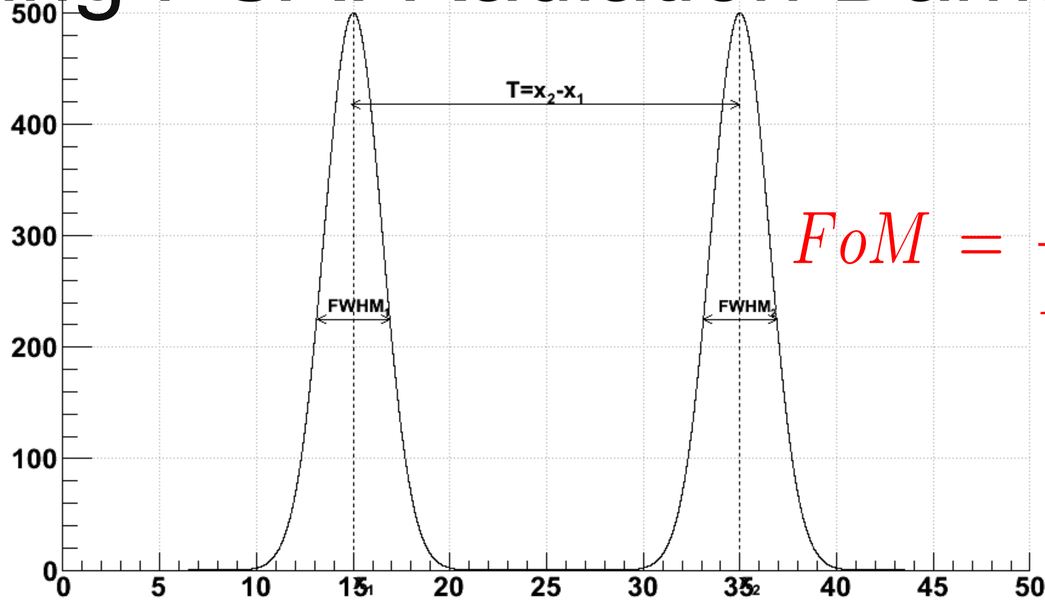




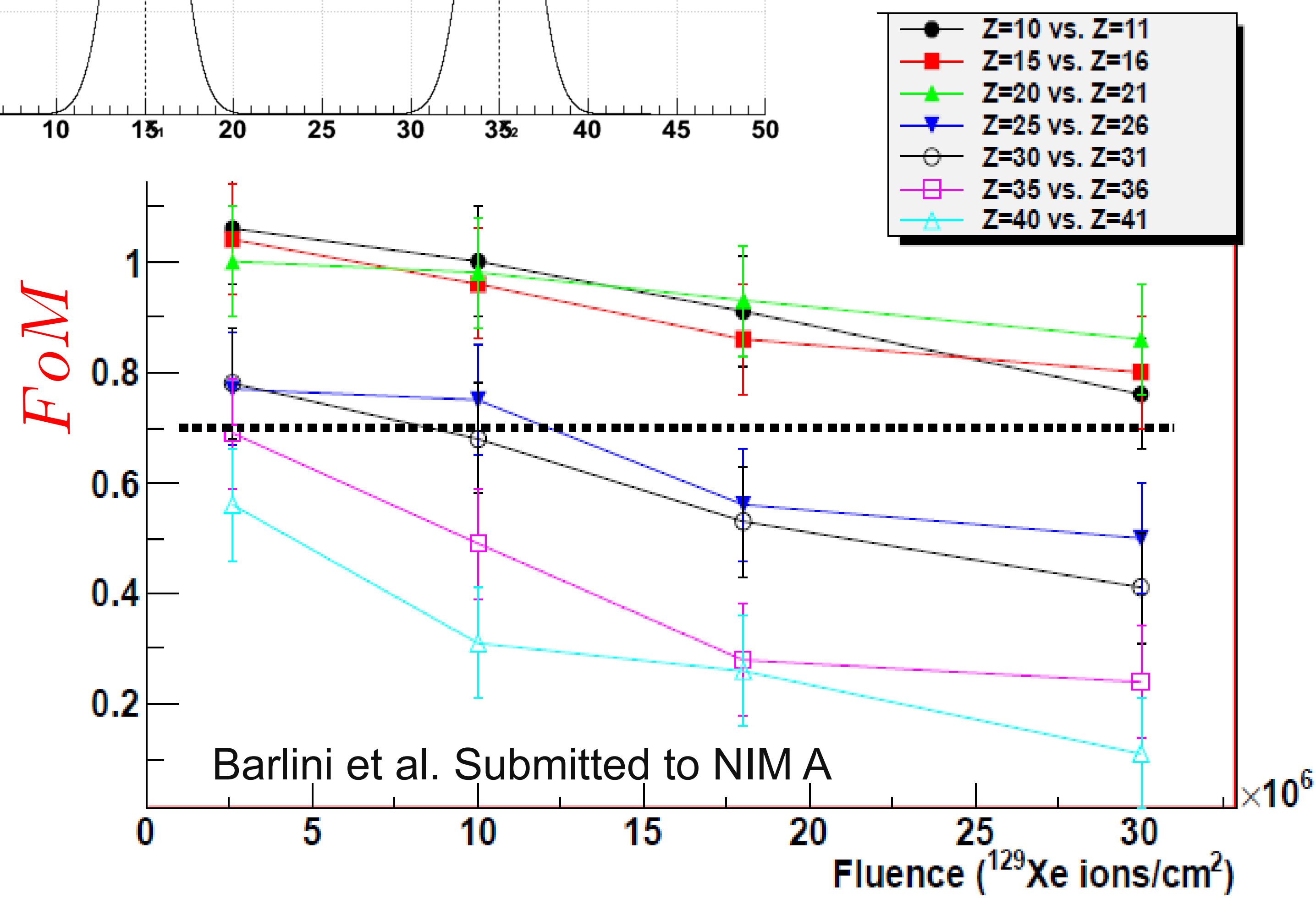
$$FoM = \frac{(x_2 - x_1)}{FWHM_1 + FWHM_2}$$

Spoiling PSA: Radiation Damage



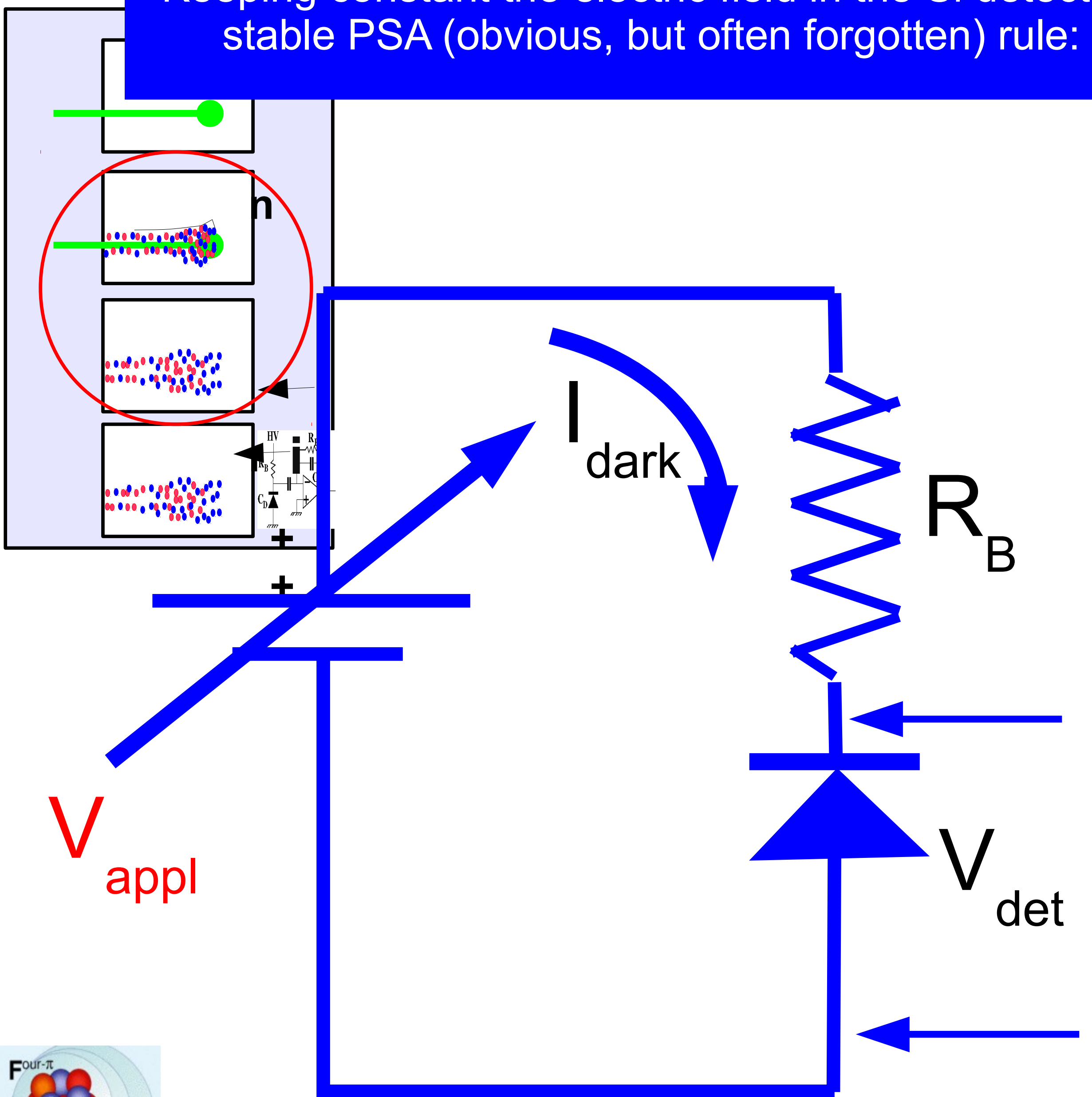


$$FoM = \frac{(x_2 - x_1)}{FWHM_1 + FWHM_2}$$



Spoiling PSA: Detector Bias

Keeping constant the electric field in the Si detector is mandatory for reliable and stable PSA (obvious, but often forgotten) rule:

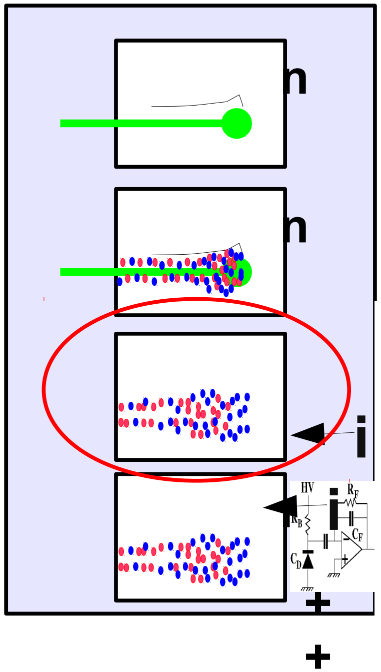


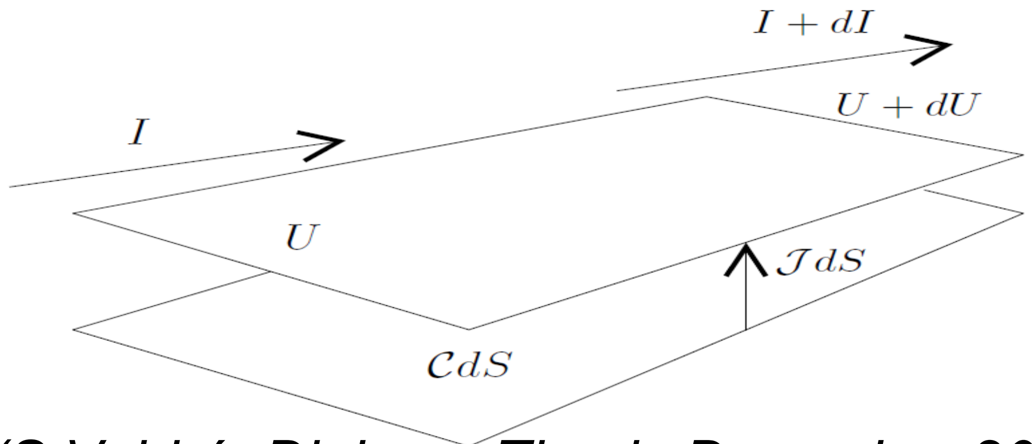
If I_{dark} changes (normally increases) V_{appl} is modified in order to compensate for the voltage drop on the bias resistor R_b -- normally a high value for reducing the electronic noise.

<u>All our bias systems are provided with an automatic control to keep V_{det} constant to well within 1%.</u>

<u>It is indeed very important.</u>

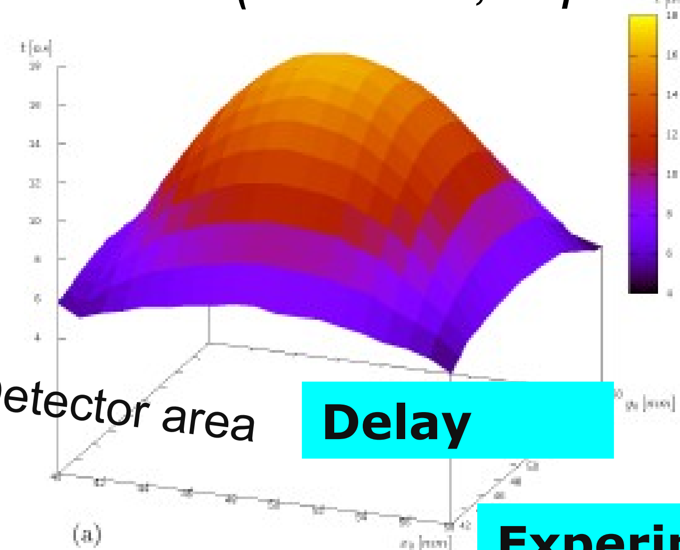
Spoiling PSA: Sheet resistance

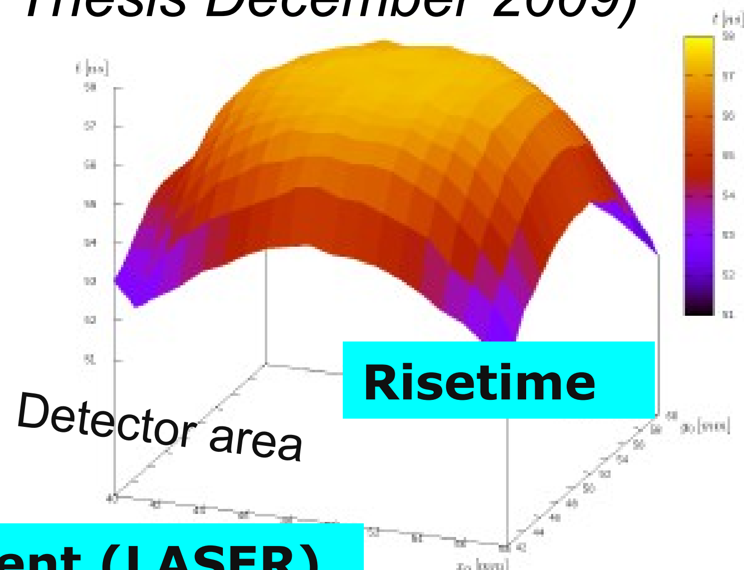




Delay

(S.Valdré, Diploma Thesis December 2009)





Experiment (LASER)

w/o Al

$R_\square\ 100 - 500\Omega$

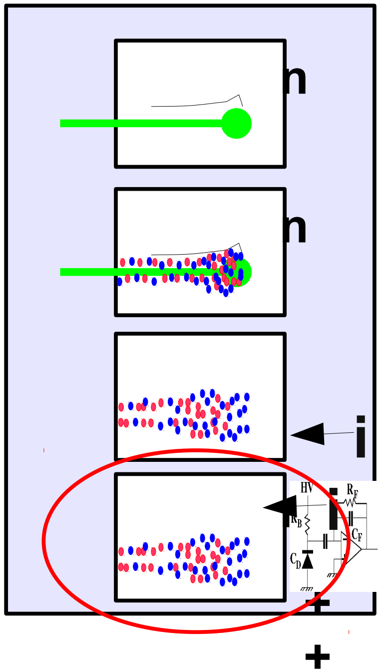
w/ Al (30nm)

$R_\square \approx 1\Omega$

In order to get good timing properties (and thus good PSA) from Silicon the sheet resistance has to be kept slow. Metalization of the two sides (junction and ohmic) of the Silicon detector is necessary. Sufficiently thin metalization is necessary in order to permit doping uniformity determination with UV or visible light pulses.

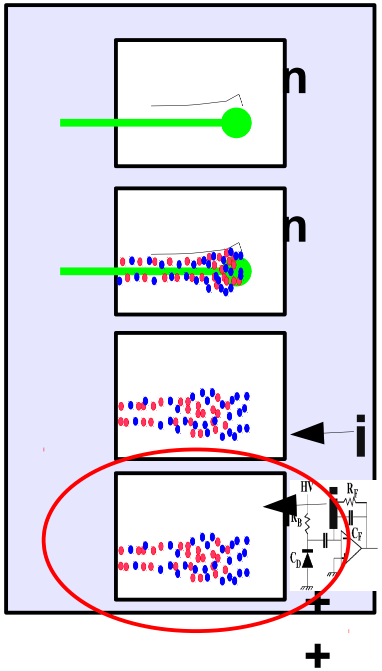
Front End Electronics

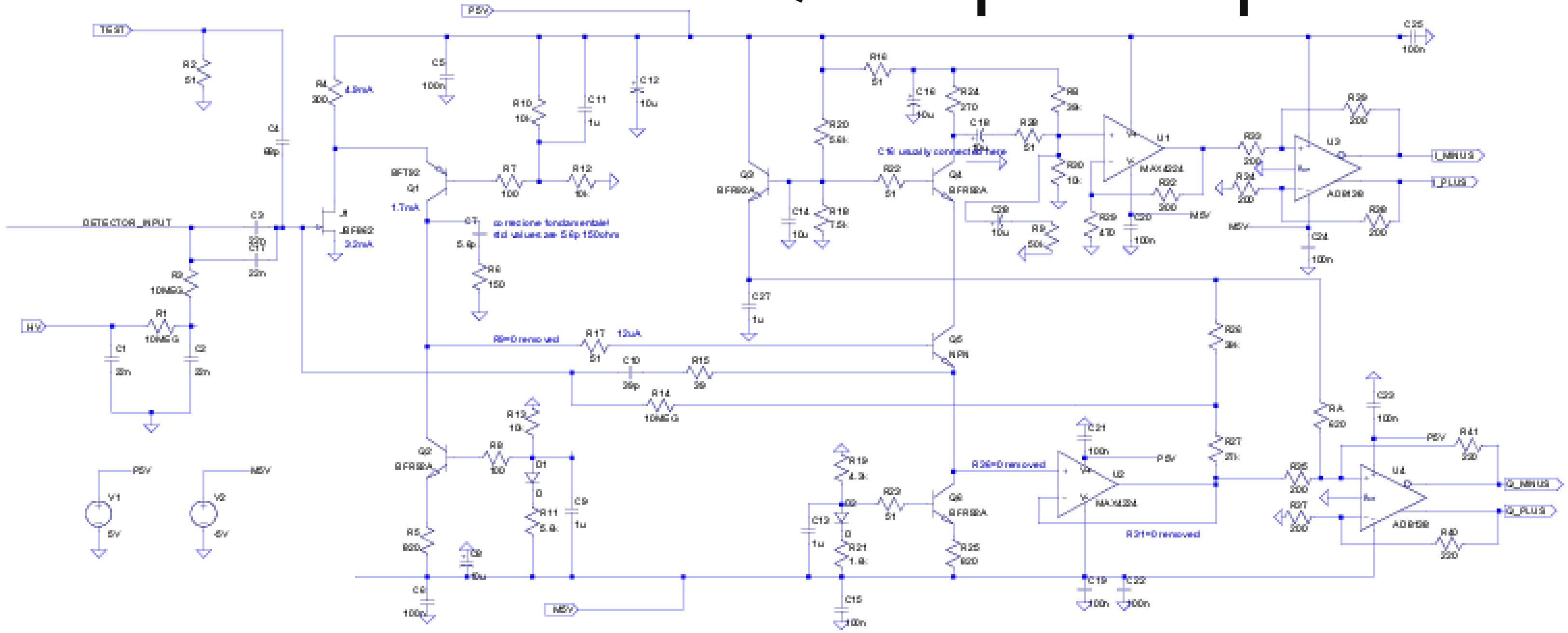
Front End Electronics: General Requirements



- **FEE must digitize the charge and/or current signal(s) preserving most of the relevant info!**
- **Amplitude (energy) is not enough**
- **Info is coded in shape => e.g. Leading edge of charge signal**
- **Minimize signal distortion**
- **Minimize noise**

Front End Electronics: Q & I preamplifier

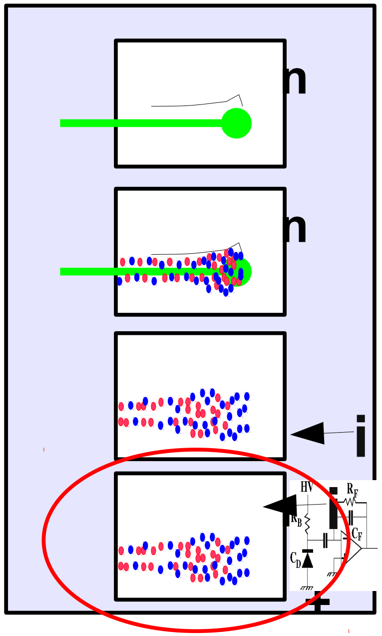


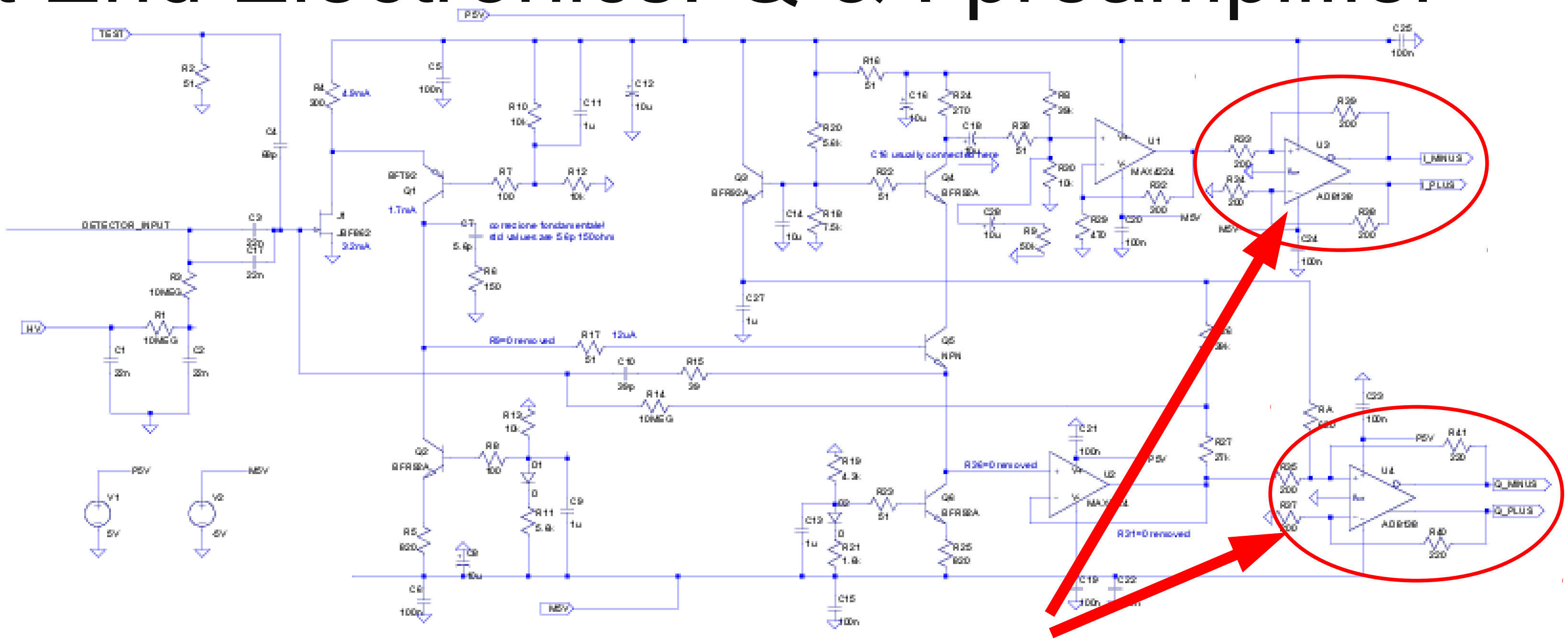


PACI (Orsay)

--- J:\lavoro\electronics\ltspice\paci.asc ---

Front End Electronics: Q & I preamplifier



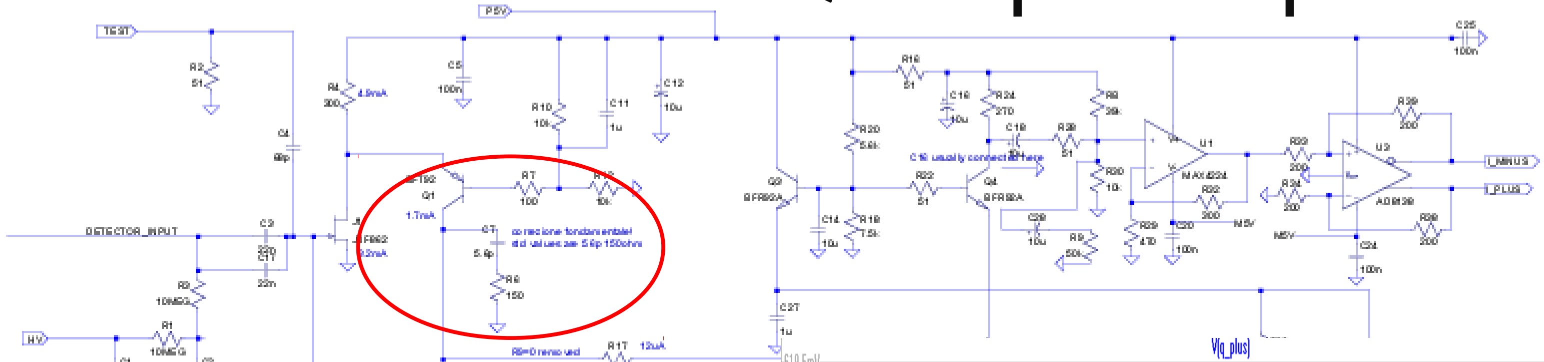


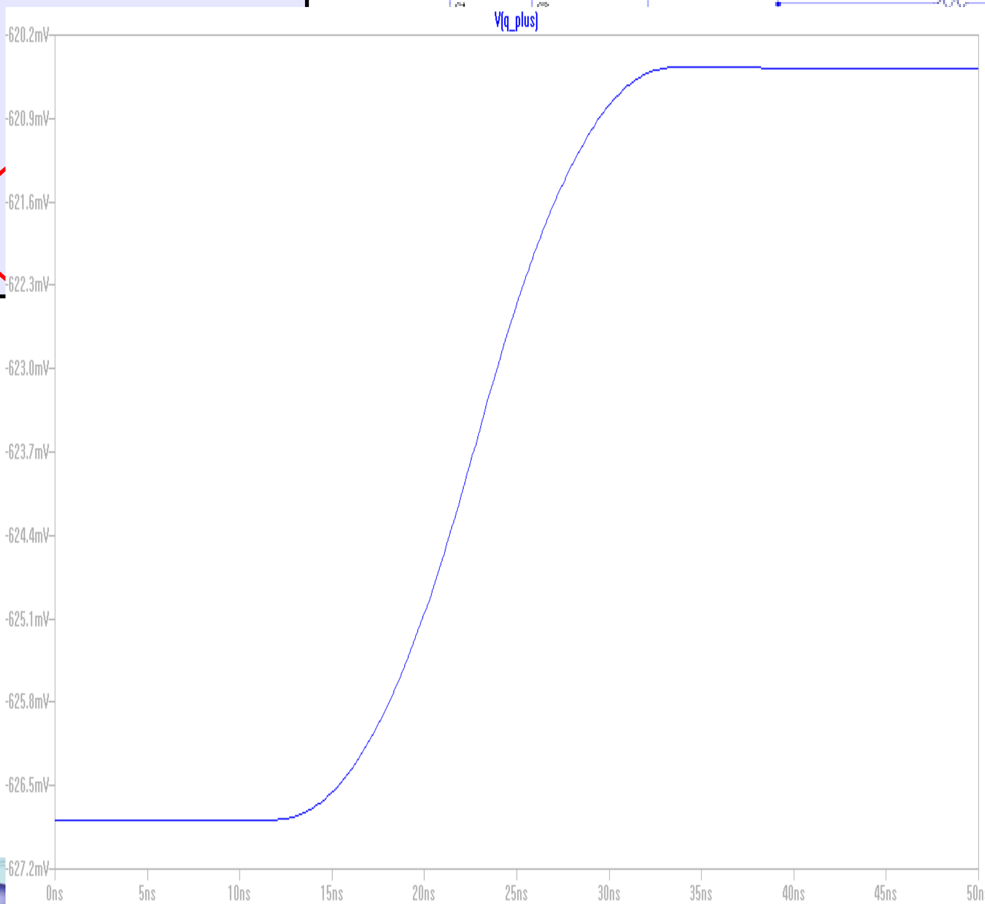
Differential outputs=> minimize pick up noise (e.g. Digital clocks) and cross talk

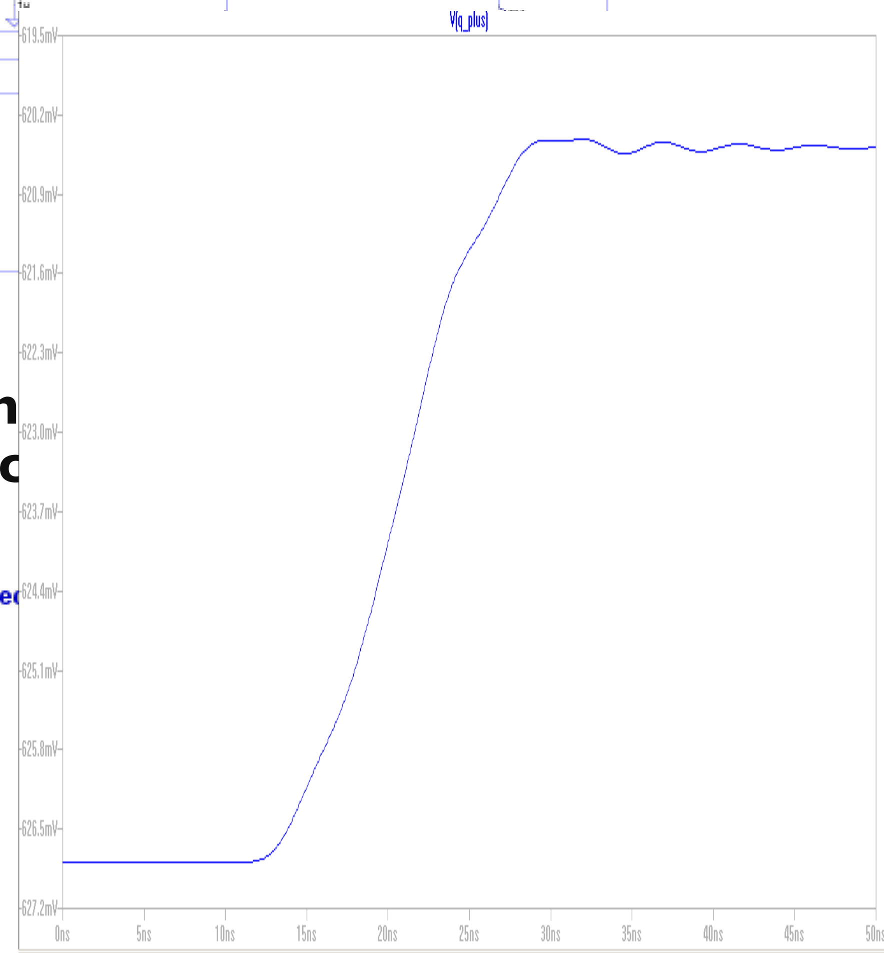
PACI (Orsay)

--- J:\lavoro\electronics\ltspice\paci.asc ---

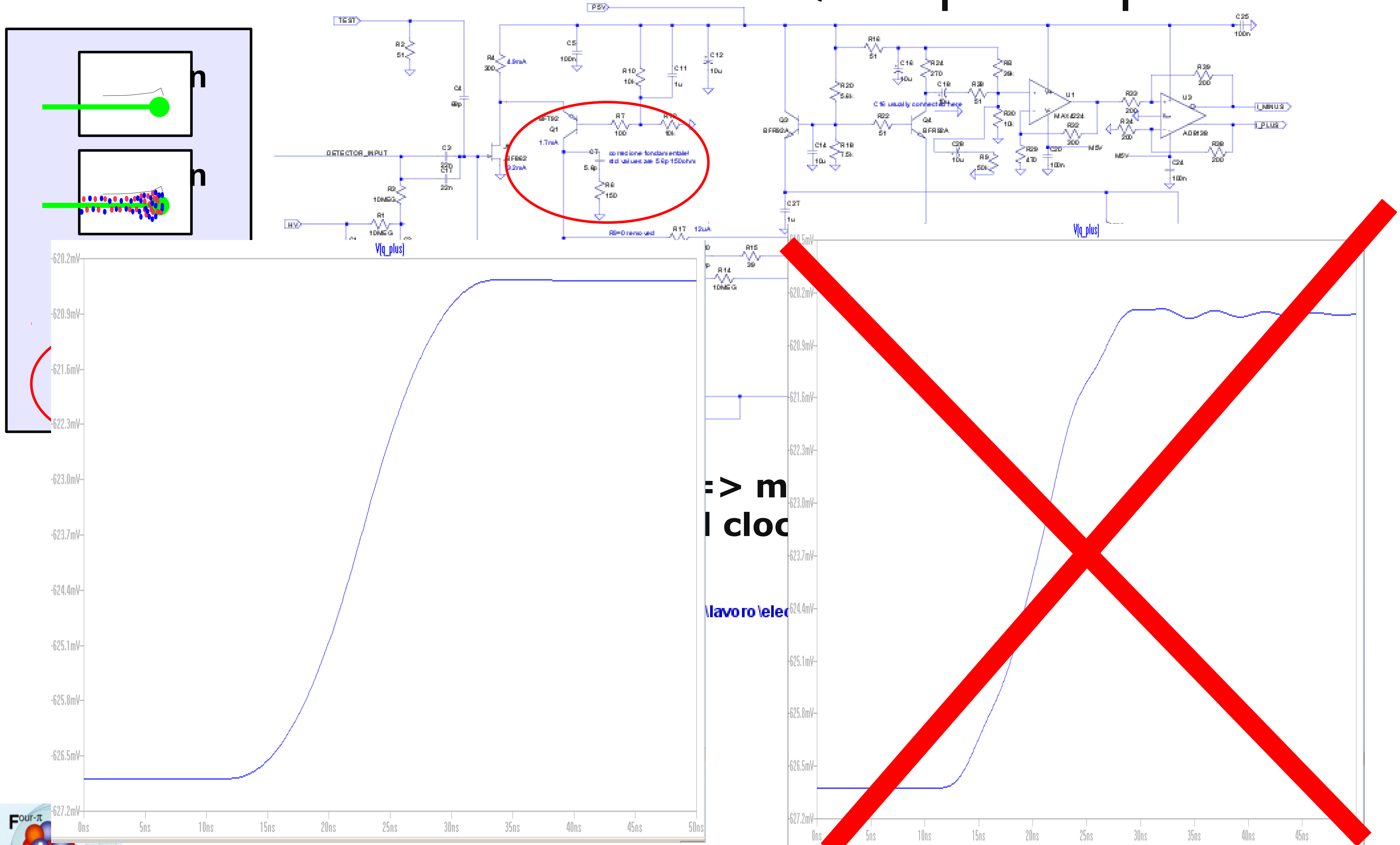
Front End Electronics: Q & I preamplifier



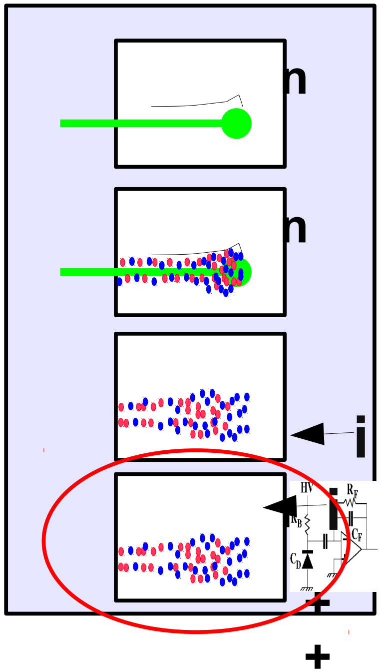




Front End Electronics: Q & I preamplifier

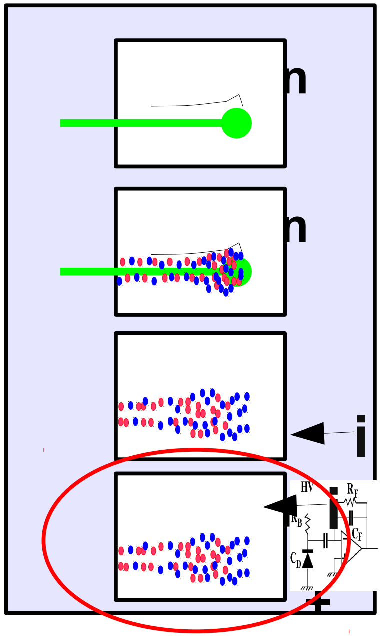


Front End Electronics: Digitizer

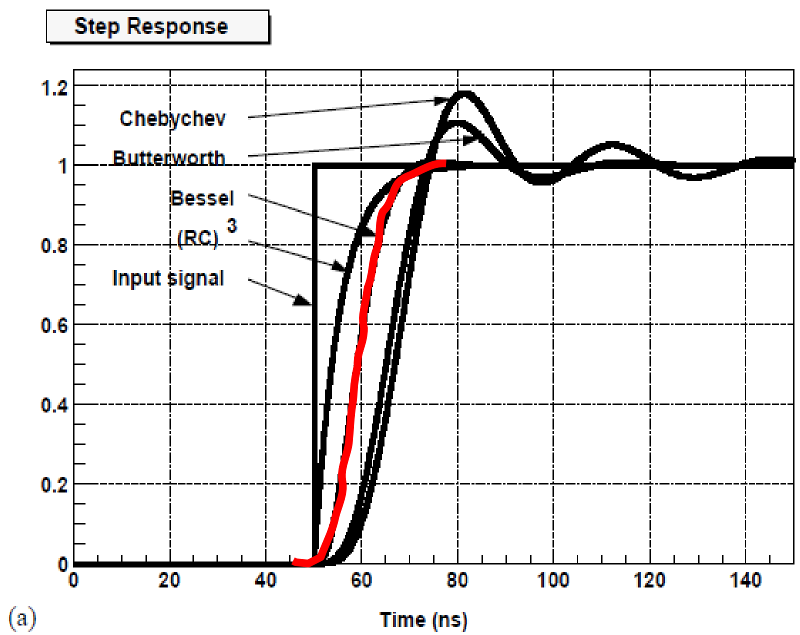


- **Differential path throughout**
- **In vacuum, close to PA (heat dissipation!)**
- **Low analog stage noise: for 14 bit ADC, 1 LSB ~ 100μV!**
- **Carefully chosen antialias filter**

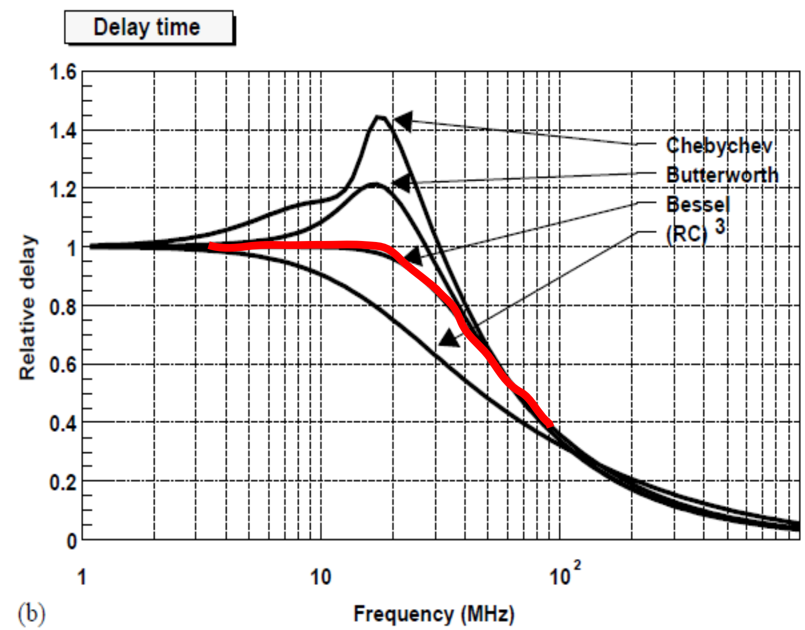
Front End Electronics: Anti-Alias Filter



- **No use in step response faster than PA**
- **Optimize for clean time response (fidelity)**
- **Constant delay vs frequency preferred (Bessel)**

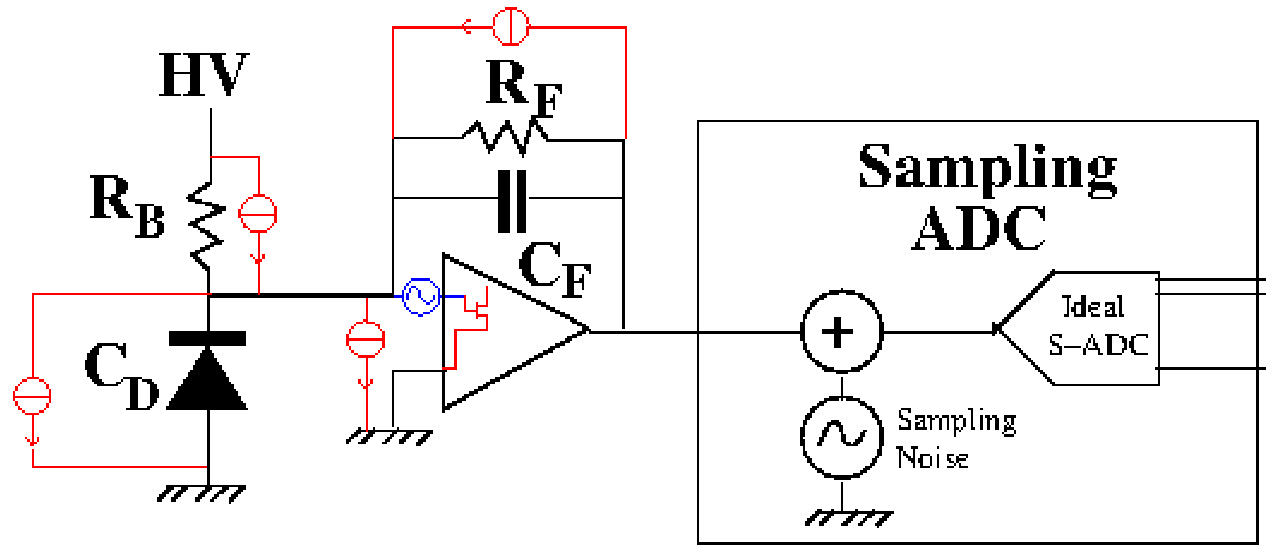


(a)

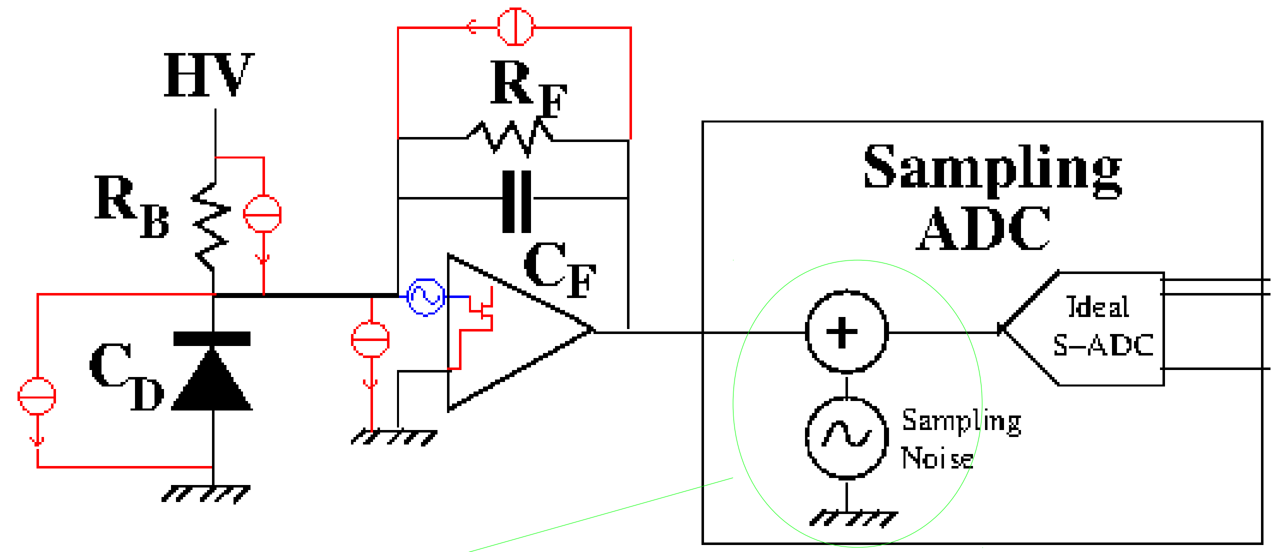


(b)

Front End Electronics: sampling ADC noise



Front End Electronics: sampling ADC



$$\sigma_n = \frac{2^{N_{bit}-ENOB}}{\sqrt{12}}$$

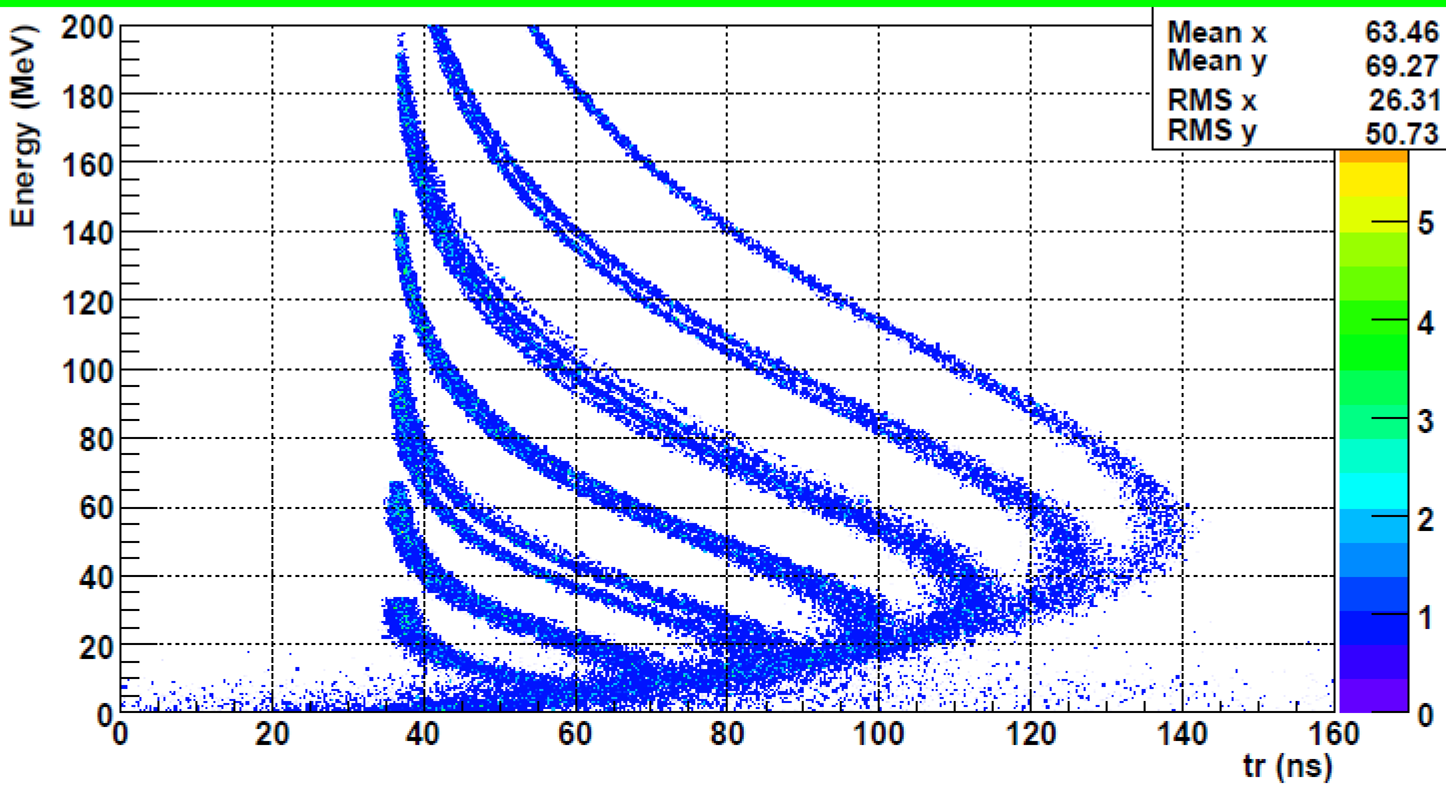
ENOB=effective number of bits

ENOB limits the obtainable Time and max{I} resolution =>limit on PS identification.

Straggling, noise, doping: which is the main culprit?

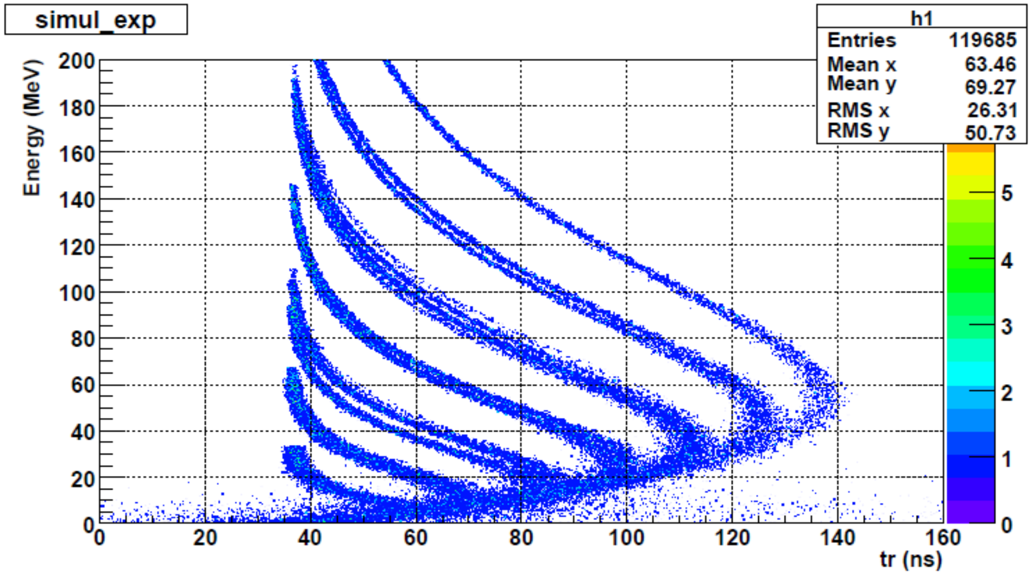
Range straggling, noise, doping

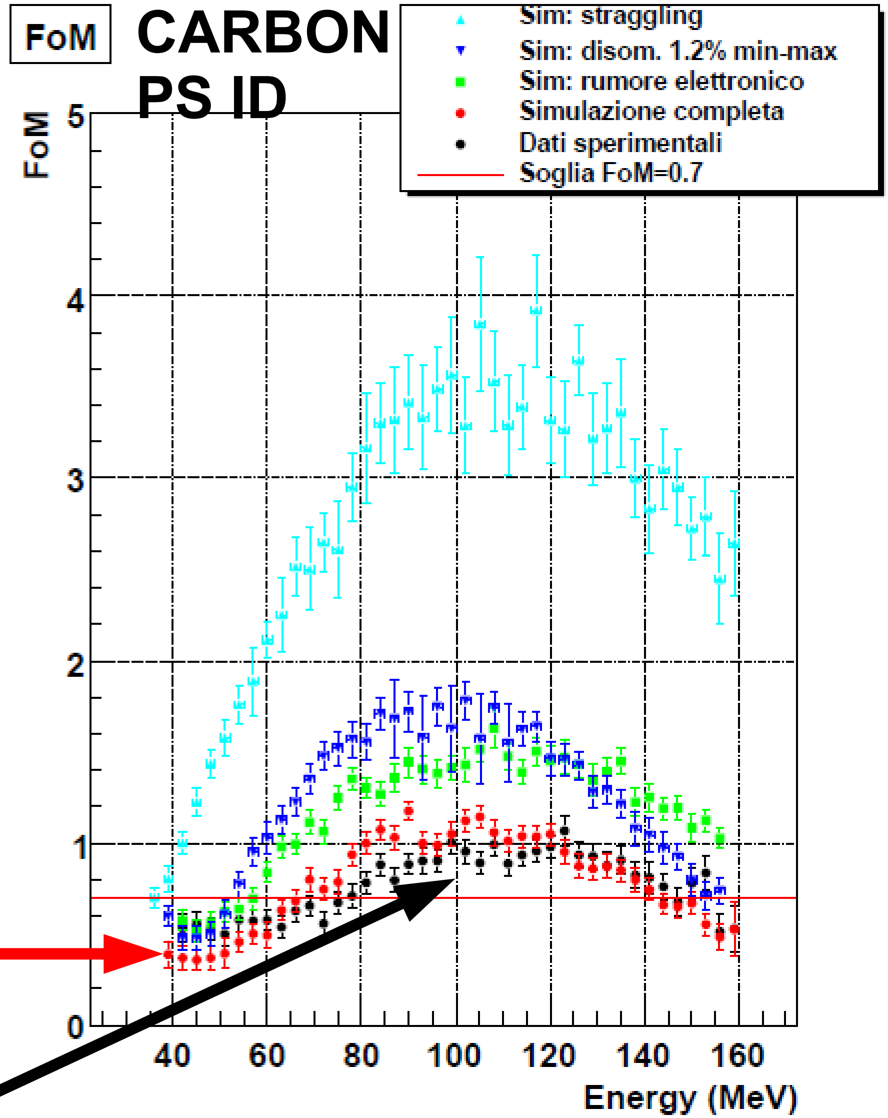
Average behaviour of curves: experimental data.
Fluctuations: simulations including range straggling, noise and doping non-uniformity



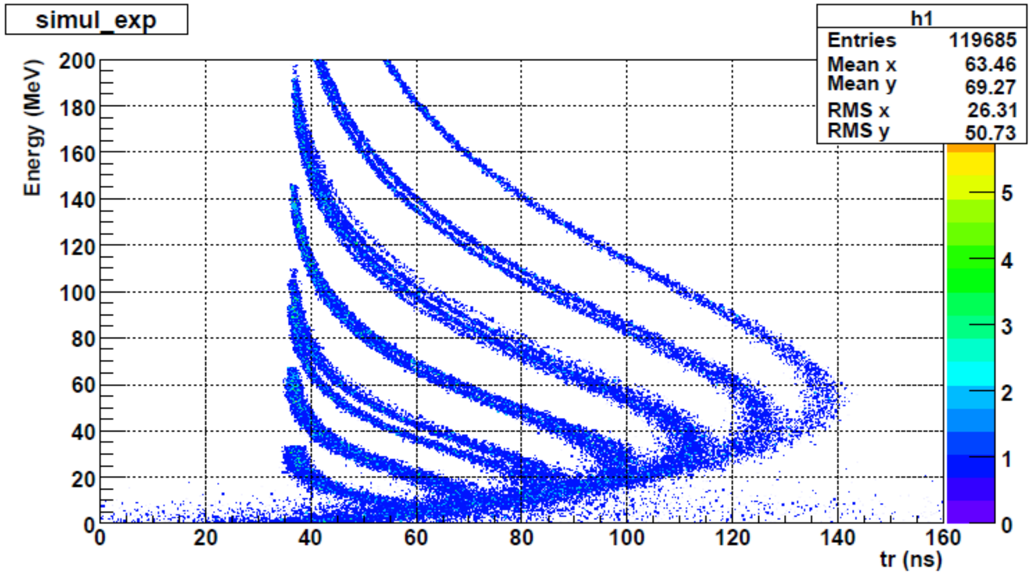
Stefano Carboni Master's Thesis – A.A. 2007/2008 University of Florence

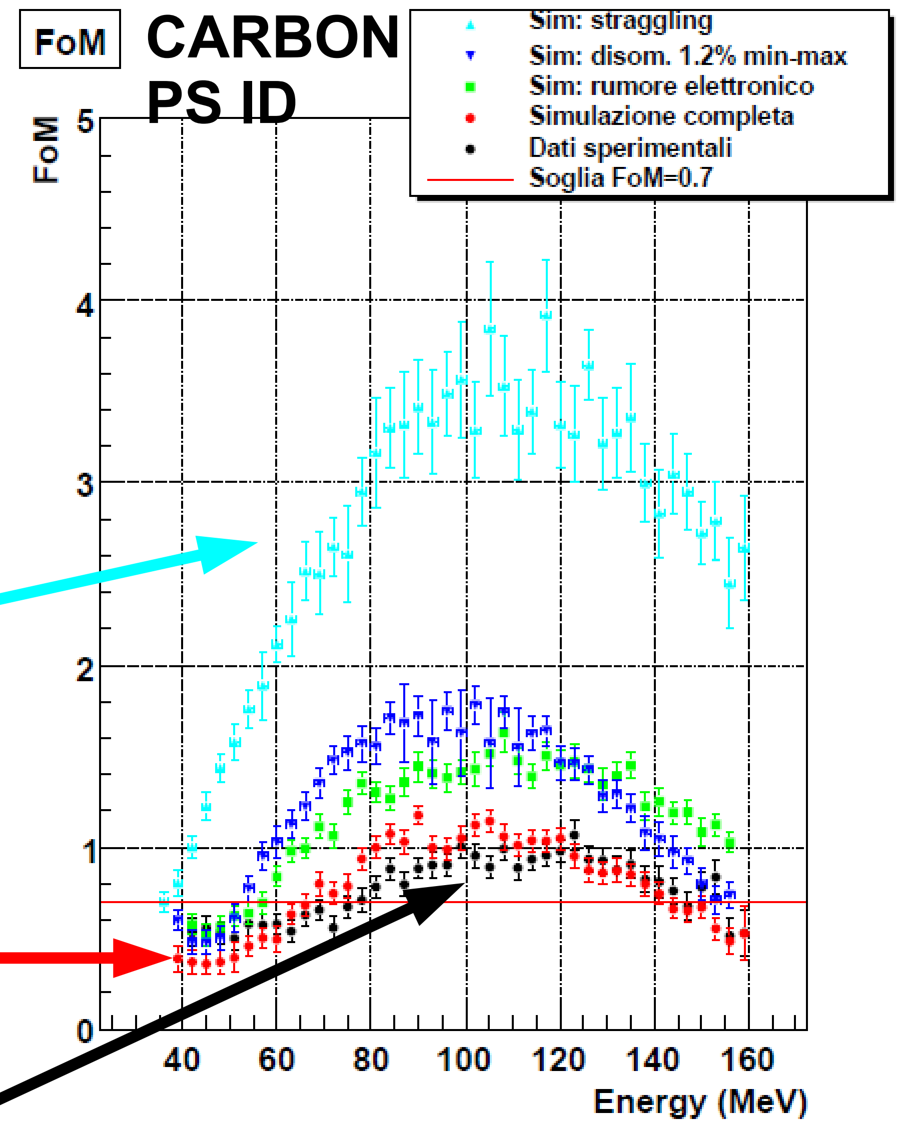
Range straggling, noise, doping





Range straggling, noise, doping



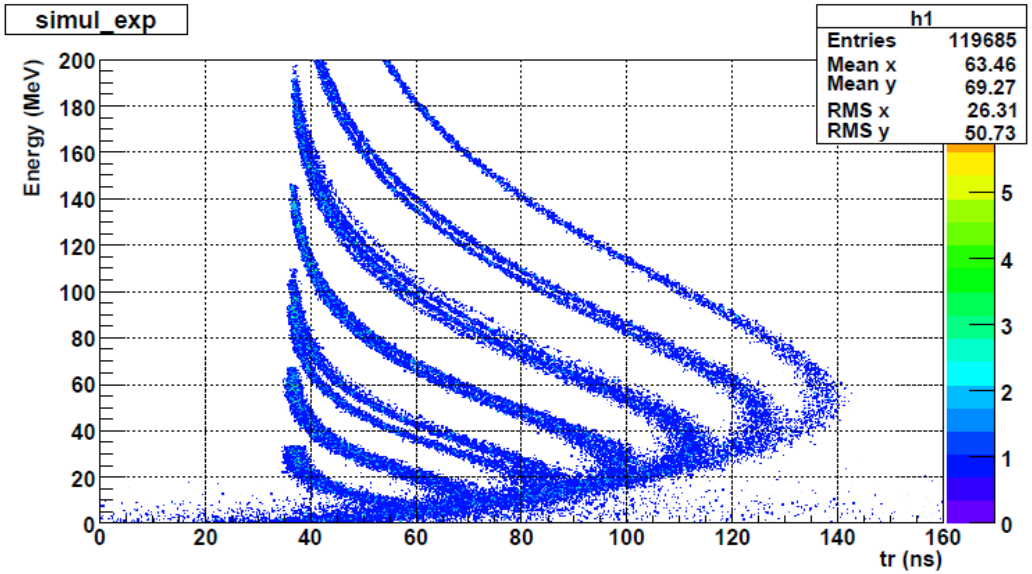


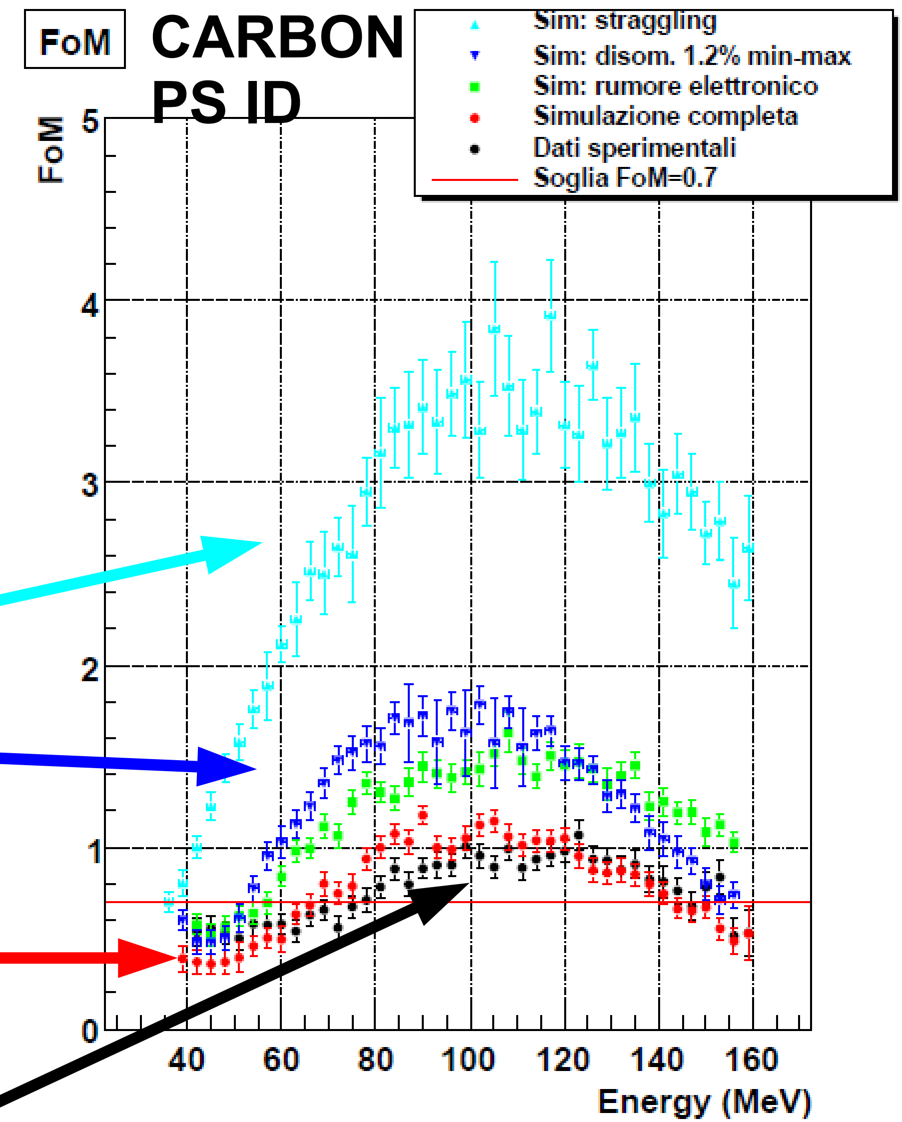
Straggling

Complete Simulation

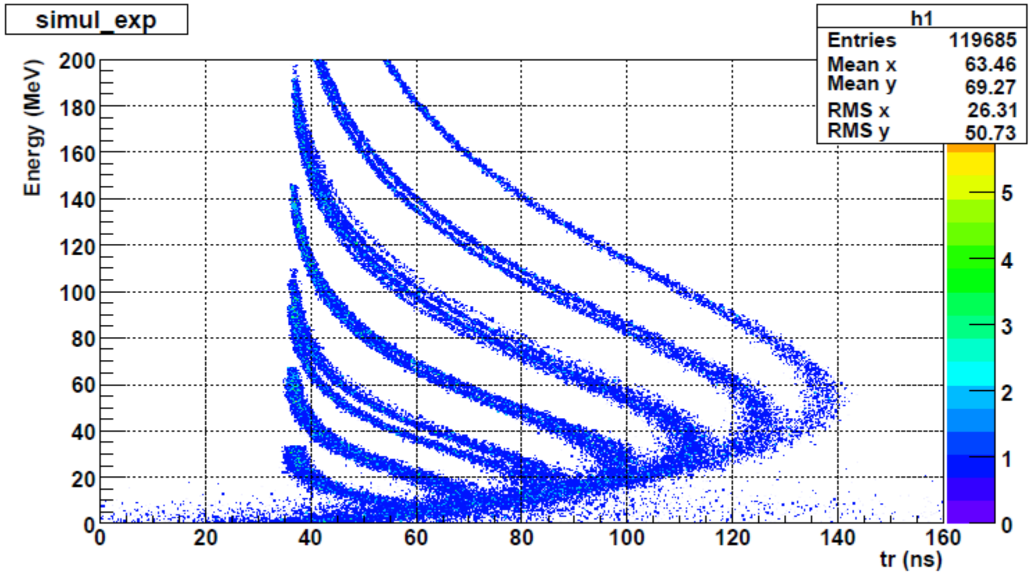
Experiment

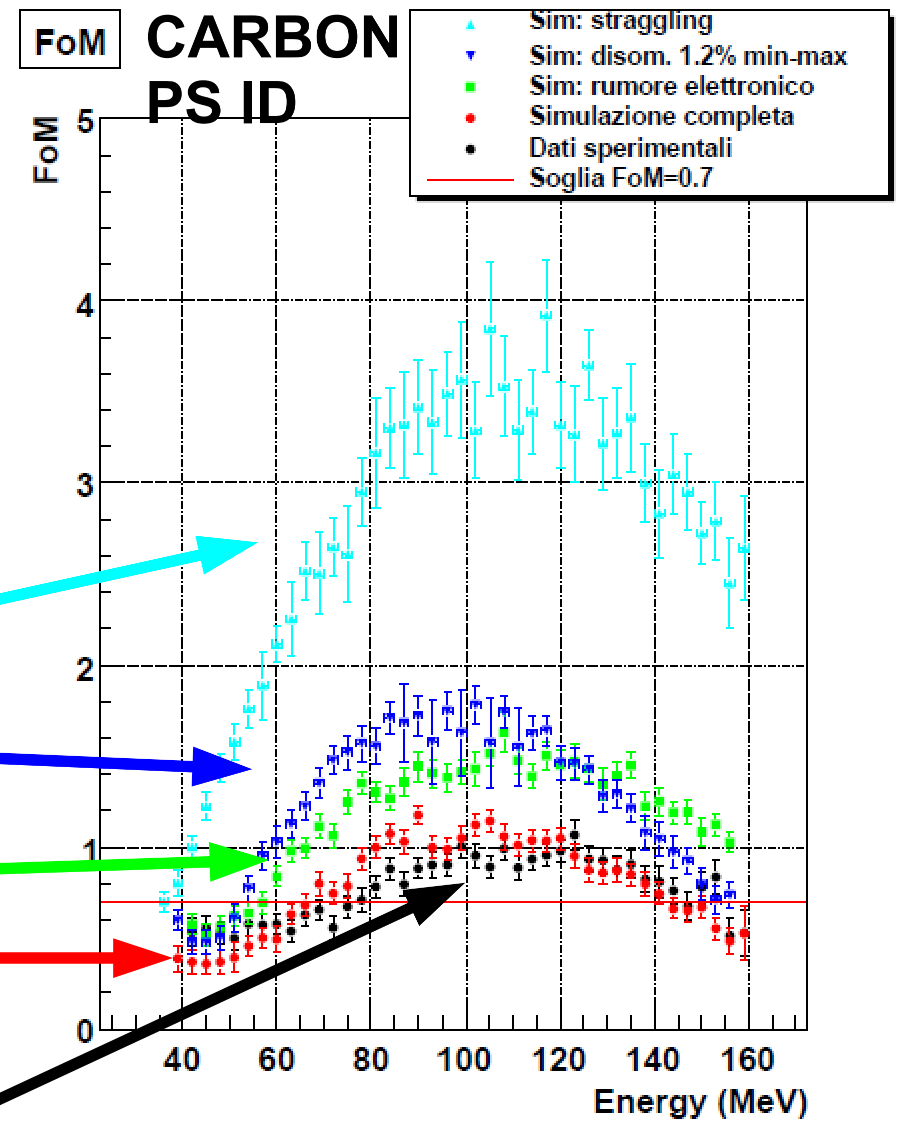
Range straggling, noise, doping





Range straggling, noise, doping





Straggling

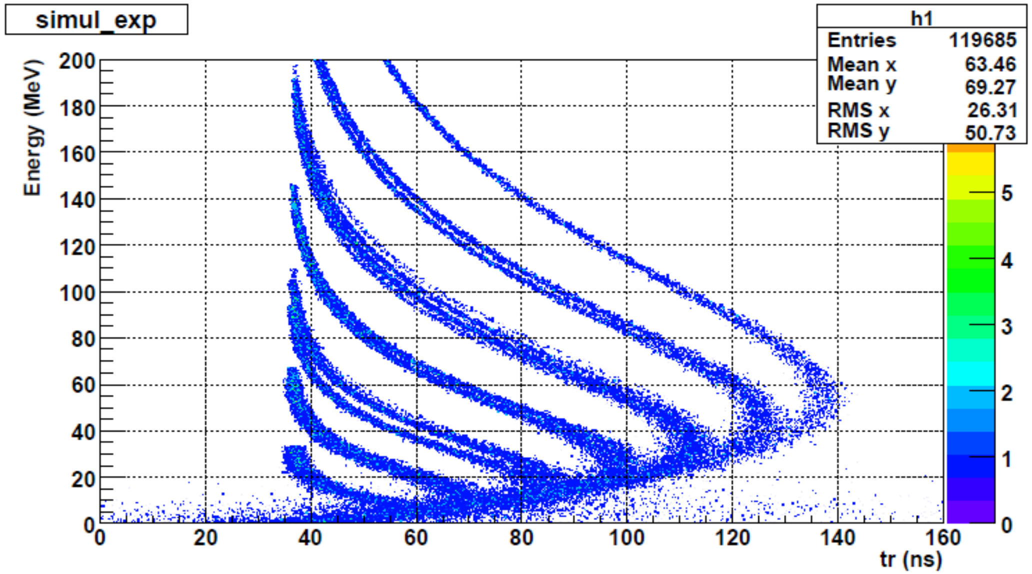
Doping non-unif.

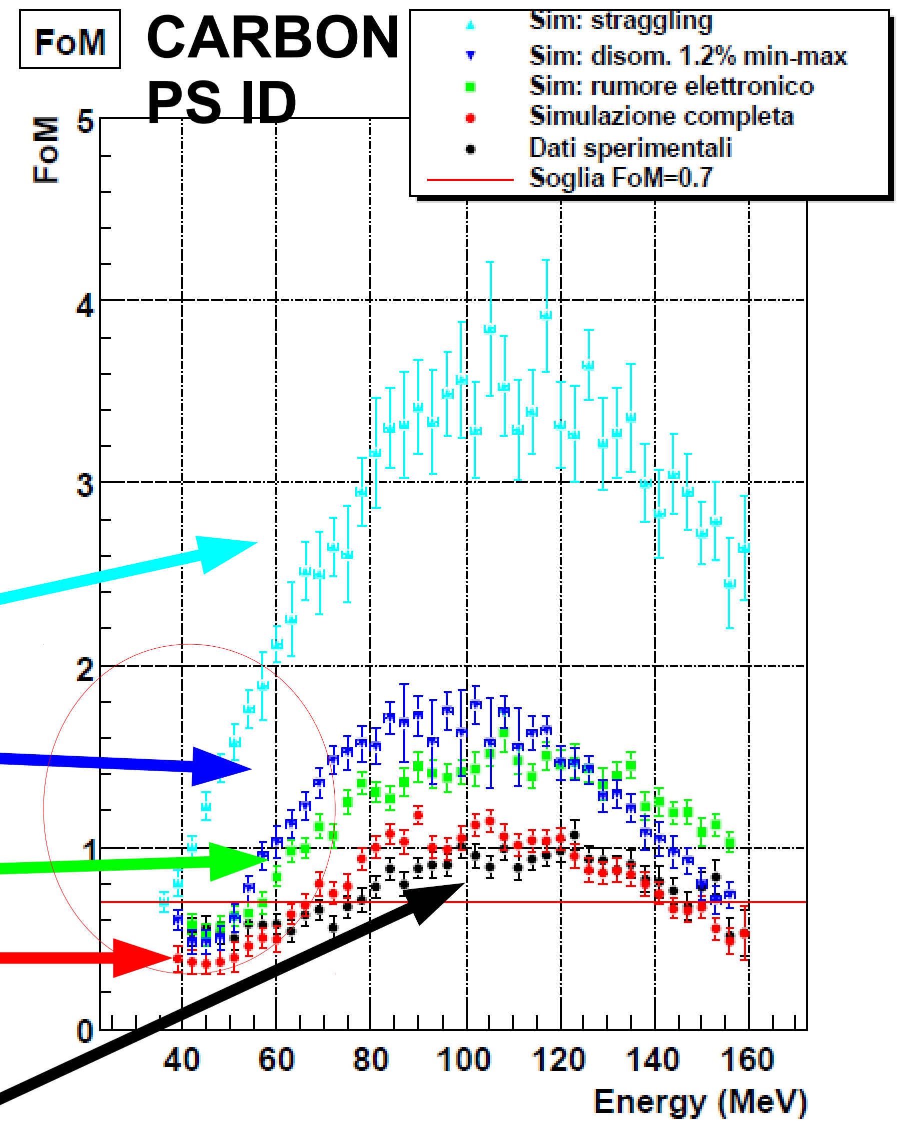
Electronic Noise

Complete Simulation

Experiment

Range straggling, noise, doping





Straggling

Doping non-unif.

Electronic Noise

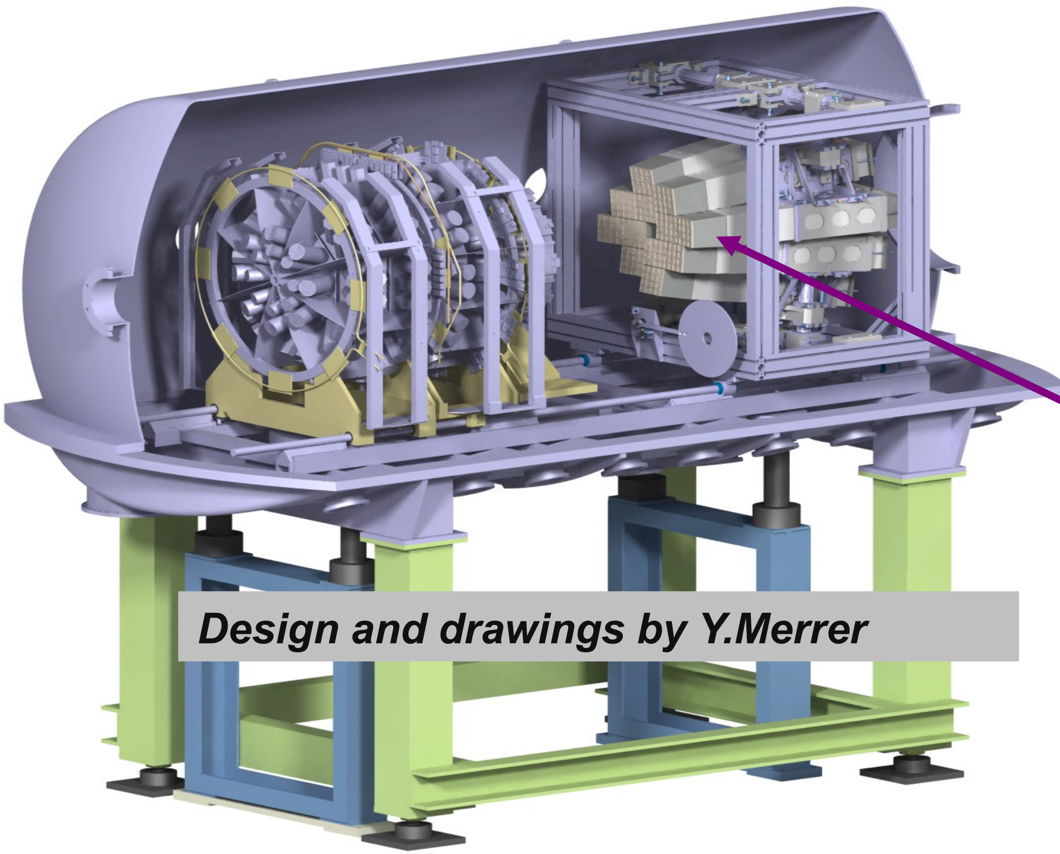
Complete Simulation

Experiment

FAZIA demonstrator

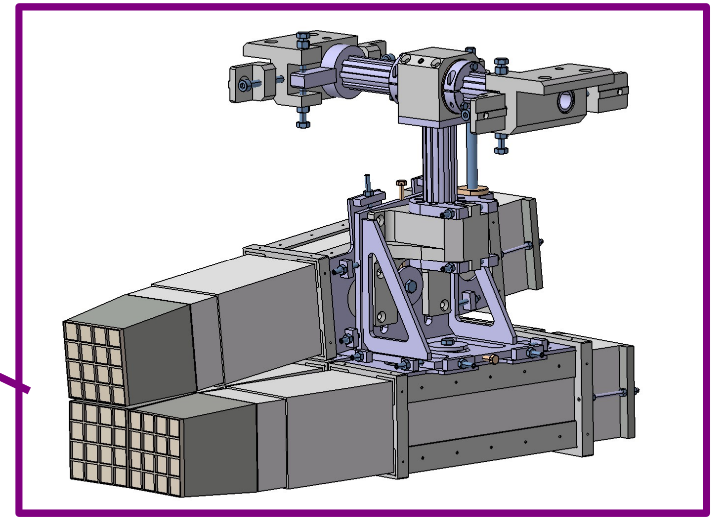
FAZIA demo: Mechanical setup

Demonstrator together with **INDRA at GANIL**

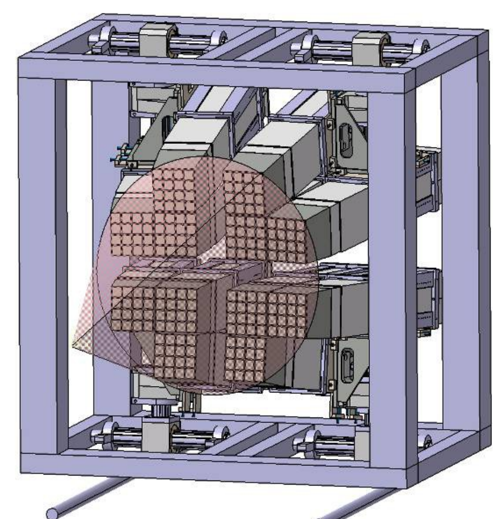


Design and drawings by Y.Merrer

Schedule: **fall 2013 to 2016**

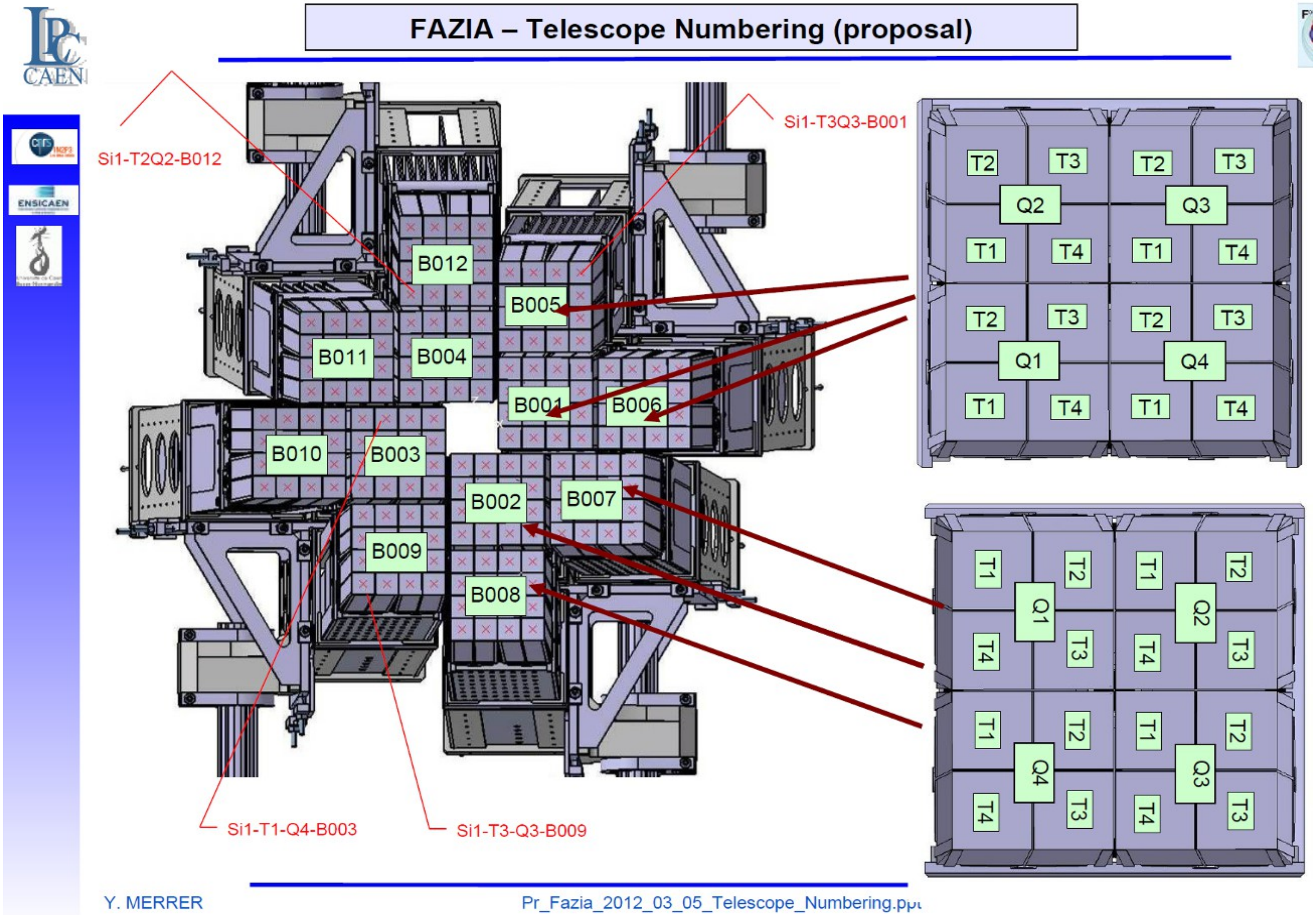


Block held by supports in group of three



- **192 telescopes organized in 12 blocks, mounted at 100cm from target**

FAZIA demo: Mechanical setup



FAZIA demo: Front End Electronics (Orsay)

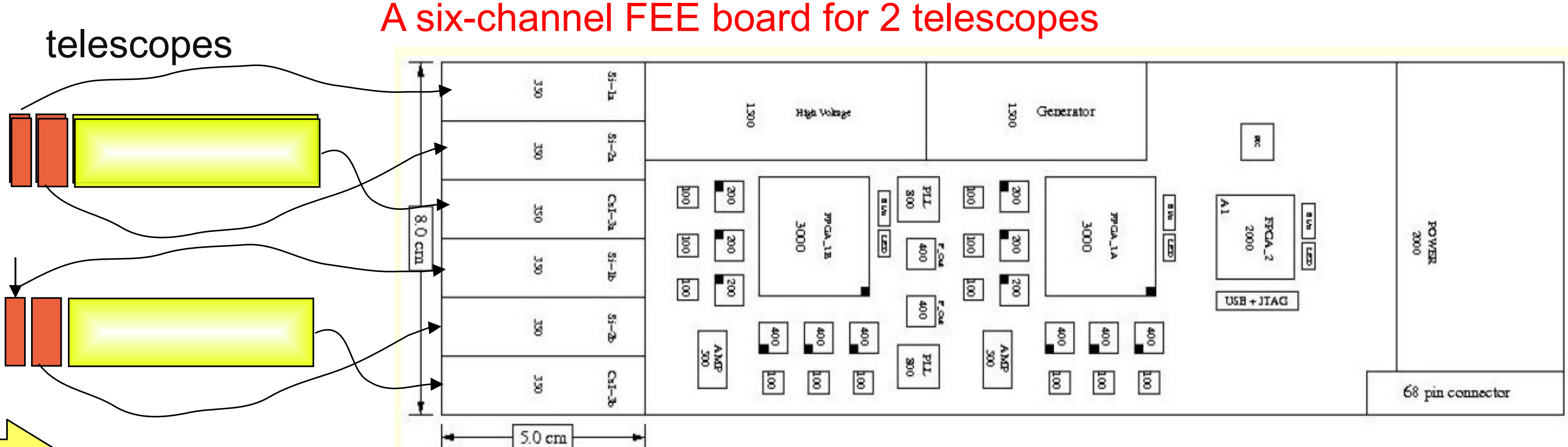
- Stage 1 (silicon 300 μm)
  - Charge 250 MeV full scale 250 Ms/s 14 bit
  - Charge 4 GeV full scale 100 Ms/s 14 bit
  - Current 250 Ms/s 14 bit
- Stage 2 (silicon 500 μm)
  - Charge 4 GeV full scale 100 Ms/s 14 bit
  - Current 250 Ms/s 14 bit
- Stage 3 (CsI + photodiode)
  - Charge 4 GeV full scale 100 Ms/s 14 bit

Services to the detectors

- Single low voltage power supply 48 V
- High voltage bias production/monitoring
  - 30_000 individually monitored voltages
- Temperature monitoring
- Pulser and other calibration facilities
- In-situ, in-vivo configuration of the FPGAs
- Software dowload (slow control, calibration)

Everything under VACUUM

A six-channel FEE board for 2 telescopes

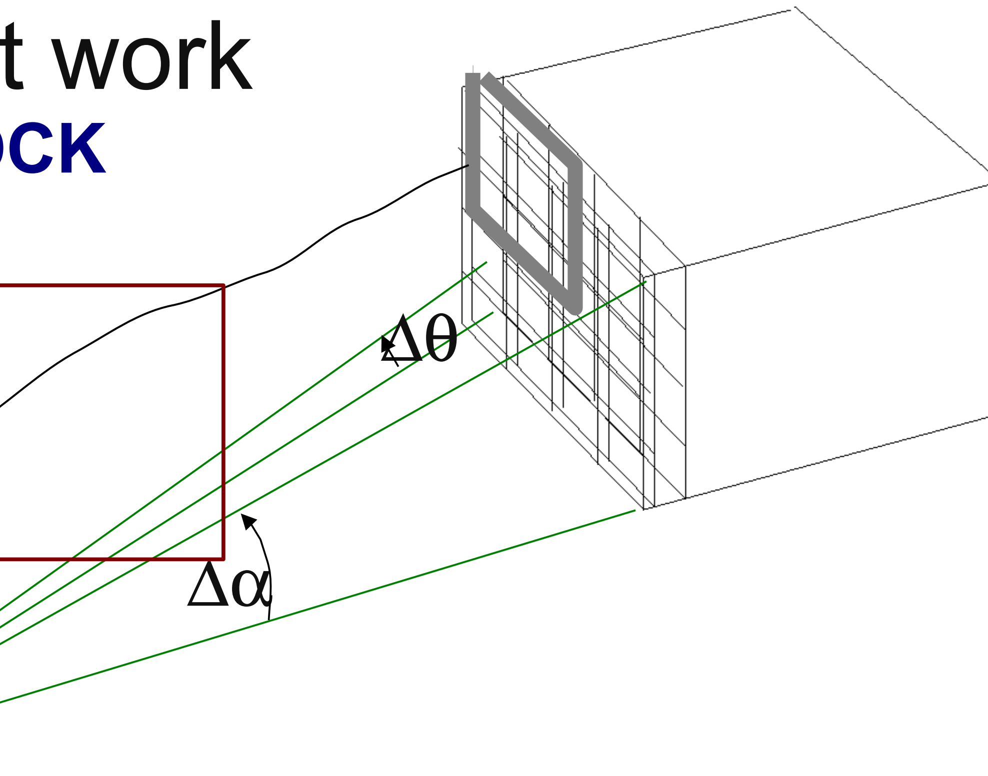


25W /board: **cooling** is an issue (Naples, Bologna UNI+INFN Sections)

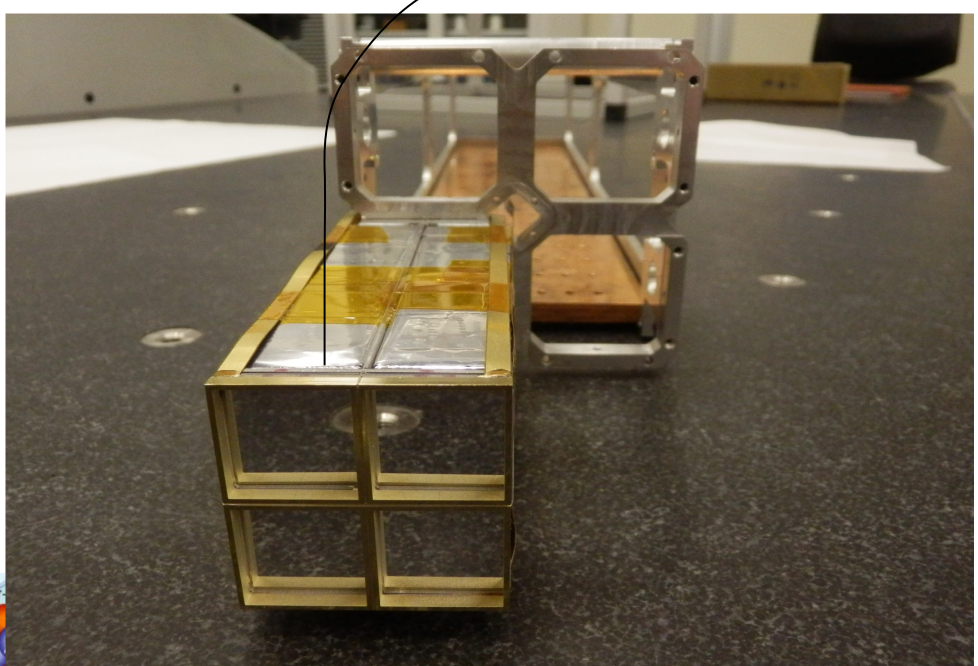
FAZIA demo: Men at work

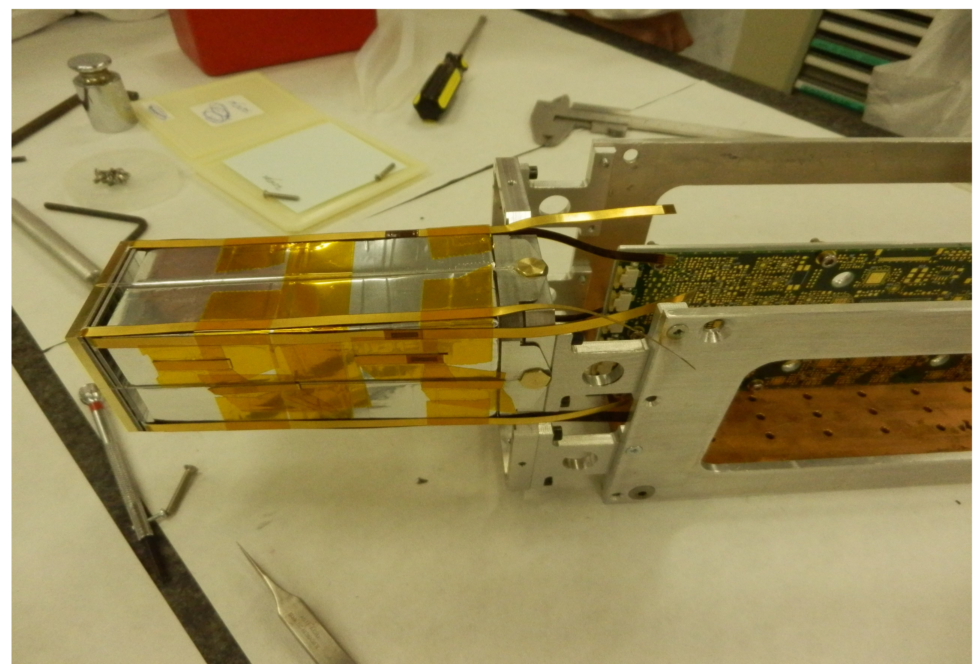
The Quartets and the BLOCK

distance from target	Δα	Δθ	ΔΩ
mm	**deg**	**deg**	**msrad**
600	**8.4**	**1.9**	**1.1/17.6**
1000	**5.0**	**1.1**	**0.4/6.4**



Mounting tests in FLORENCE
March to May 2012





Conclusions (1)

Many effects limit PS identification...

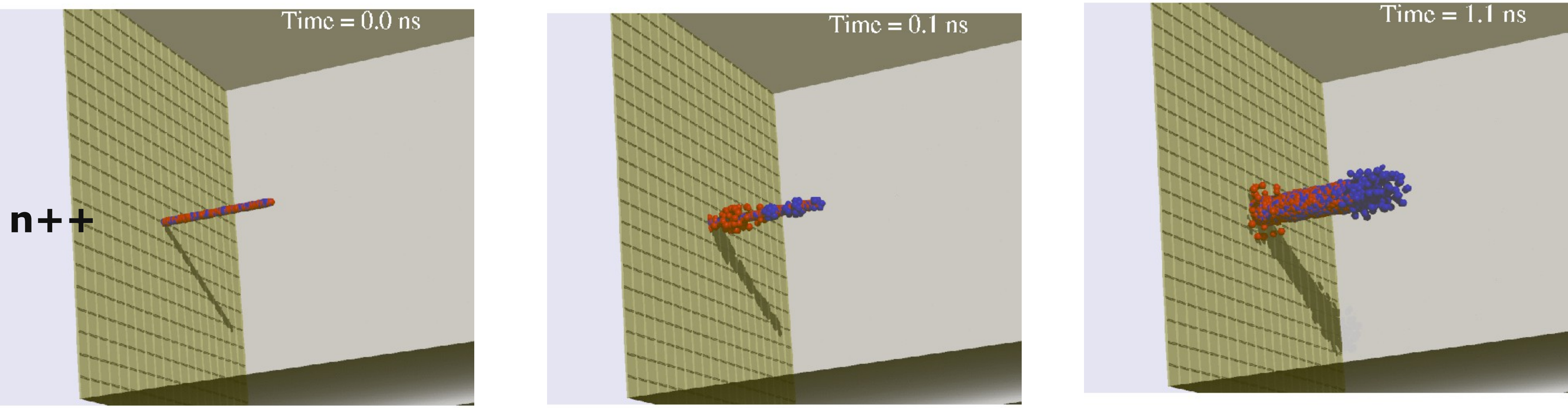
- Energy deposition and e-h creation:
  - longitudinal straggling, channeling,
- Signal formation:
  - non unif. doping, rad. Damage, Vbias instab., sheet resistance
- Signal treatment:
  - Noise and pick up
  - FEE response (pa, cables, antialias filter...)
  - Sampling noise

Conclusions (2)

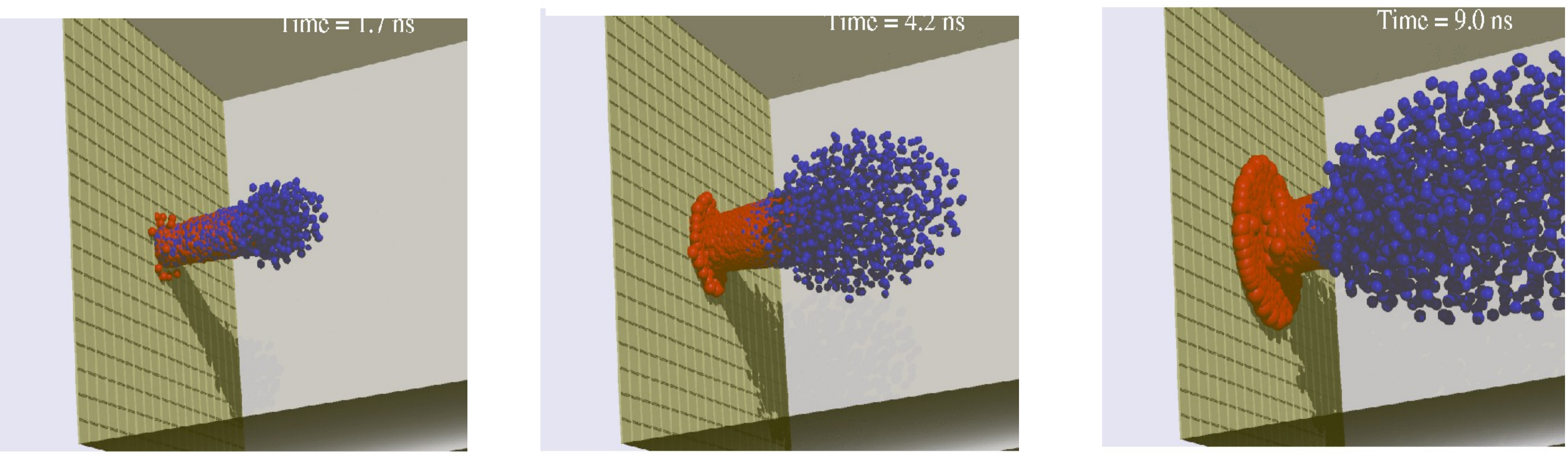
- Long. Straggling=> unavoidable low energy threshold for A identification (for a given Z)
- In FAZIA: doping and sampling noise=> similar contribution, straggling important only at low E
- Solutions:
  - Double gain to get better SNR for LCP id and for IMF mass id.
  - select better unif. Ingots! Cut wafers at an angle
  - Higher sampling rate (not comprimising ENOB) to get better time resolution for LCP

Thanks!

Signal formation and treatment

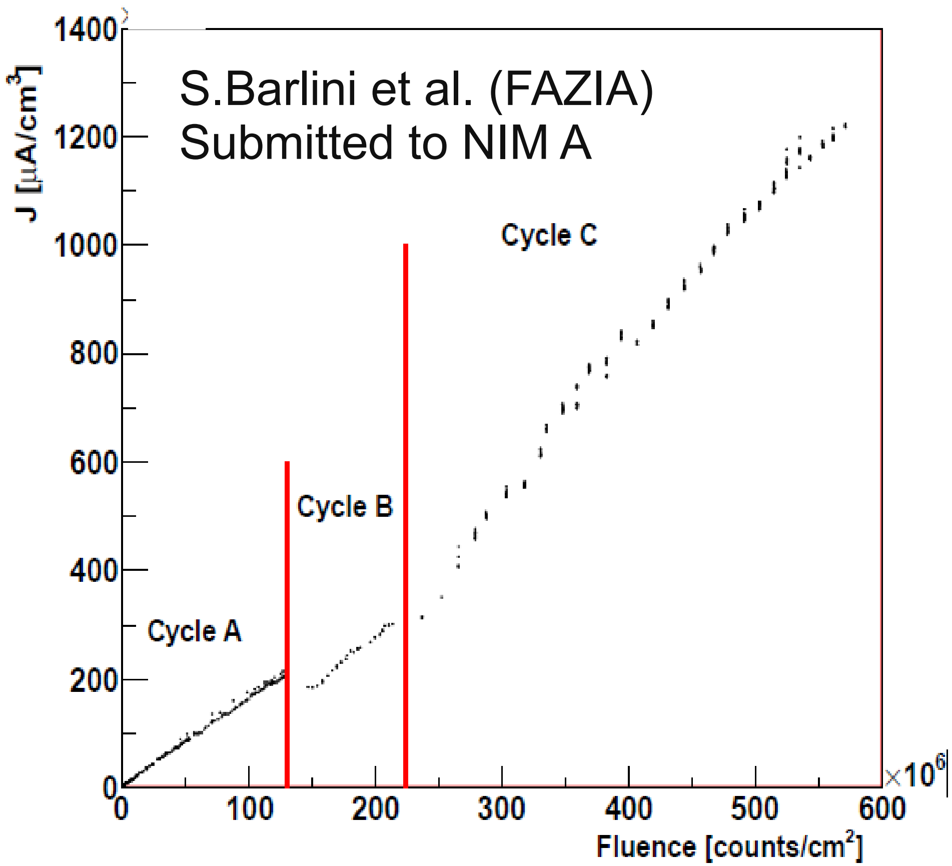


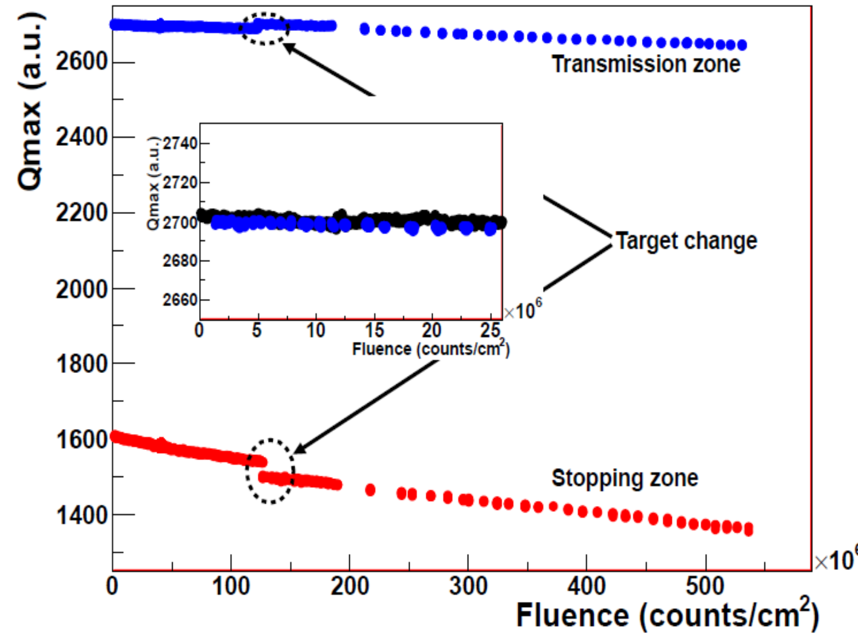
Simulation of a 50 MeV ^{12}C ion

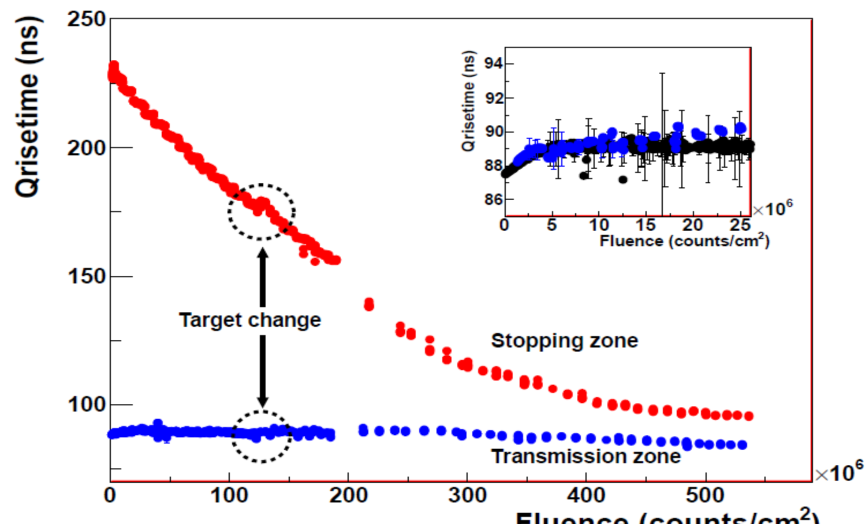


Sensor: Effects of RD

Effects of RD in Si detectors vs. fluence (ions/cm²)

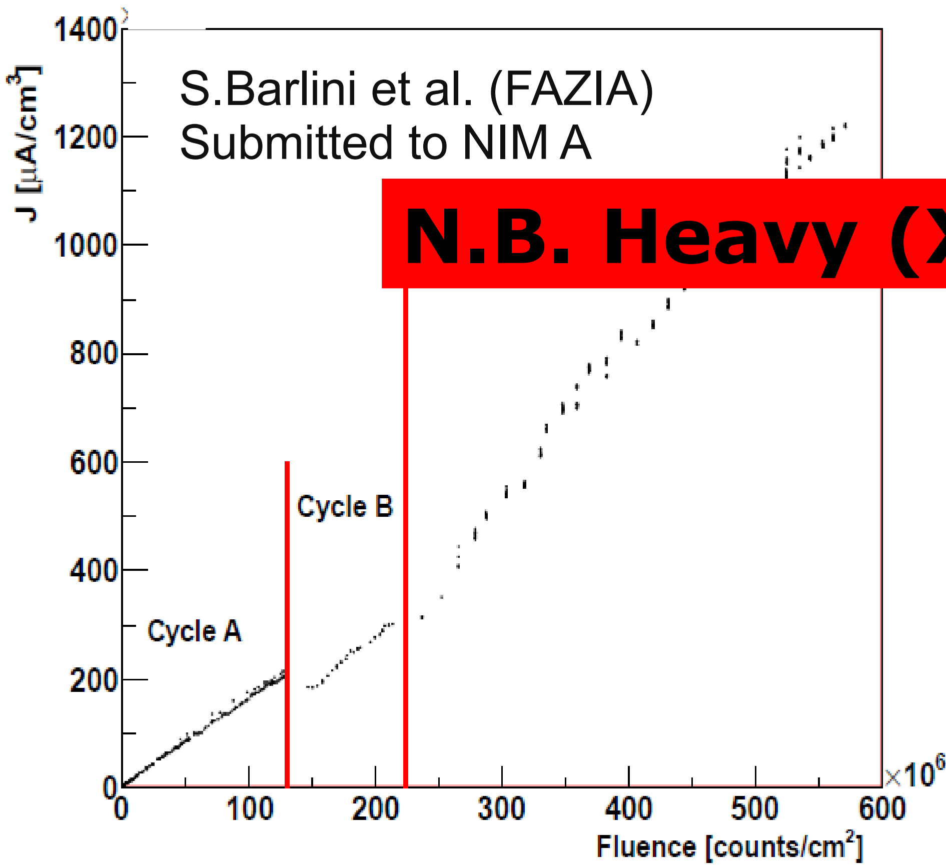




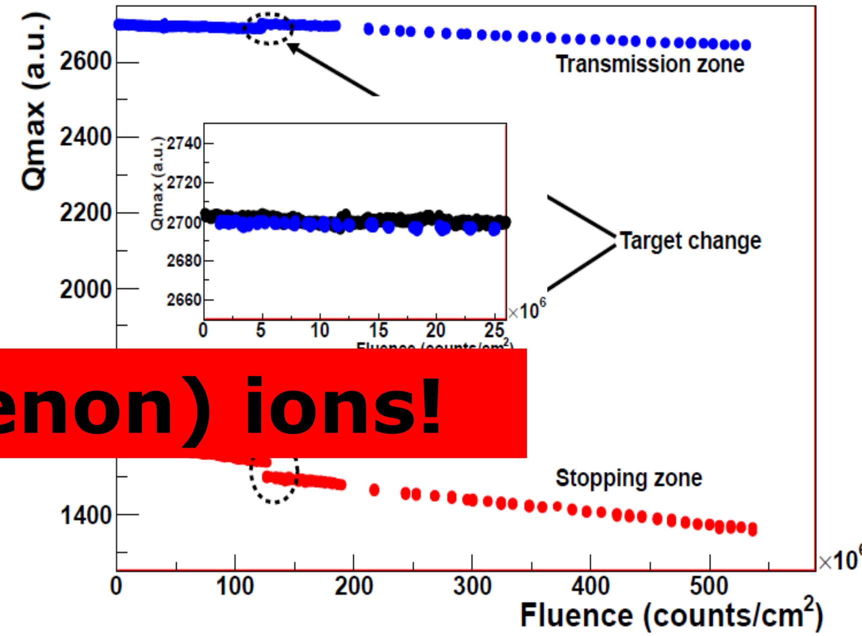


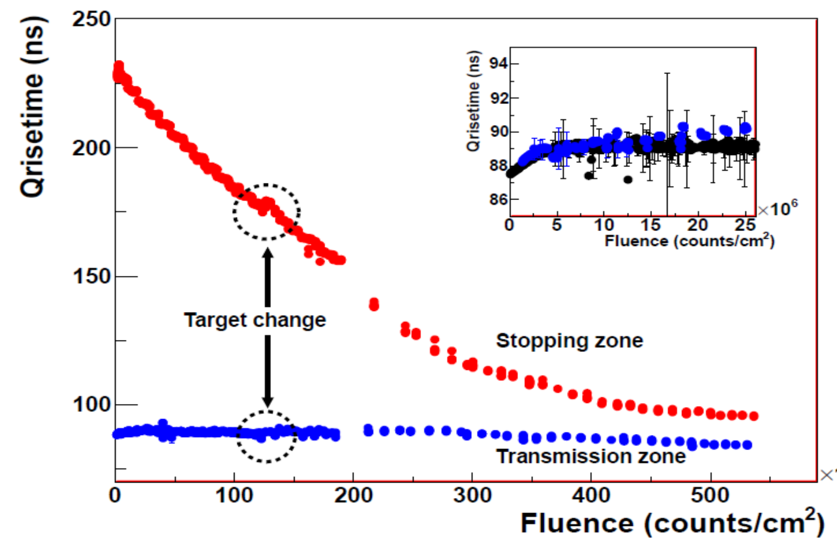
Sensor: Effects of RD

Effects of RD in Si detectors vs. fluence (ions/cm²)



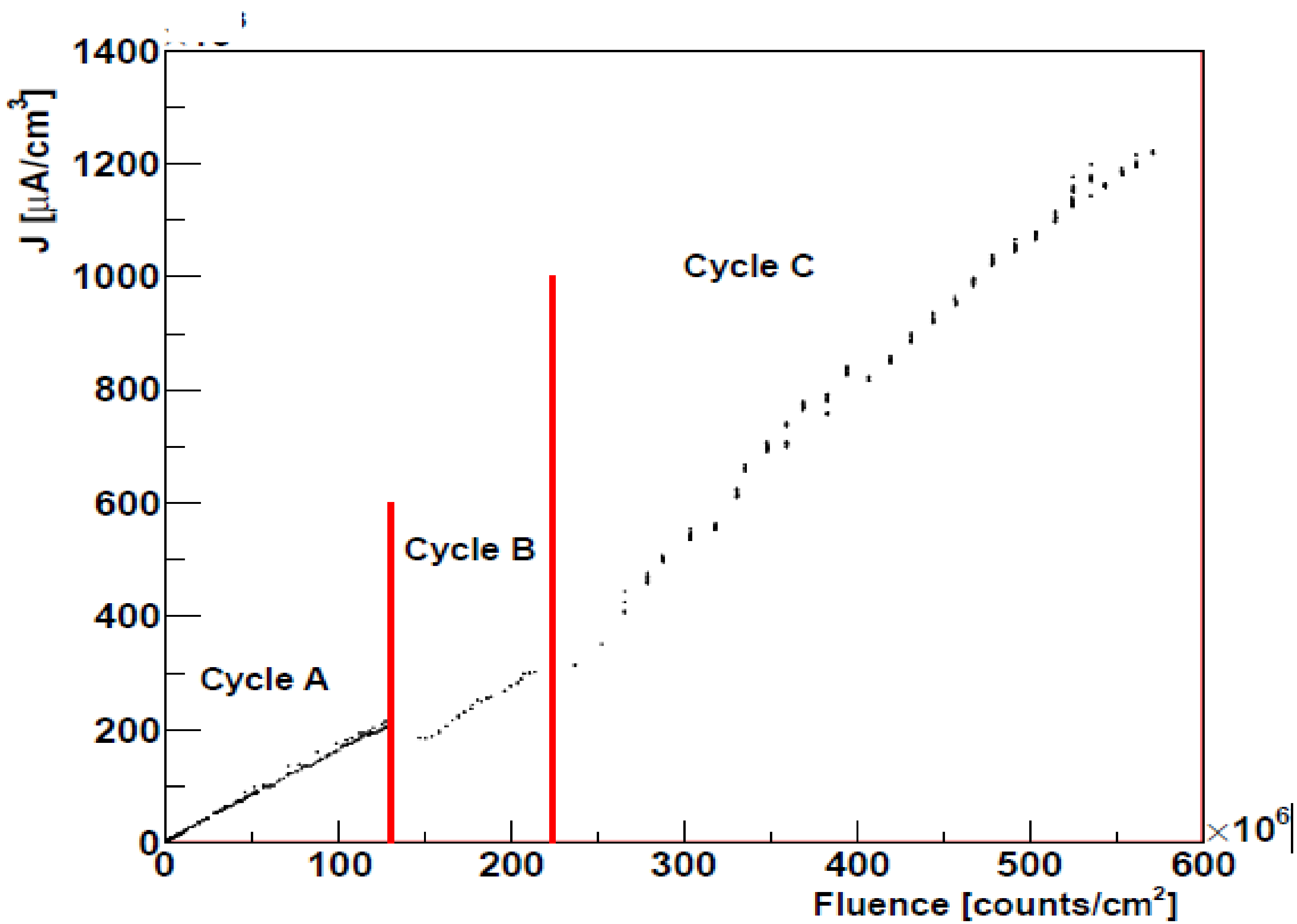
N.B. Heavy (Xenon) ions!

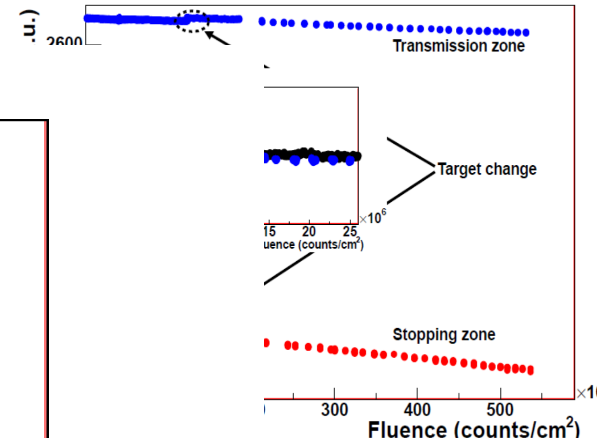


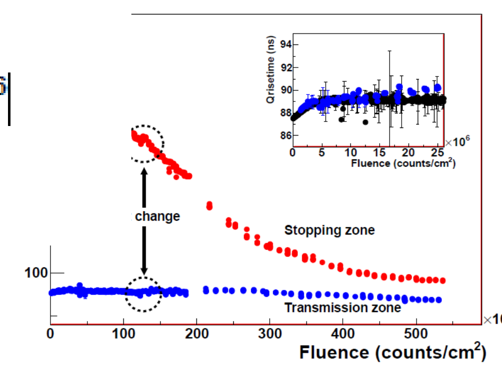


Sensor RD: leakage current

Effects of RD in Si detectors vs. fluence (ions/cm²)

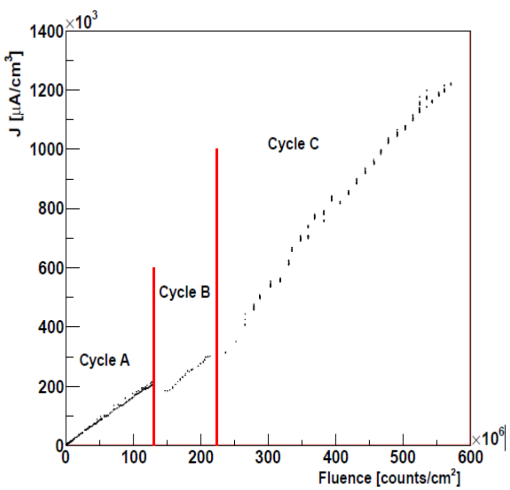






Sensor RD: collection efficiency

Effects of RD in Si detectors vs. fluence (ions/cm²)



S.Barlini et al. (FAZIA)
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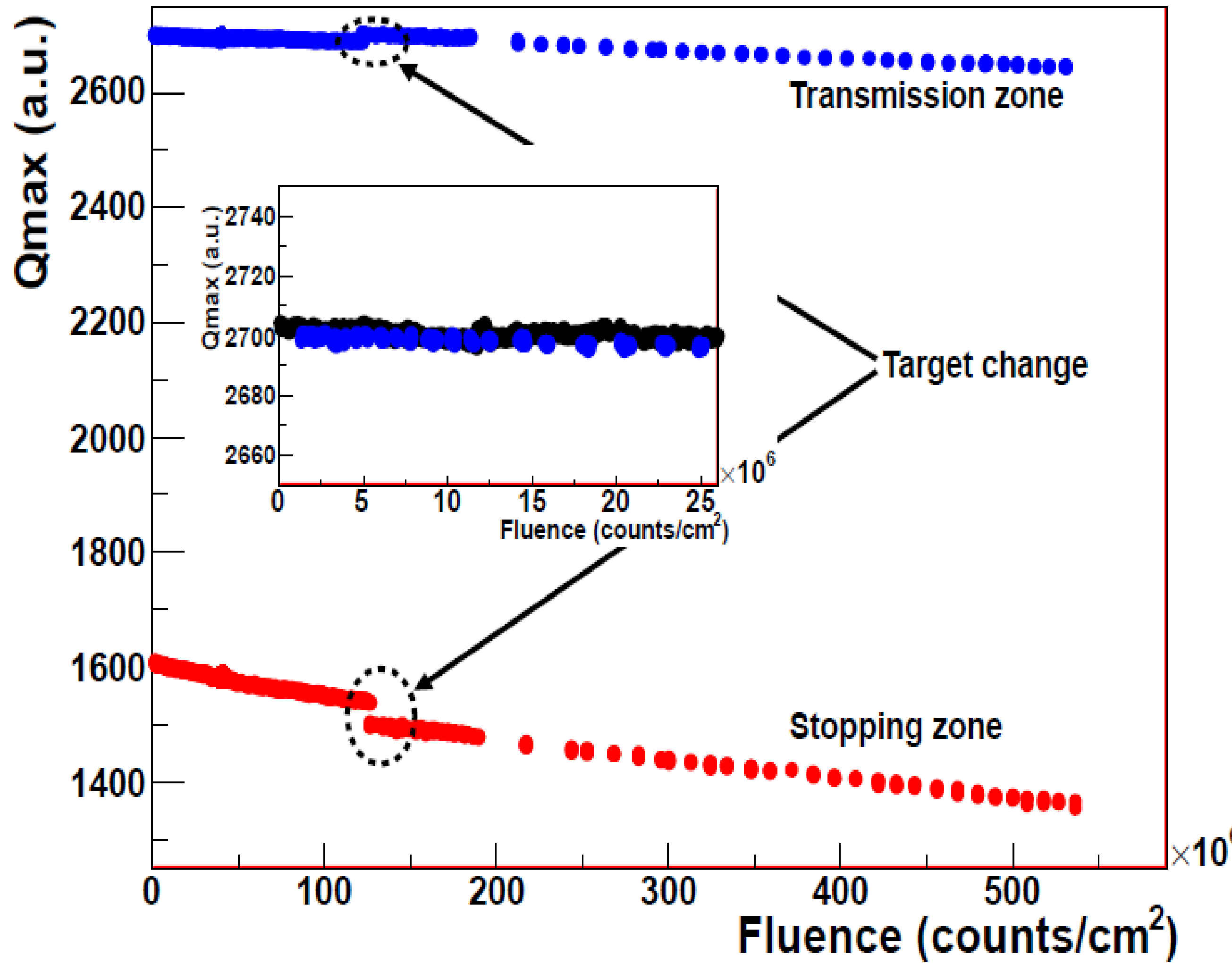
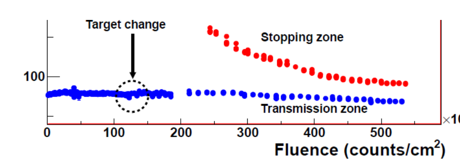
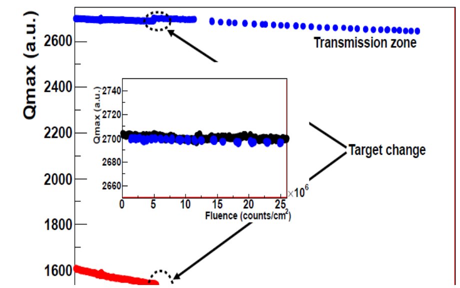
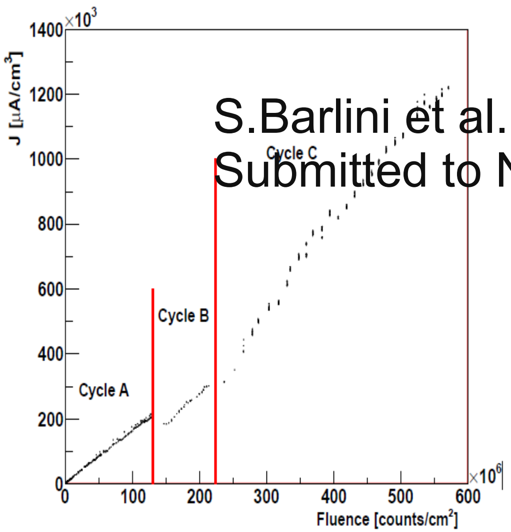




Sensor RD: collection time

Effects of RD in Si detectors vs. fluence (ions/cm²)





S.Barlini et al. (FAZIA)
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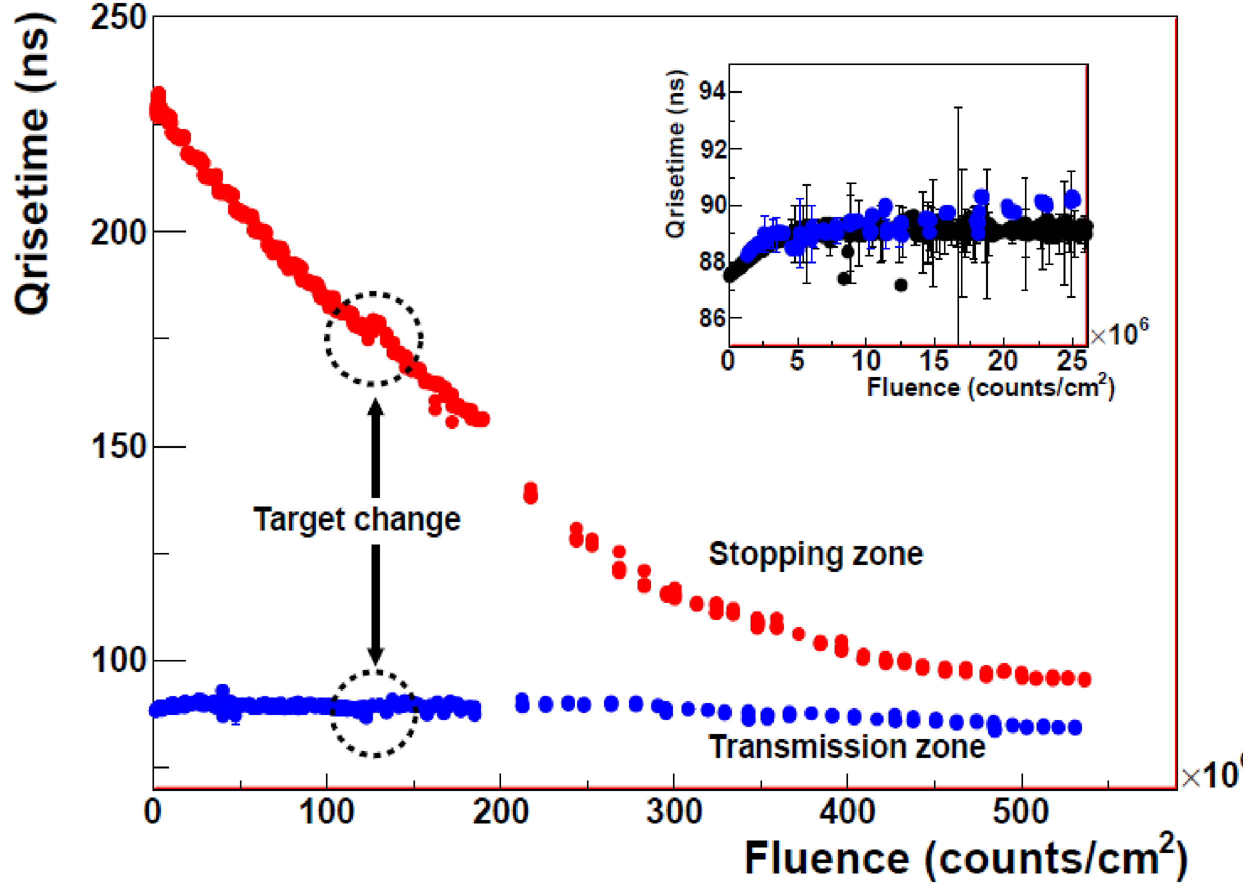
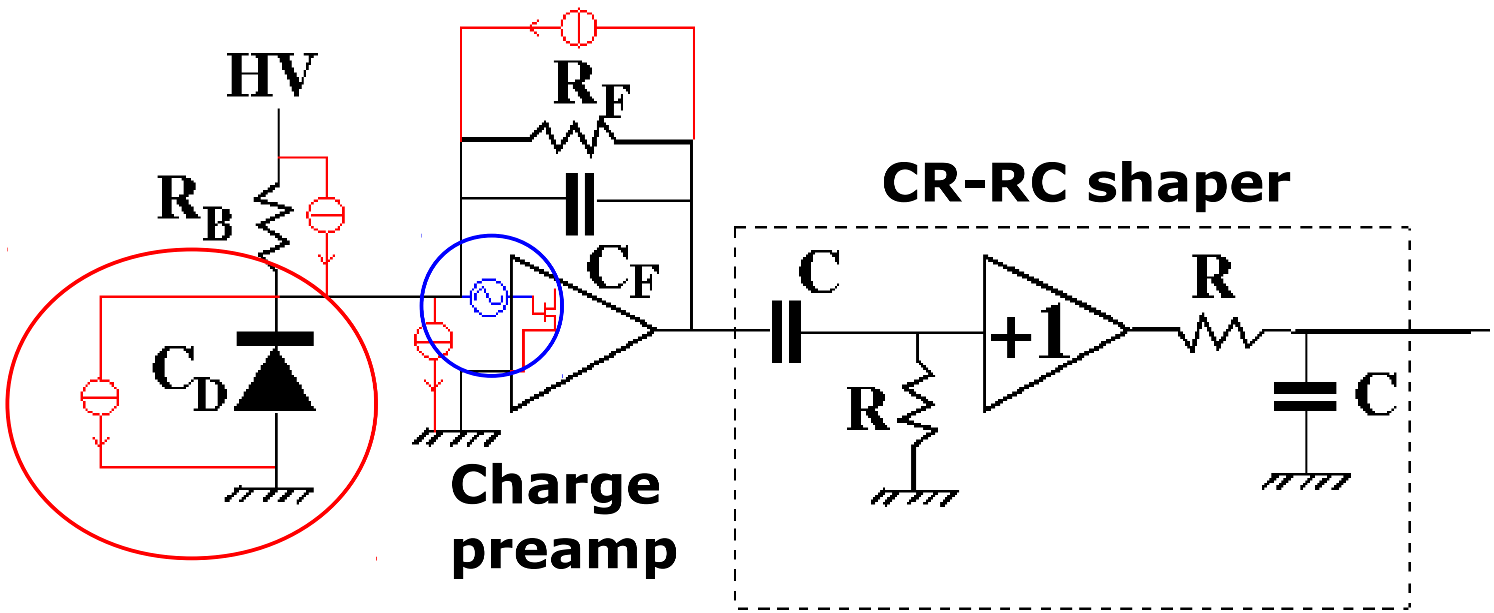


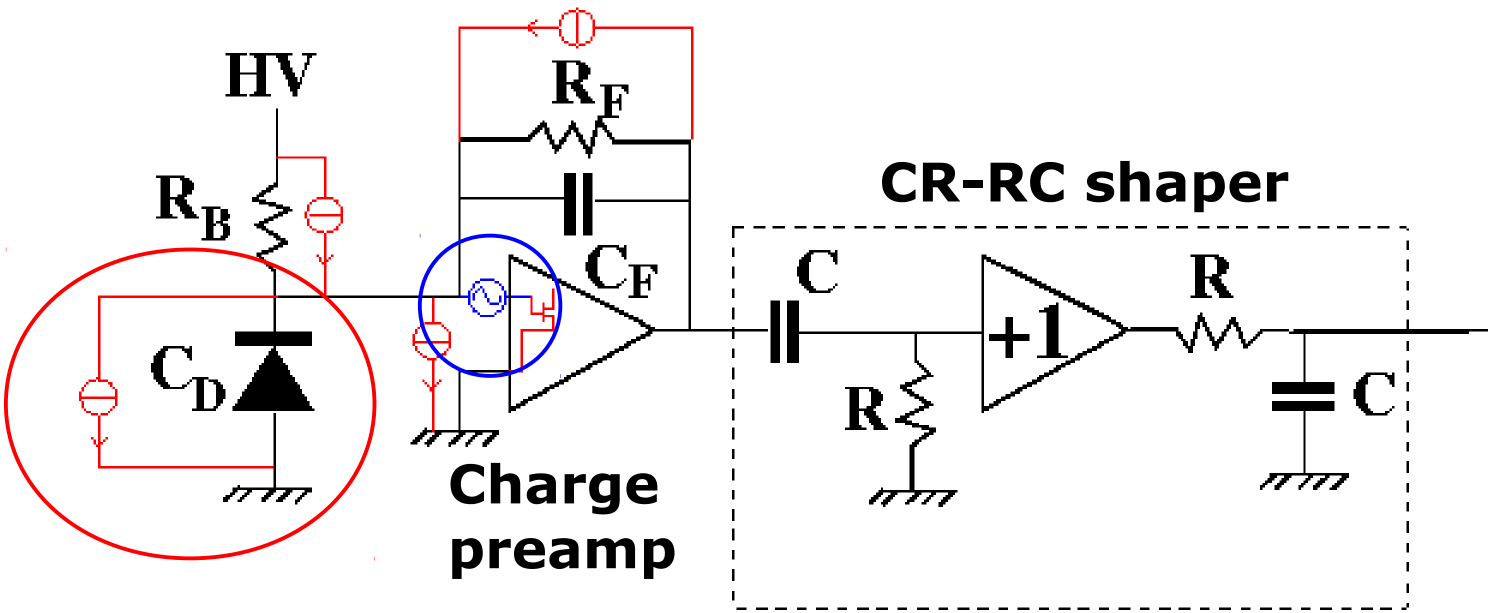
FEE: Electronic noise



Charge signal variance Q_n^2 (measured, e.g., in squared Equivalent Noise Charge, ENC²)

ENC: input charge giving an output voltage signal equal to the rms voltage noise.

FEE: Electronic noise



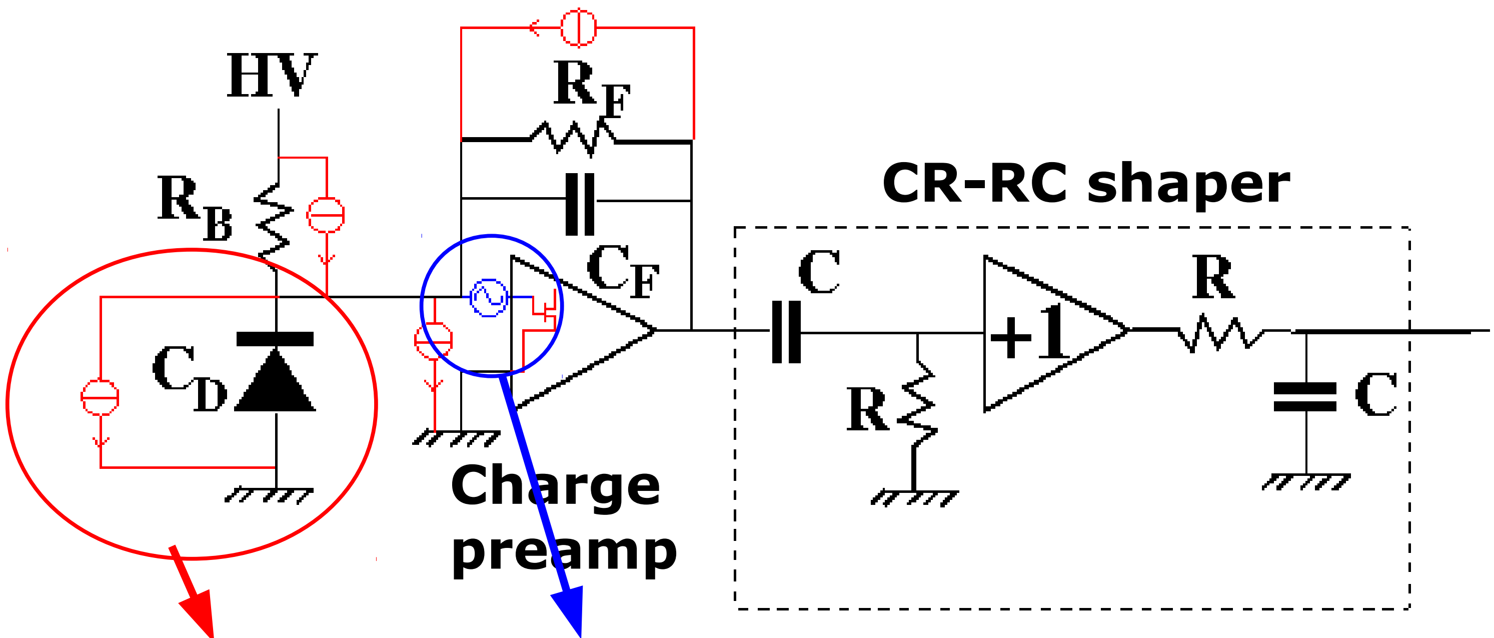
$$Q_n^2 \;=\; i_n^2\,\mathcal{F}_i\,T_s \;+\; e_n^2\,\mathcal{F}_v\,\frac{C_{in}^2}{T_s}$$

T_s : measure time (e.g. CR − RC shaper : $T_s = RC$)
T : absolute temperature

Long T_s => current noise dominates

Short T_s =>voltage noise dominates

FEE: Electronic noise



$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s}$$

$$T_s: \quad \text{measure time} \;\; (\text{e.g. CR} - \text{RC shaper}: \; T_s = RC)$$

Long T_s => current noise dominates

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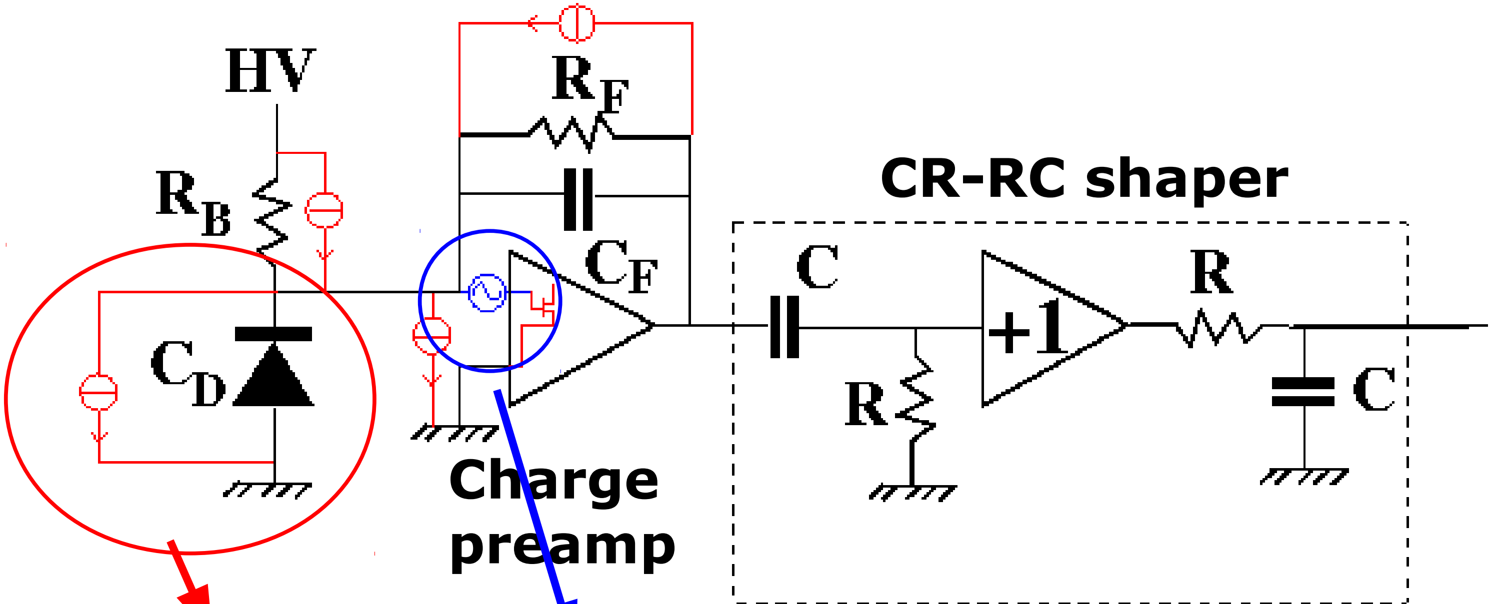
FEE: Electronic noise



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FEE: Electronic noise

$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s}$$

$$i_n^2 \qquad i_n^2 \approx 2\, e\, I_D \qquad I_D(T) \propto T^2 e^{-E/k_B T}$$

- **increases linearly with leakage current**
- **leakage current increases with damage**

FEE: Electronic noise

$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s}$$

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$$e_n^2 \qquad e_n^2 \approx \frac{2.7\, k_B\, T}{g_m} \propto \frac{2.7\, k_B\, T}{I_{FET}}$$

- **increases w/ decreasing input transistor transconductance => decreasing power**
- **“amplified” by input capacitance squared**

FEE: Electronic noise

$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s}$$

$$i_n^2$$

$$i_n^2 \approx 2\, e\, I_D \qquad I_D(T) \propto T^2 e^{-E/k_B T}$$

- **increases linearly with leakage current**
- **leakage current increases with damage**

$$e_n^2$$

$$e_n^2 \approx \frac{2.7\, k_B\, T}{g_m} \propto \frac{2.7\, k_B\, T}{I_{FET}}$$

- **increases w/ decreasing input transistor transconductance => decreasing power**
- **“amplified” by square on input capacitance**

FEE: Electronic noise

$$Q_n^2 = i_n^2 F_i T_s + e_n^2 F_v \frac{C_{in}^2}{T_s}$$

$$i_n^2 \qquad i_n^2 \approx 2\, e\, I_D \qquad I_D(T) \propto T^2 e^{-E/k_B T}$$

- **increases linearly with leakage current**
- **leakage current increases with damage**

$$e_n^2 \qquad e_n^2 \approx \frac{2.7\, k_B T}{g_m} \propto \frac{2.7\, k_B T}{I_{FET}}$$

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- **"amplified" by input capacitance squared**

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$$i_n^2$$

$$i_n^2 \approx 2\, e\, I_D \qquad I_D(T) \propto T^2\, e^{-E/k_B T}$$

- increases linearly with leakage current
- leakage current increases with damage

$$e_n^2$$

$$e_n^2 \approx \frac{2.7\, k_B\, T}{g_m} \propto \frac{2.7\, k_B\, T}{I_{FET}}$$

- increases w/ decreasing input transistor transconductance => decreasing power
- "amplified" by input capacitance squared

Both increase with temperature!

Some ASIC specific issues

- relatively low bias voltage=>need bigger feedback capacity for the same dynamic energy range with respect to discrete of higher bias voltage

- big capacity => occupy large area on ASIC chip

- low voltage noise needs high transconductance, i.e. Large JFET bias current => needs large area for JFET

- taking out preamp signal for digitizers problematic

- slow (sequential) readout. Sparse readout faster though it needs some timing logic (CFD,…). Dead time after sample/hold.

Performances

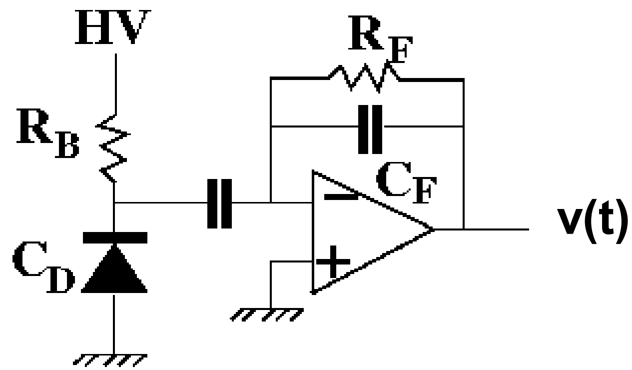
Deposited energy => collected charge

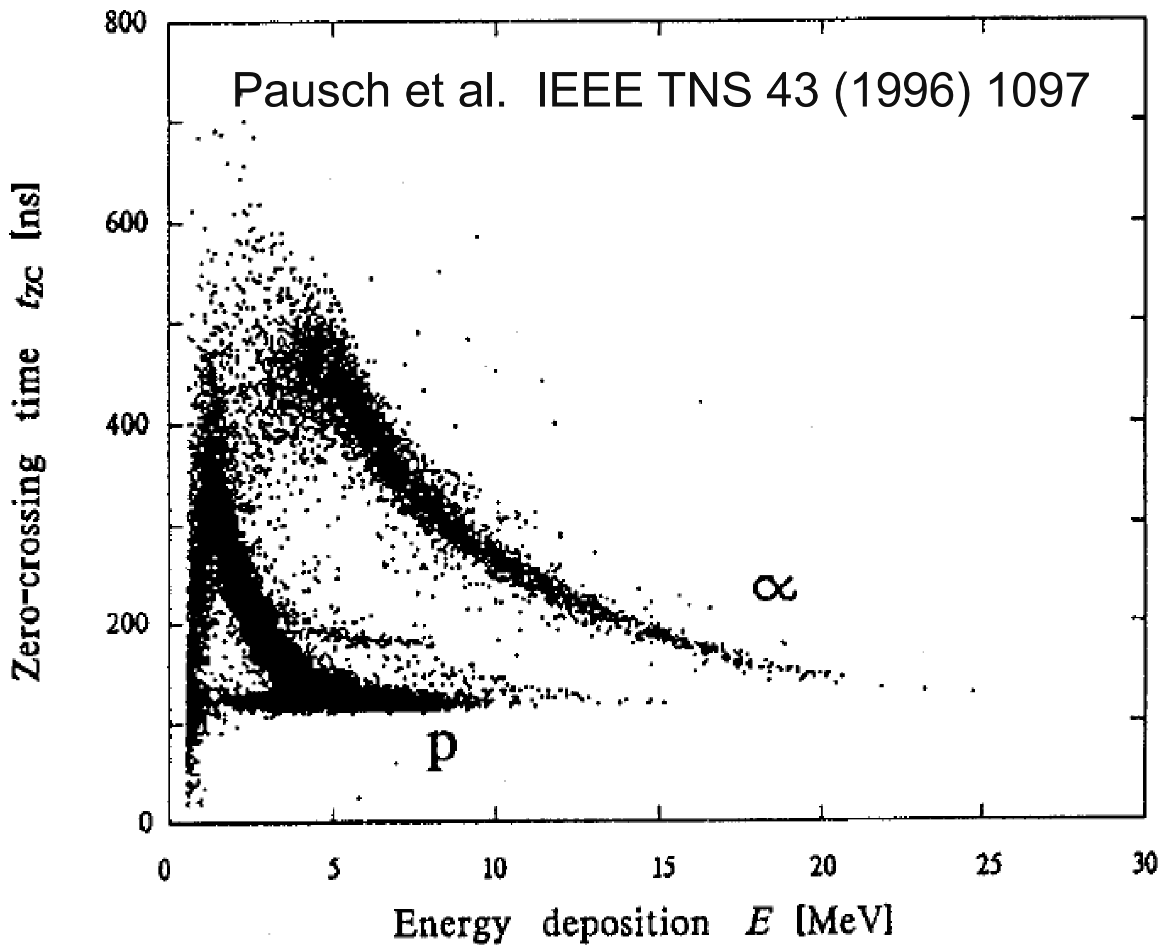
Fluctuations in carrier number, electronic noise etc => finite resolution in determining charge (energy).

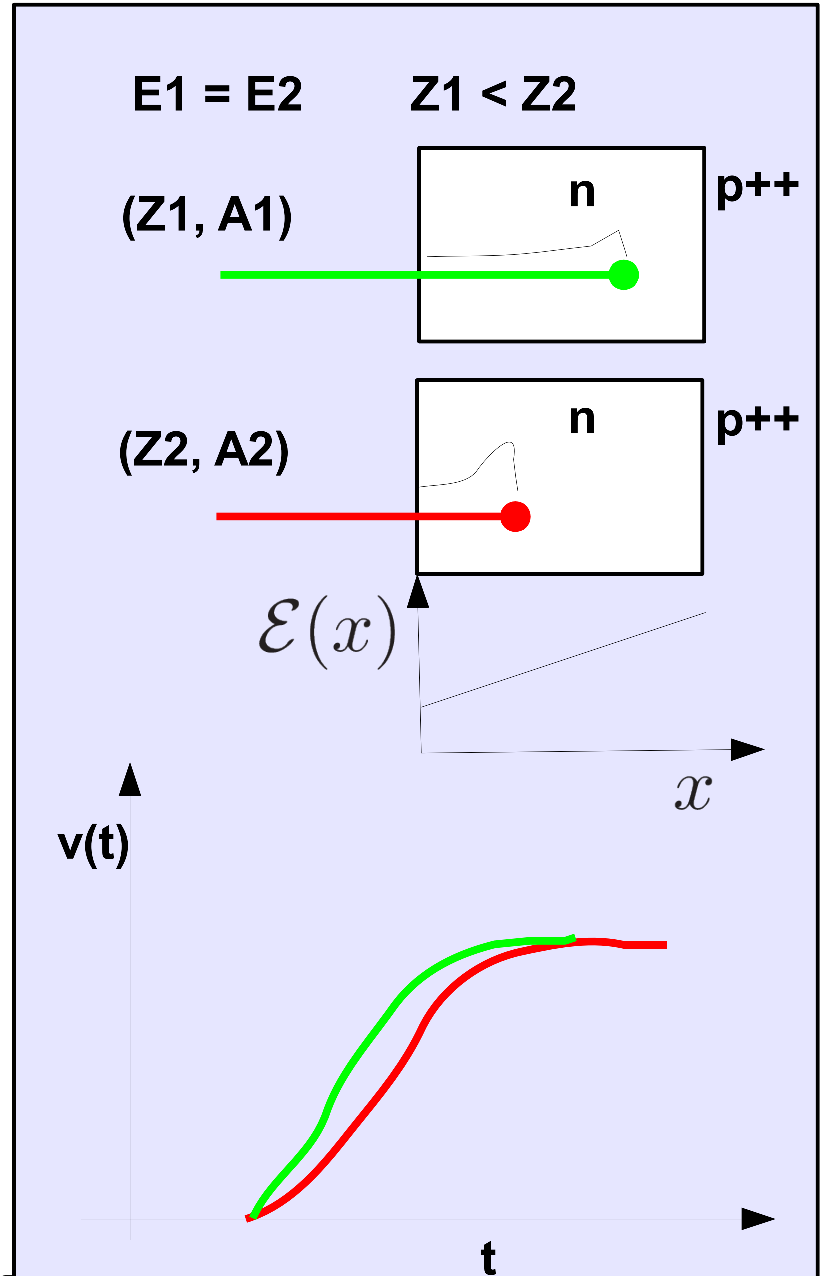
Collection time=>timing and resolving time.

	Scintillator	Gas	Solid State
Energy/carrier	100−500 eV	20−40 eV	~3 eV
Energy resol. @ 1 MeV	100−500 keV	20−50 keV	1−10 keV
Timing resol. @ 1 MeV	~0.03−1 ns	0.1−1 ns	0.1−2 ns
Detectable particle charge	1−6	>20	all
pulse shape	y	n	y/n
Area limits	100 cm^2	m^2	cm^2
Easy to handle	y	y/n	y
Cost/cm^2	medium	medium	high

Particle ID: Pulse Shape Ident. in Silicon

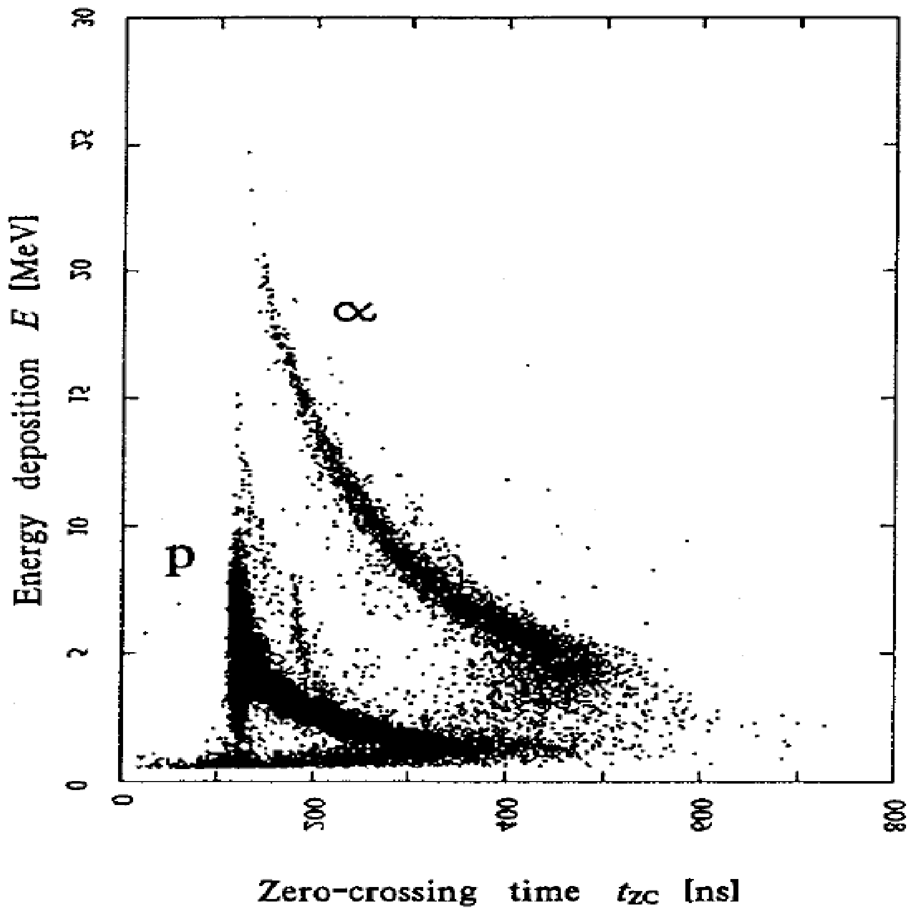




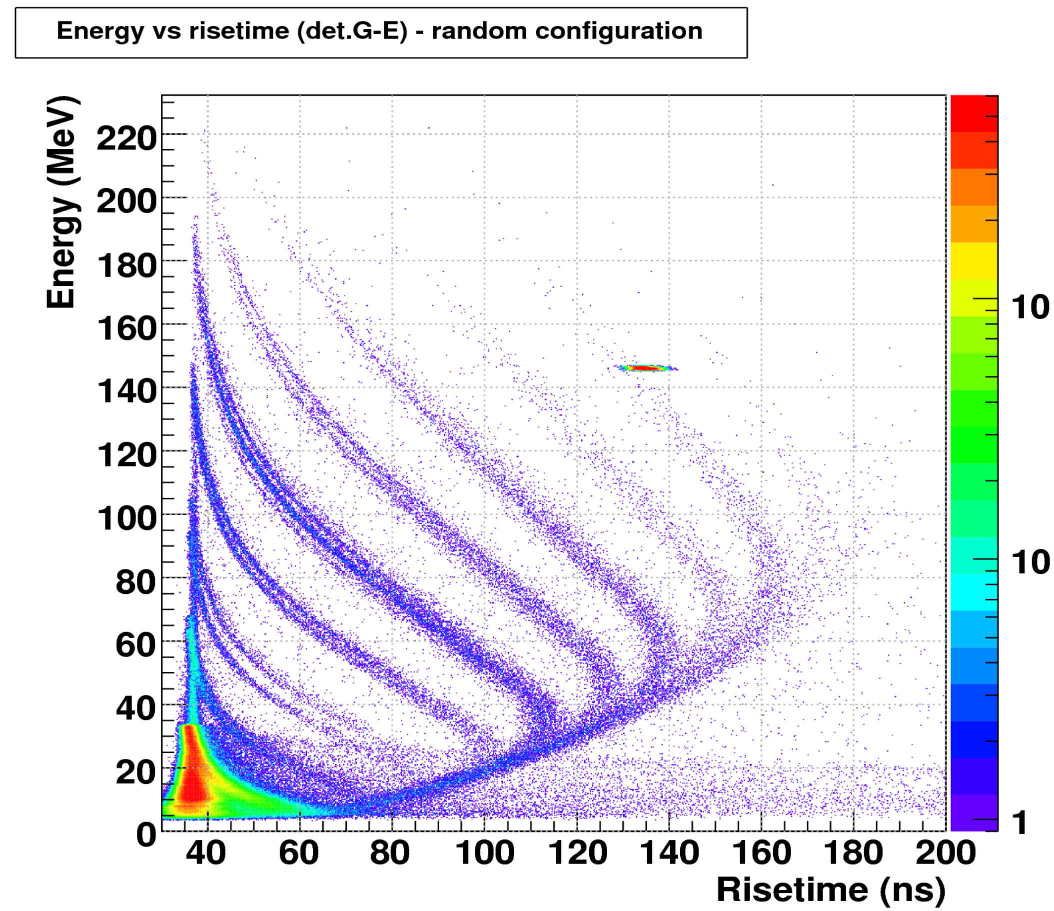


Particle ID: Pulse Shape Ident. in Silicon

Pausch image rotated and flipped for easier comparison.



Pausch et al. IEEE TNS 43 (1996) 1097



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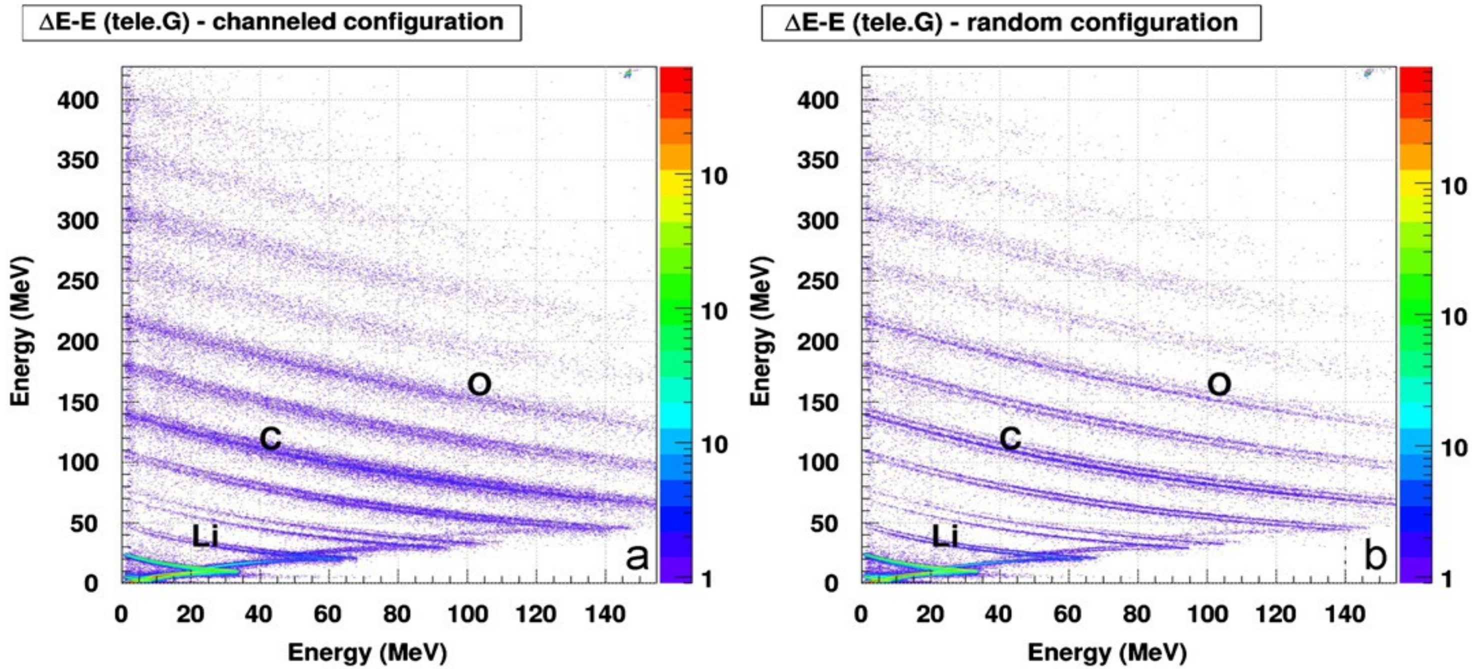
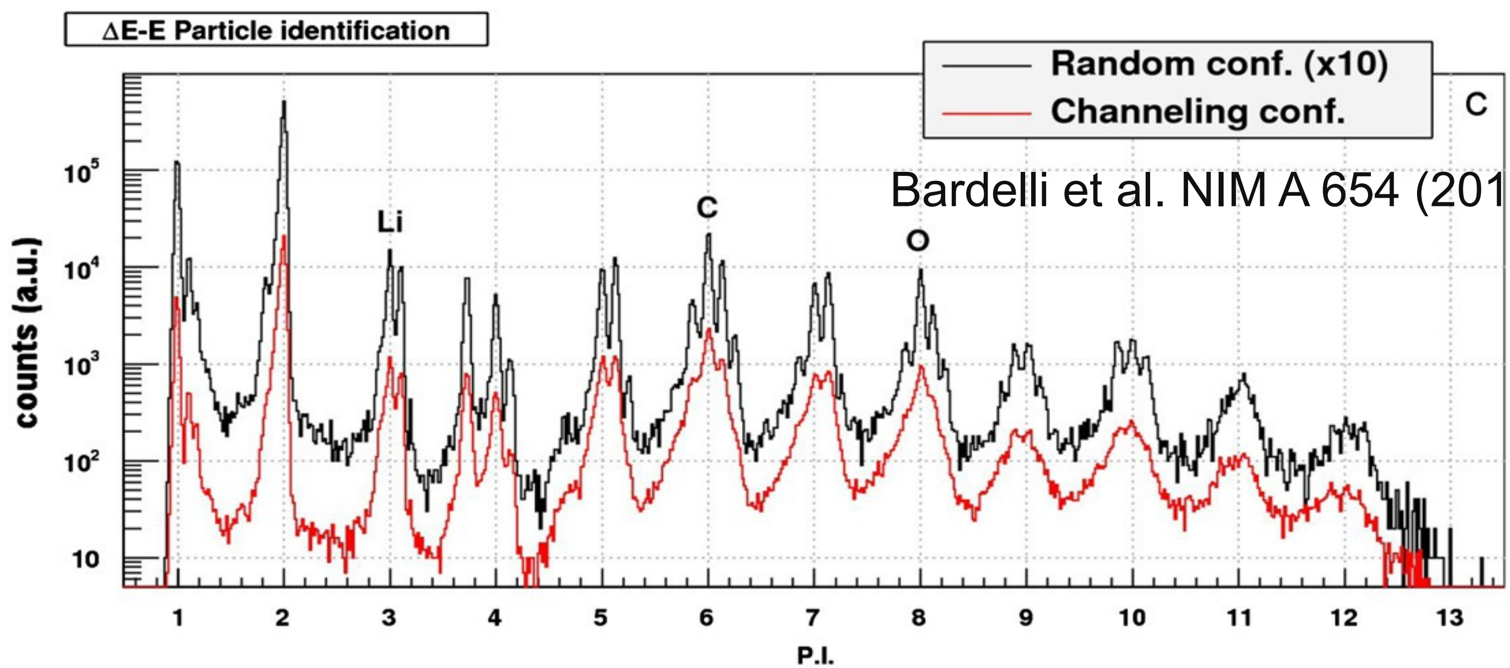
Particle ID: ΔE-E and Channeling





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PSA of Si signals: what we have learnt within the FAZIA collaboration

G. Pasquali
pasquali@fi.infn.it
University of Florence & INFN-Sezione di Firenze

Outline

- **Introduction: The FAZIA collaboration**
- **The physical process and PSA basics**
  - **Energy deposition, Signal Formation and treatment**
  - **PSA basics: front (junction side) or rear (ohmic side) injection?**
  - **PS identification methods: "E vs Charge signal risetime" and "E vs Max I"**
- **Effects spoiling pulse shape**
  - **Straggling and channeling**
  - **Doping non-uniformity and changing bias voltage**
  - **Radiation Damage (Recombination and trapping)**
  - **Sheet resistance (when no Al layer on surface)**
- **Front End Electronics**
  - **Fidelity related issues (PA response, minimizing pick up noise and cross talk, anti-alias response etc.)**
  - **ADC noise (ENOB), ADC optimal resolution and sampling rate.**
- **FAZIA demonstrator**
- **Conclusions**

First let me thank you for inviting me. I will try to give you some idea of what the FAZIA collaboration has learnt about PS identification in silicon detectors. After a short reming about FAZIA, I will give a brief summary of the physical process and signal treatment involved in this business.

Then I will deal with the main effects spoiling Pulse Shape identification and the possible strategies to reduce them.

I can't really go deep in the subject of electronic treatment of signals and digital signal processing.

Nevertheless I will try to touch a few select topics.

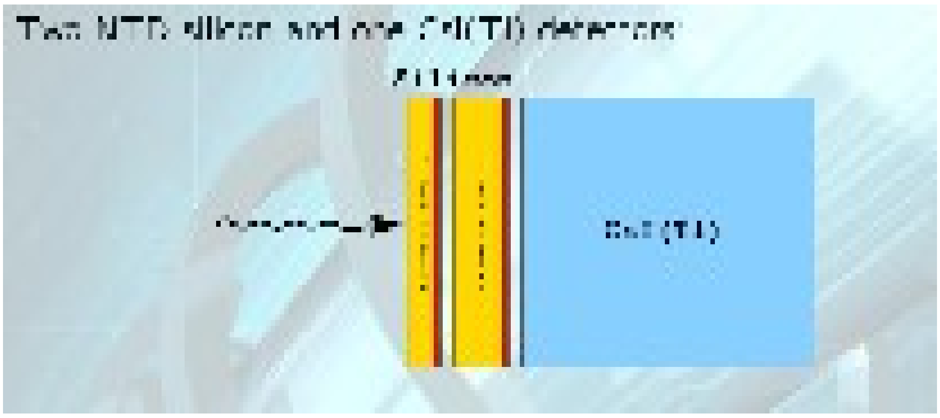
The FAZIA collaboration

- **Established in 2006 (FAZIA= "Four π A and Z Identification Array")**
  Members' nations: France, Italy, Poland, Spain, Rumania (+Canada, India and US)
- **Started as an R&D project to improve PSA and ΔE-E**
- **Goal: to design and build a new-generation detector for charged particles, suited for Isospin Physics to be done at Radioactive Beam Facilities like Spiral2, SPES and FAIR. The main partners are INFN and CNRS (~90 members)**
- **Experiments performed: CIME'06, LNL'07, LNS'09, GANIL'10, LNS'11**

The FAZIA collaboration has been established in 2 thousand six, as an R&D project.
Since isotopic identification of ejectiles will be all the more important at radioactive beam facilities, we wanted to improve it and also to lower the energy thresholds for identication.
We choosed a basic detection cell which is a deltaE-E telescope and we studied both deltaE-E and pulse shape identification, both for light ions and heavier ones, from few MeV/n to almost 40 MeV/n.
We have published...

FAZIA basic cell

- **Basic cell: triple telescope Si(300um)-Si(500um)-CsI(10cm)**
- **Silicon are nTD, reverse mounted, 20x20mm^2, bulk ρ~3-5 kΩcm**
- **CsI is read out by a photodiode or by second Si (Single-Chip Telescope)**

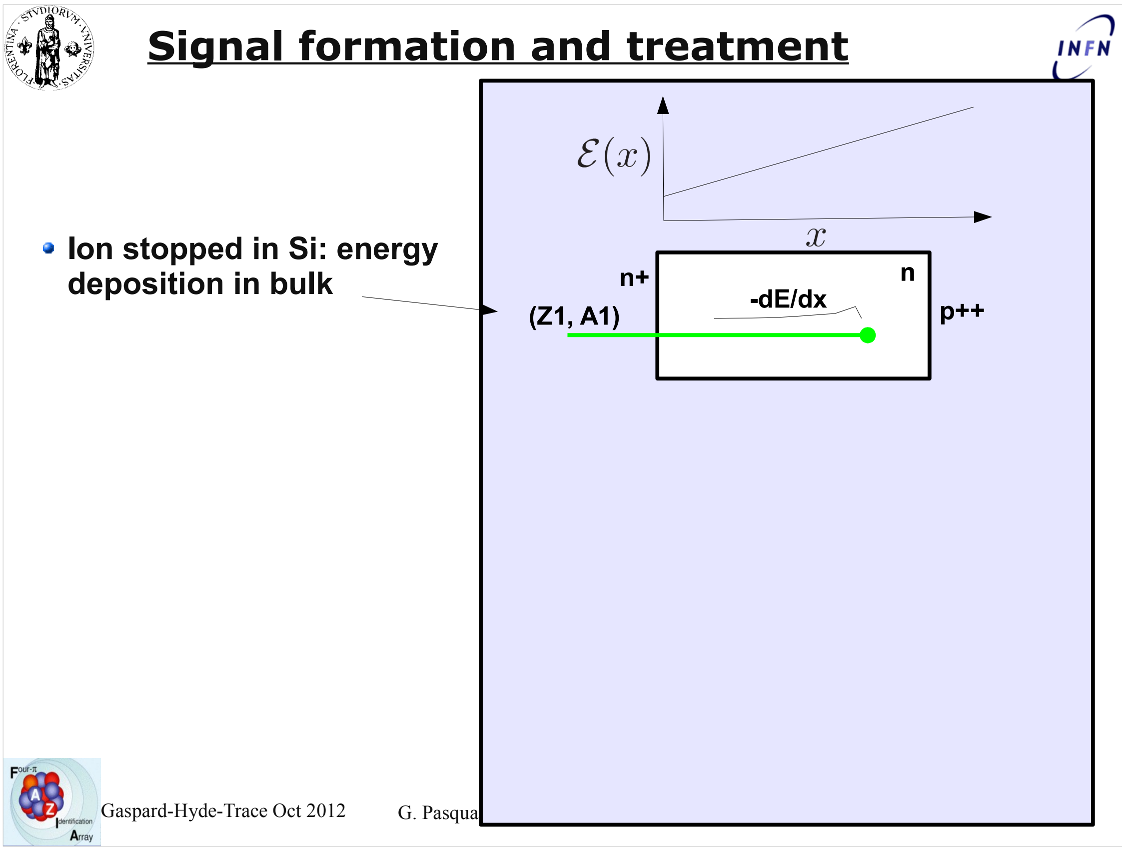


As I have just said, FAZIA basic cell is a deltaE-E telescope, actually a three stage telescope.

The first two stages are si detectors. Both are neutron transmutation doped detectors, they are mounted with the ohmic side facing the target and they have different thickness, 300um and 500um respectively.

The last stage is a 10cm long CsI scintillator, capable of stopping up to …. AMeV of protons or alphas.

Signal formation and treatment

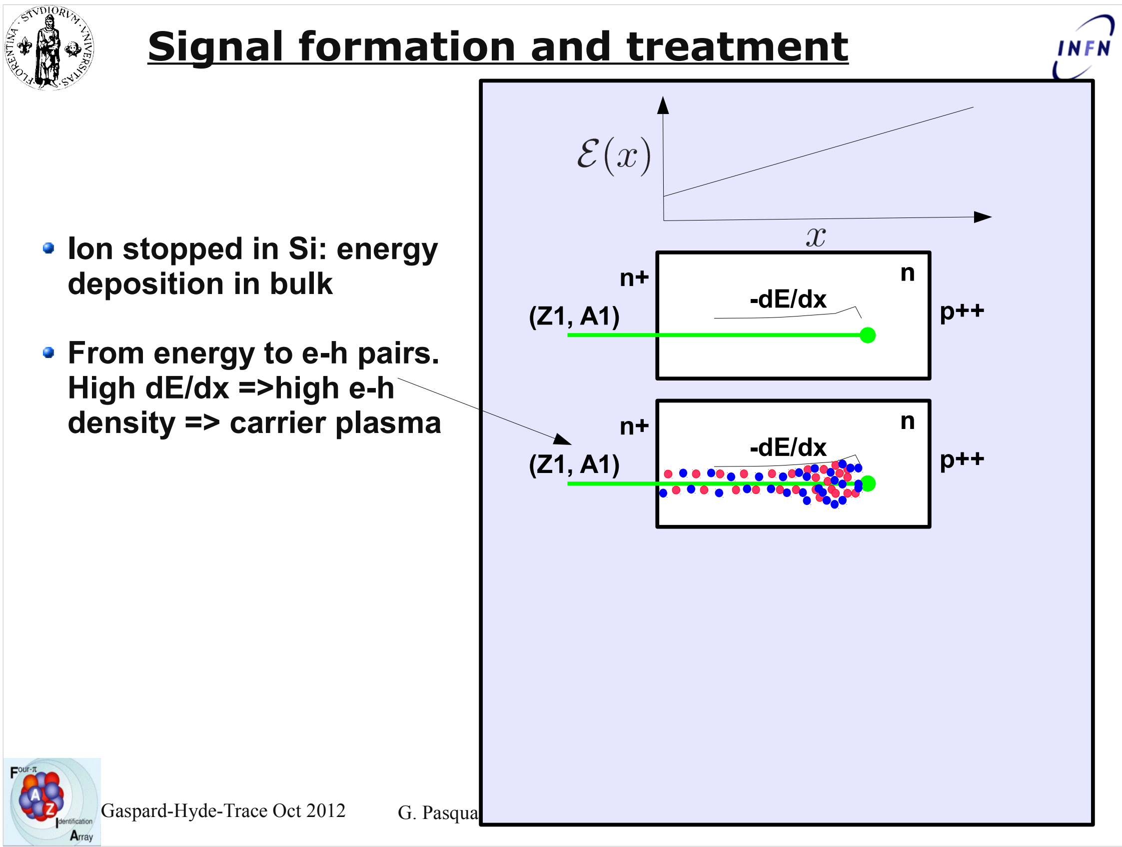


Let's consider an impinging ion stopped in a si detector. Experiment shows that charge collection evolves in a way dependent on both the ion charge and energy. Therefore, in 1963 Ammerlan proposed to exploit the different signal shapes in order to identify the detect fragments.

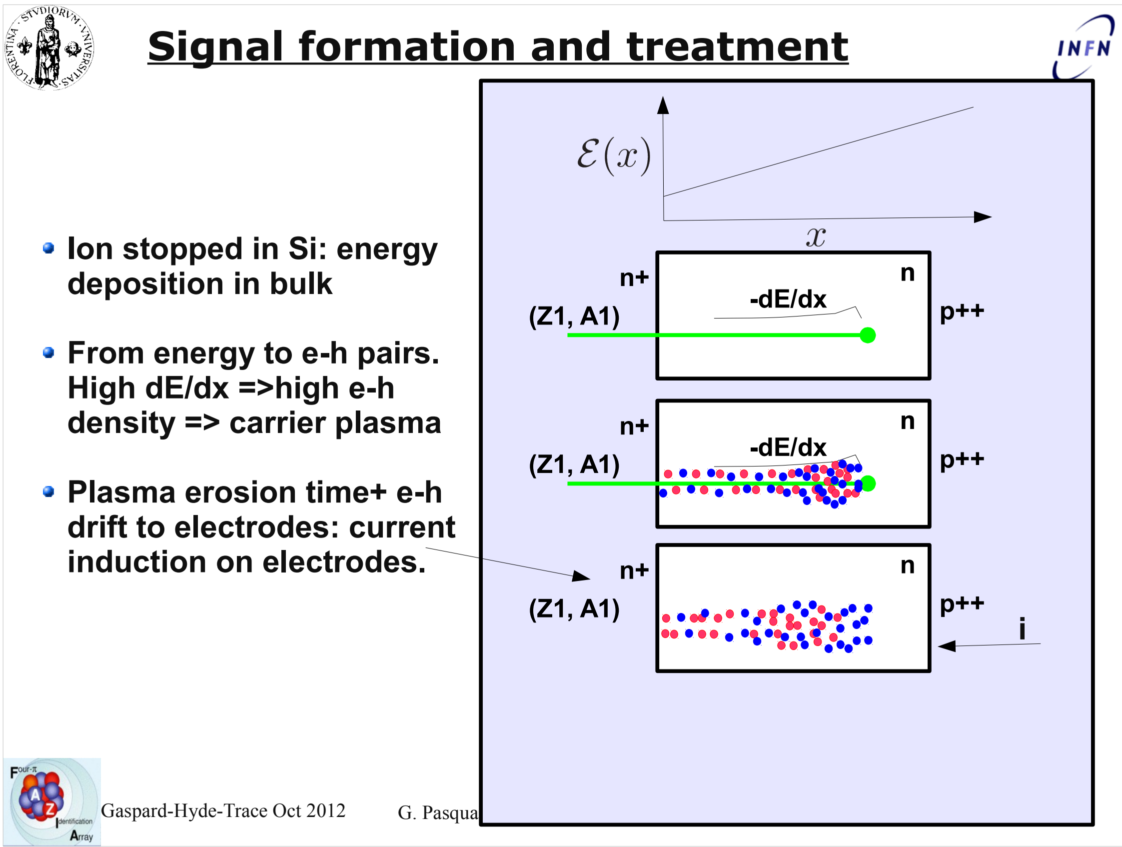
The technique has then been studied in detail in the 90ies by Pausch and collaborators, Mutterer and collaborators etc. Now everybody is trying to implement it in a way or another.

Let me remind you briefly the basic processes involved. An impinging Ion of atomic number Z and mass number A enters the silicon and slows down depositing in each slice of thickness dx and energy -dE until it stops at the end of its range.

I have plotted here the electric field as a function of Penetration depth for a reverse mounted silicon.



Part of the deposited energy is exploited to create charge carriers, electrons and holes. Their linear density follows the behaviour of the de/dx curve of the particle as a function of x. It is usually greater at the end of the range, where we have the well known Bragg peak of specific energy loss.

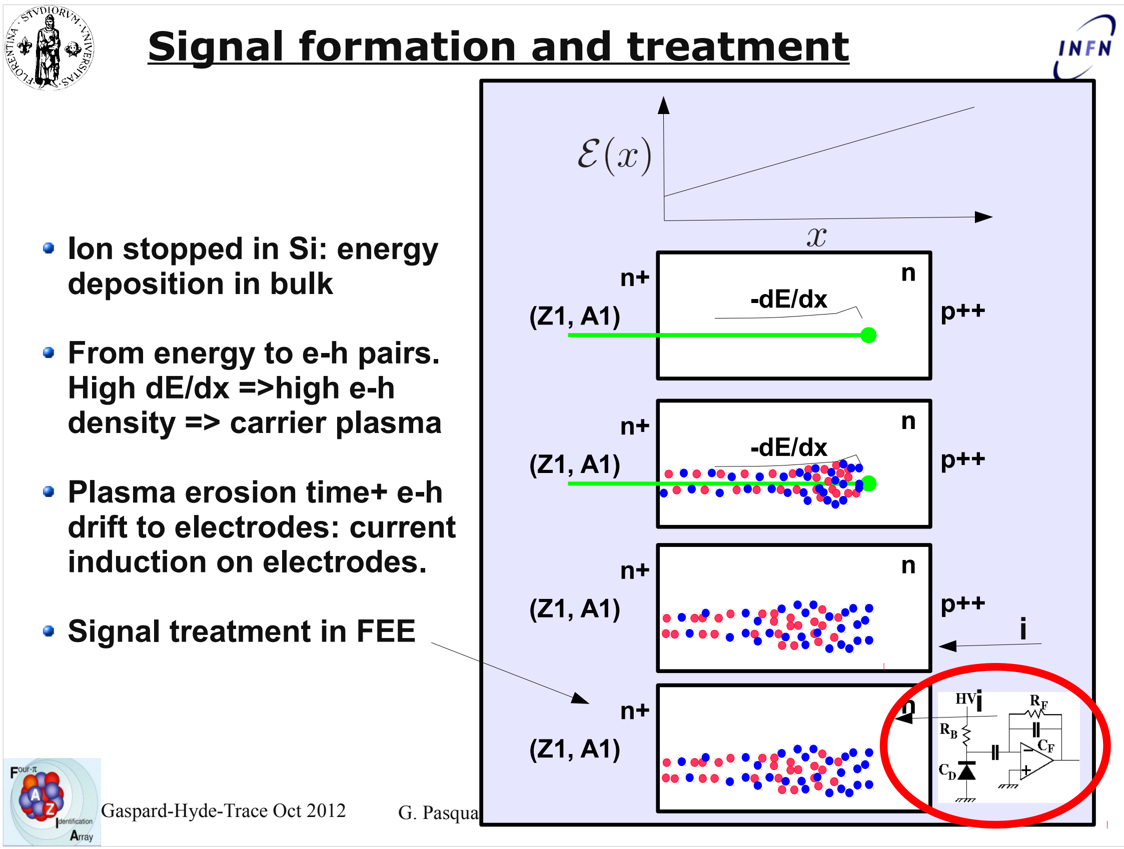


As soon as they are created,they start to diffuse in the bulk due to their concentration gradient. They also assume a drift velocity towards the electrodes, a velocity proportional to the local electric field...unless their density is so high that the charge column behaves like a charged plasma: the electric field inside the column is either zero or at least reduced and the column must be eroded by the head and the sides, thus slowing down charge collection.

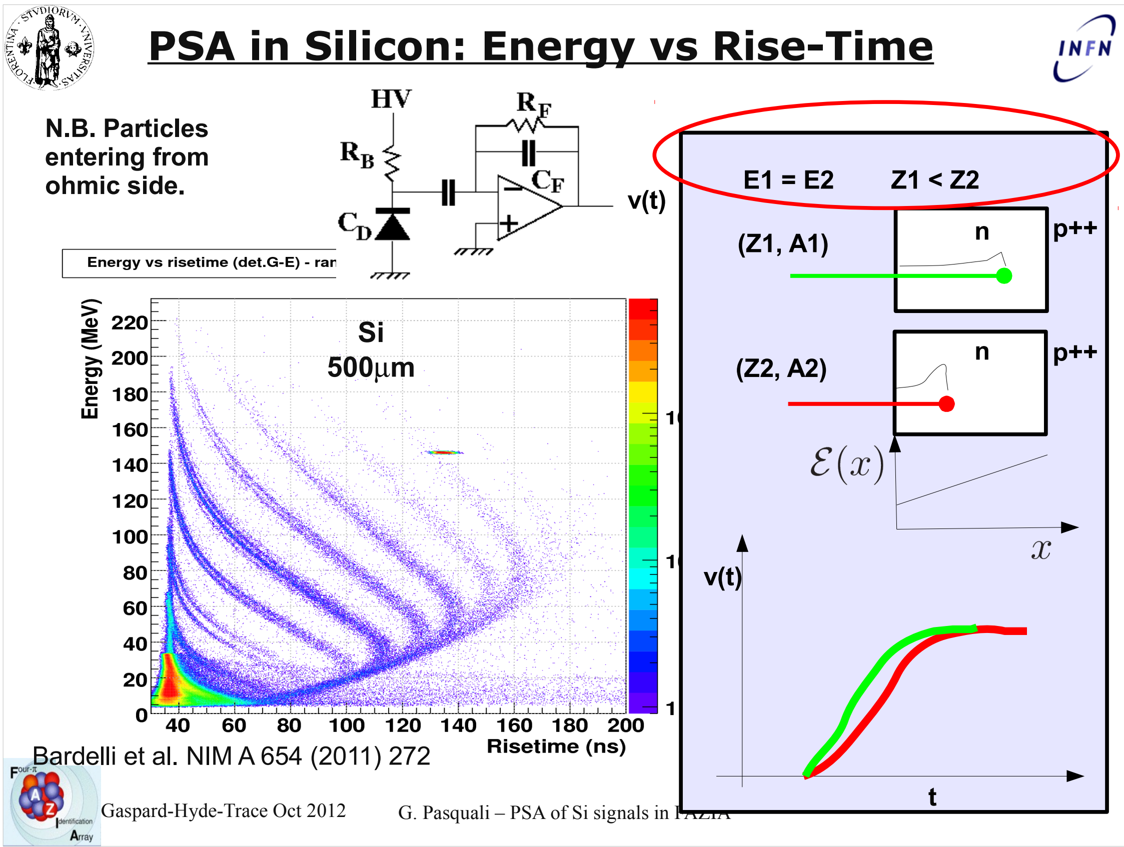
The plasma lifetime will be greater the lower the electric field in the track region.

Moreover, different energy means different range and different range means a different transit time of the charge carriers towards the electrodes.

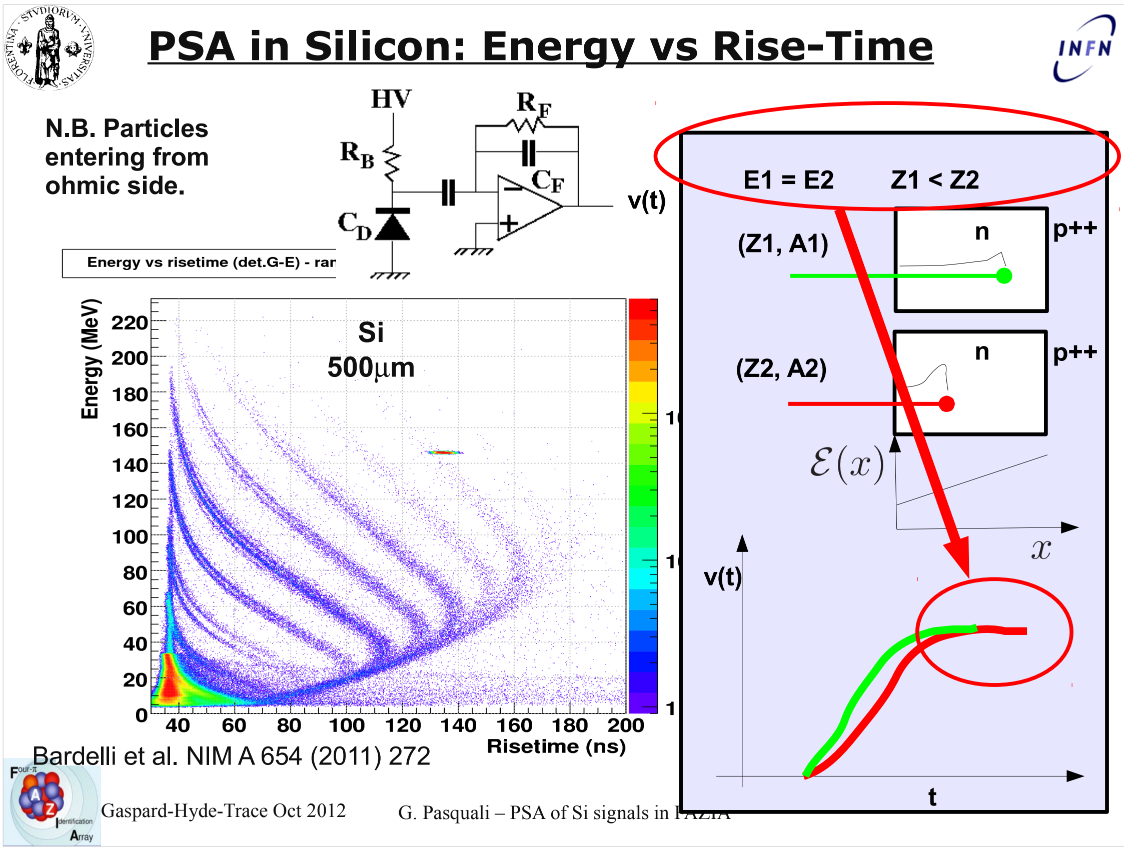
Plasma time and transit time will depend on deposited energy and particle range.



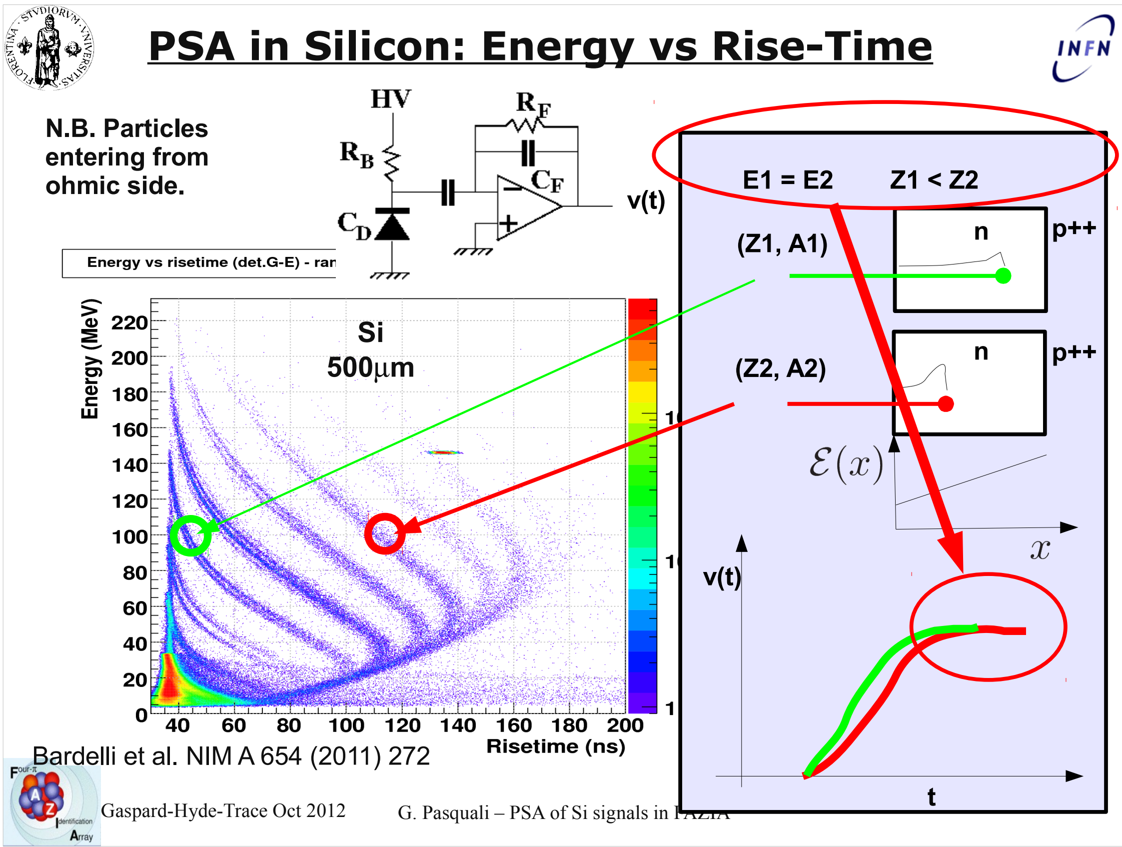
Electron and hole motion induces a changing charge on the electrodes and therefore a current in the external circuit. The current signal is treated by the front end electronics which must preserve the information as much as possible.



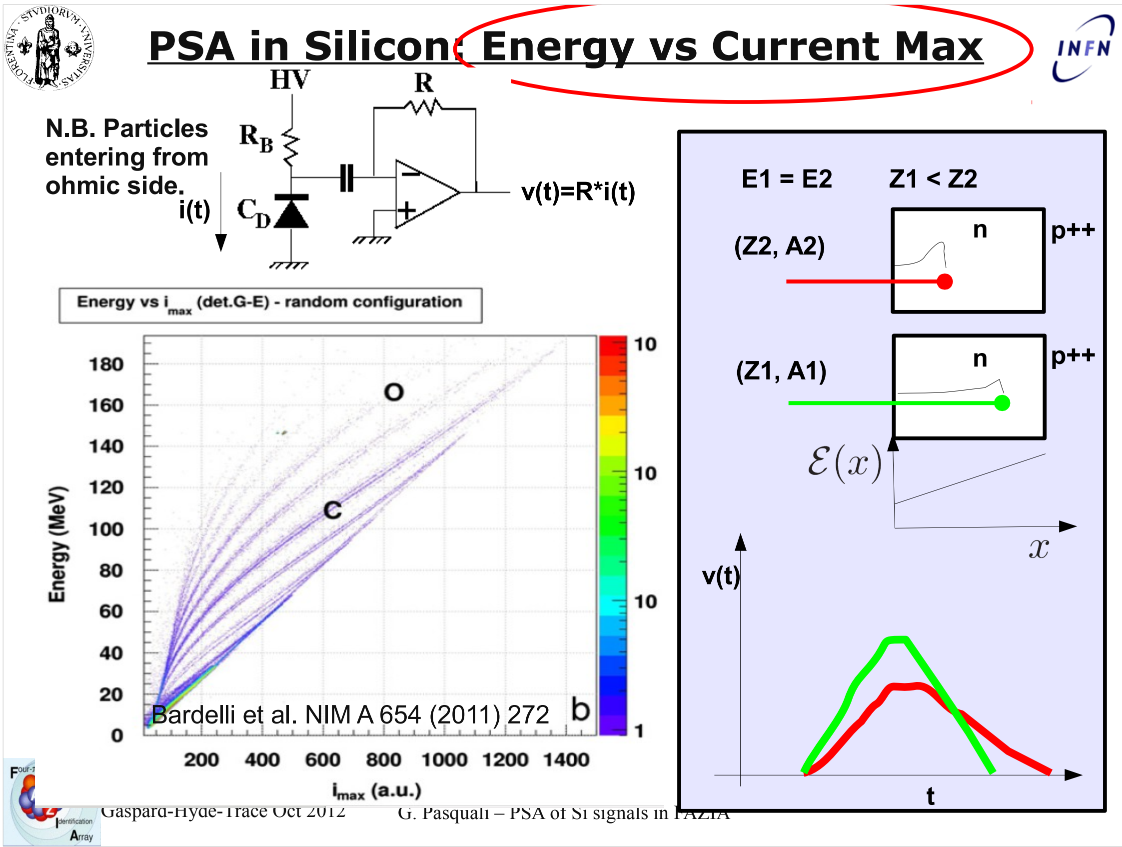
If you consider, instead, different ions at the same energy,



we will get charge signals with the same final amplitude, though again with different risetimes.

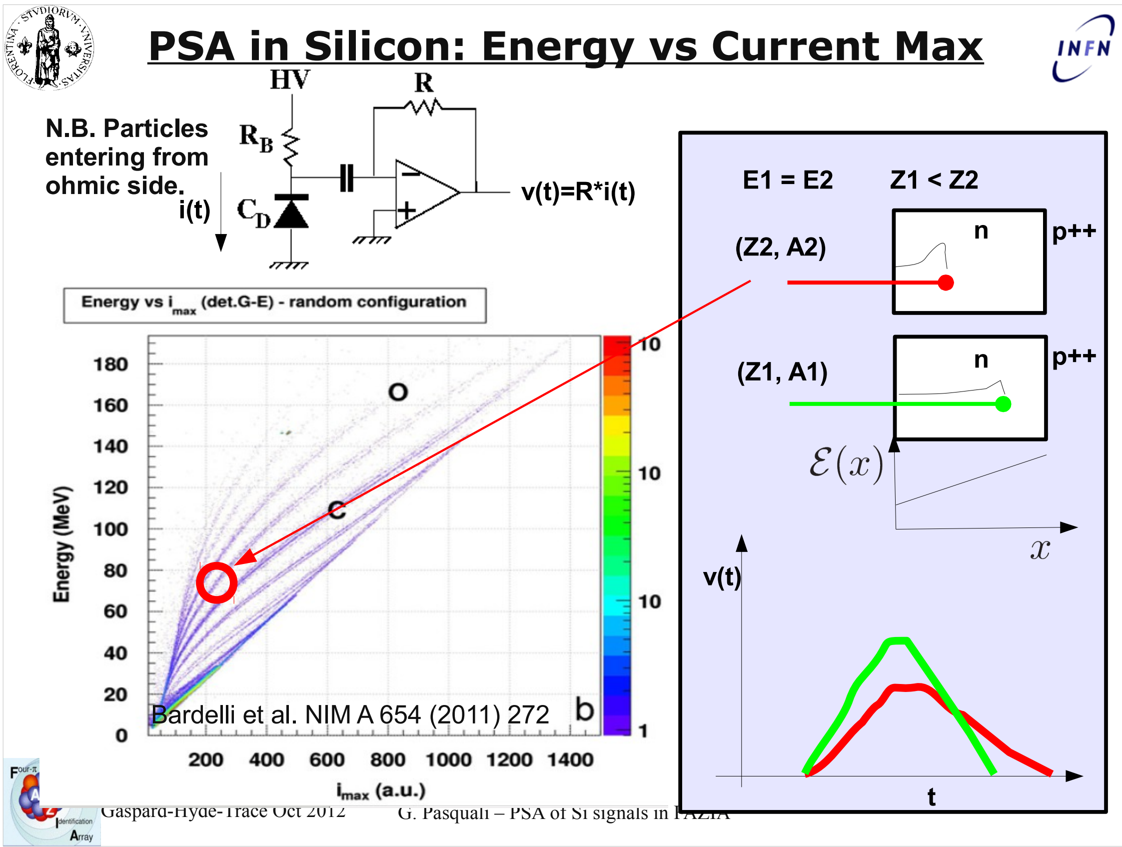


This time events will be on the same horizontal line but at different risetimes.

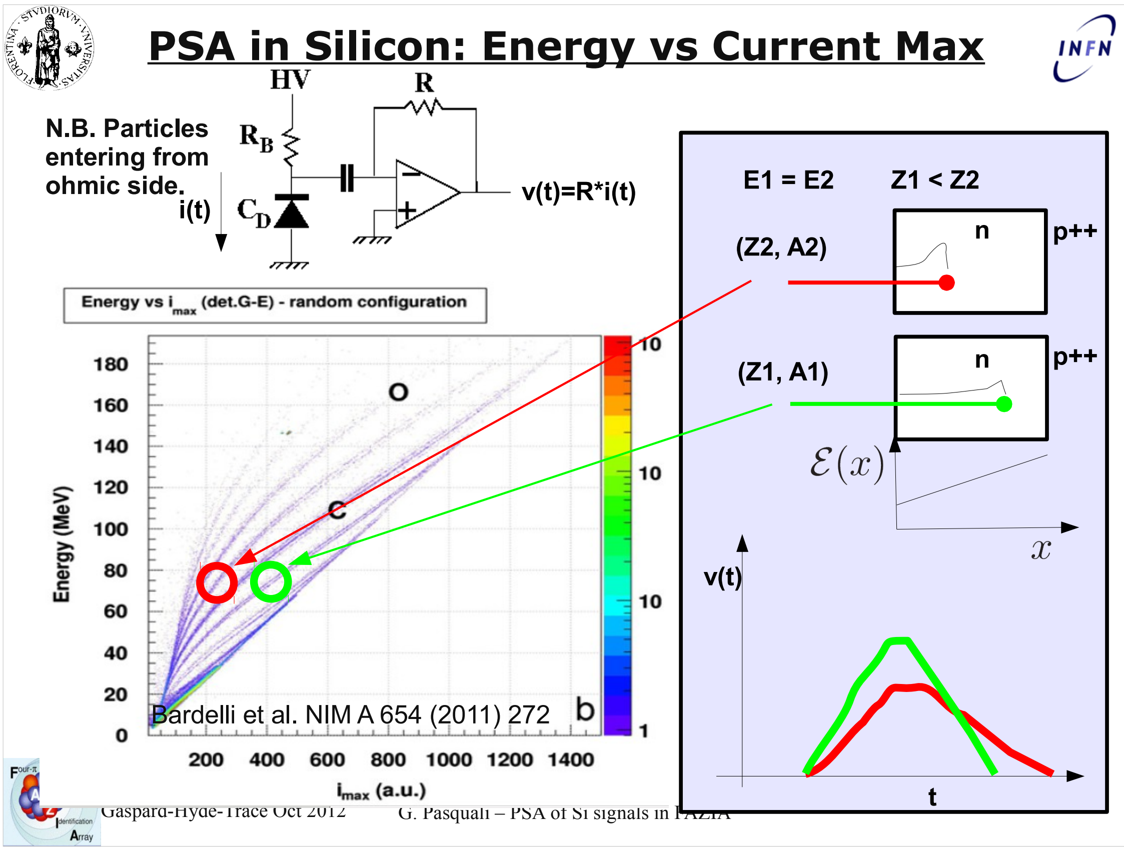


Charge signal rise time is not the only experimental parameter we can use. Again considering different particles at the same energy, which produce the same number of electron-hole pairs, we see that the current signal must last longer for the less penetrating ions, since its charge signal is slower.

The current integral, however, must be the same. It follows that the average current intensity will lower and so also its maximum value.



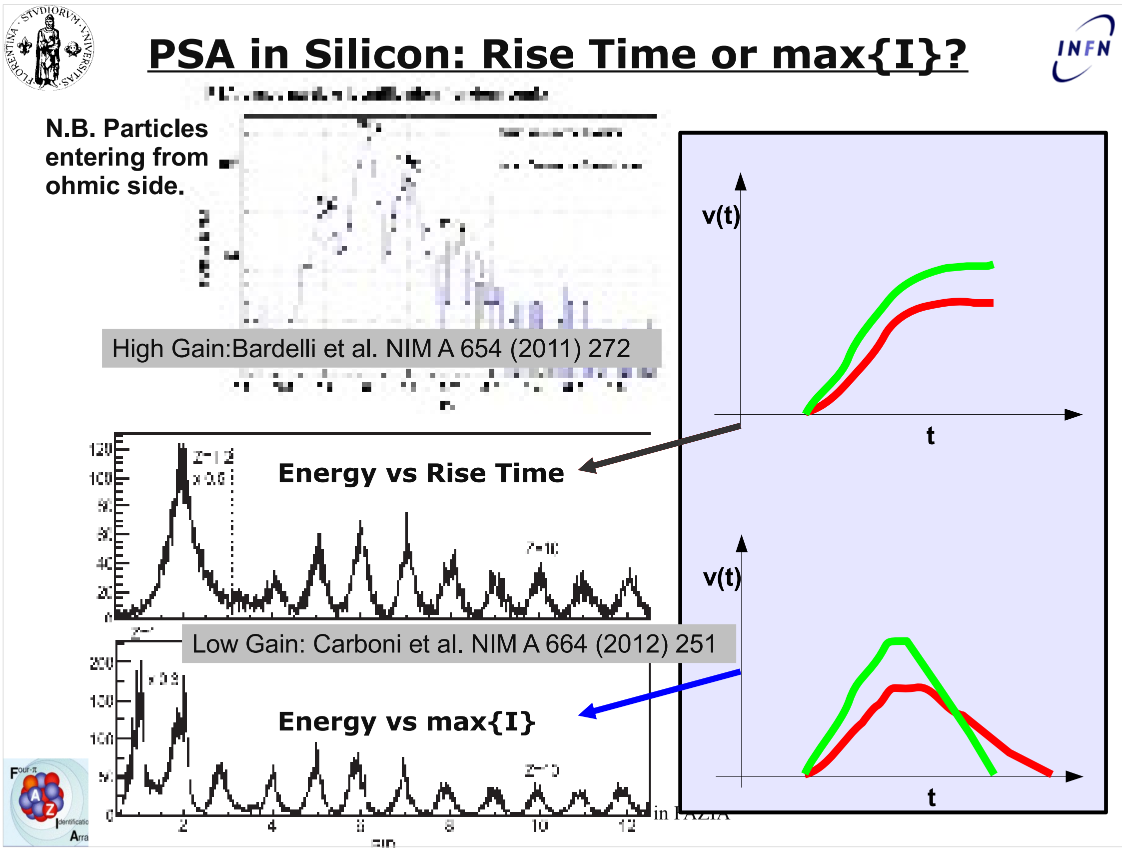
In an energy vs maximum value of the current, the less penetrating particle will be found...



...to the left of the more penetrating particle of the same energy.

Again we can distinguish different elements and even isotopes.

The current signal can be obtained from a special preamplifier with a dedicated output but it can be also obtained from the charge signal via analog differentiation: we found that we get the same quality of the identification.



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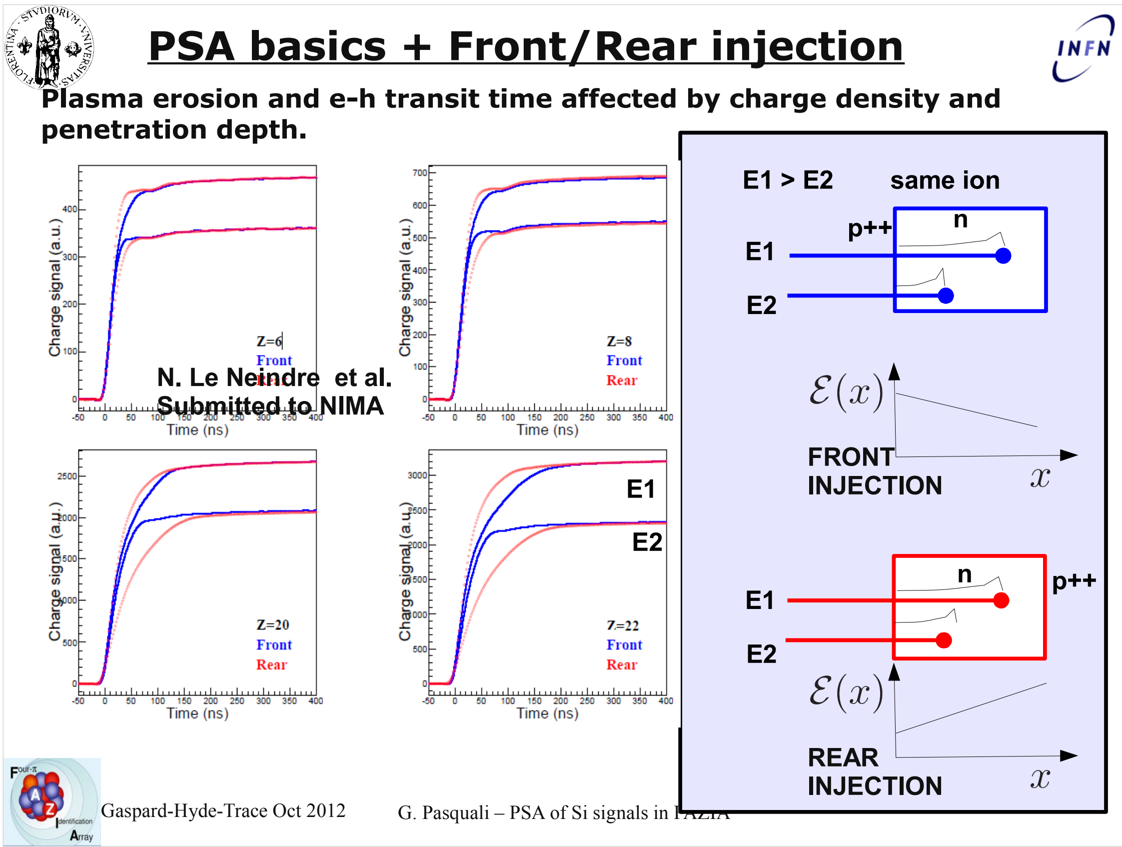


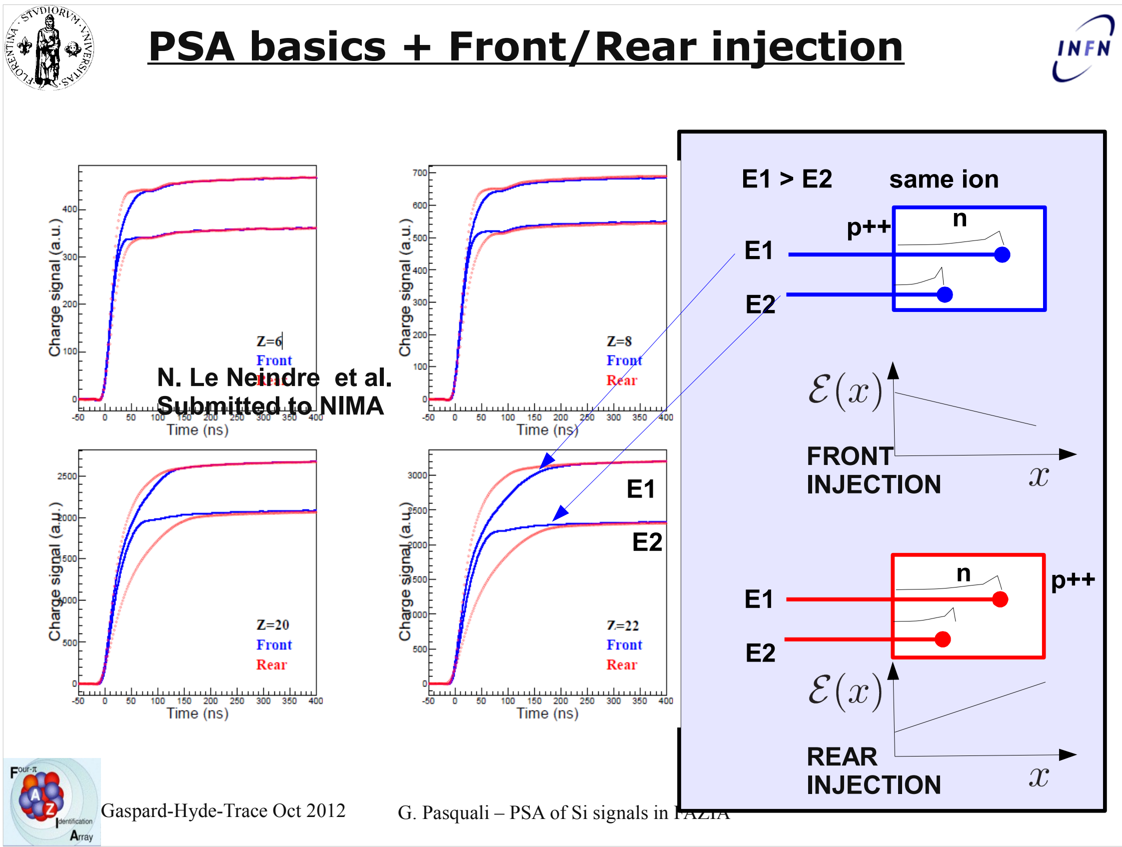
I have shown you a particle entering from the low field side (the ohmic side). Is this the best choice?

Or maybe reverse mounting is the best choice for PS identification but the worse for deltaE-E.

Recently we have found a (we hope) final answer to this question. We used the very same deltaE-E telescope both with low field and high field injection.

The deltaE-E identification didn't change at all.

Reverse mounting performed best for PSA and here I have tried to show you why: let's take the same ion type but at different incident energy.

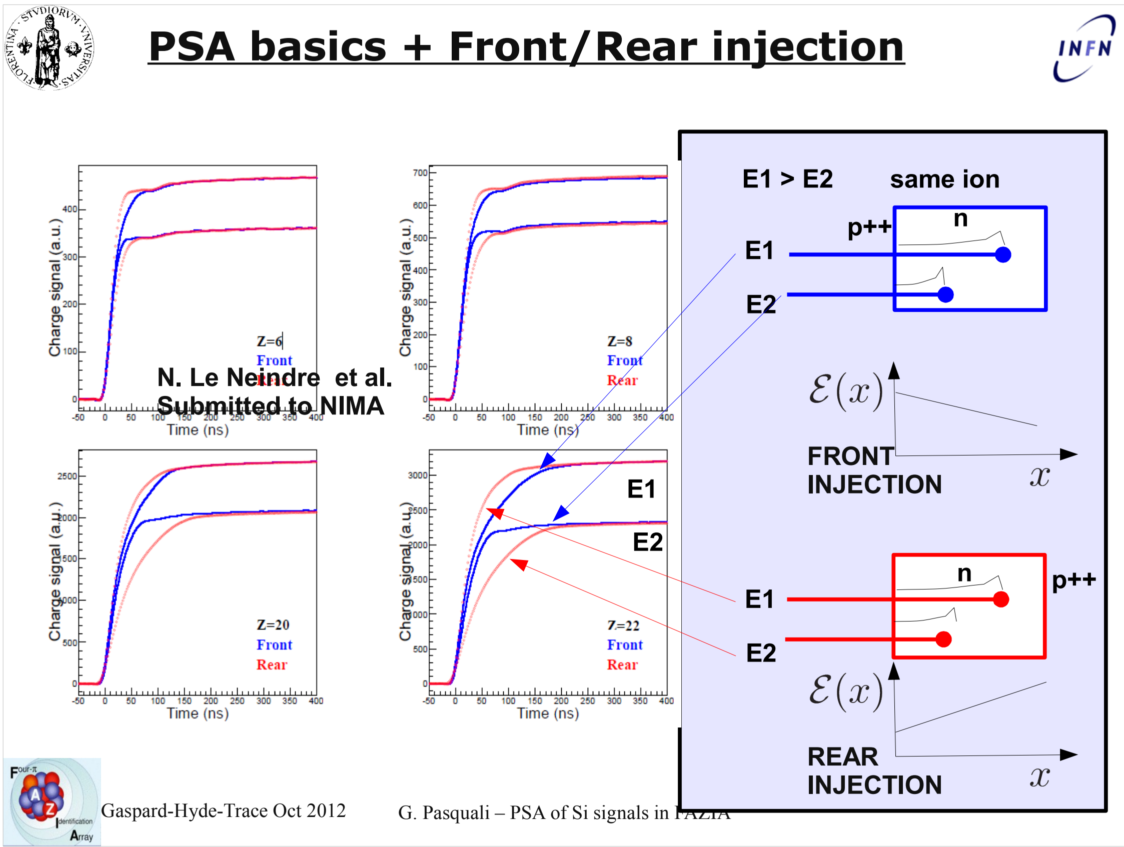


Here you can see the output of the charge preamplifier. The pulse height is obviously proportional to the deposited energy.

With high field injection we get the blue signals, for instance for carbon ions.

Their risetimes differ, though not so much: the shorter track has an higher charge density, which would give a longer plasma time, but it also experiences an higher local field which tends to shorten it.

The longer track has a lower density which would shorten the plasma time, but it will experience a lower field, which tends to make it longer.

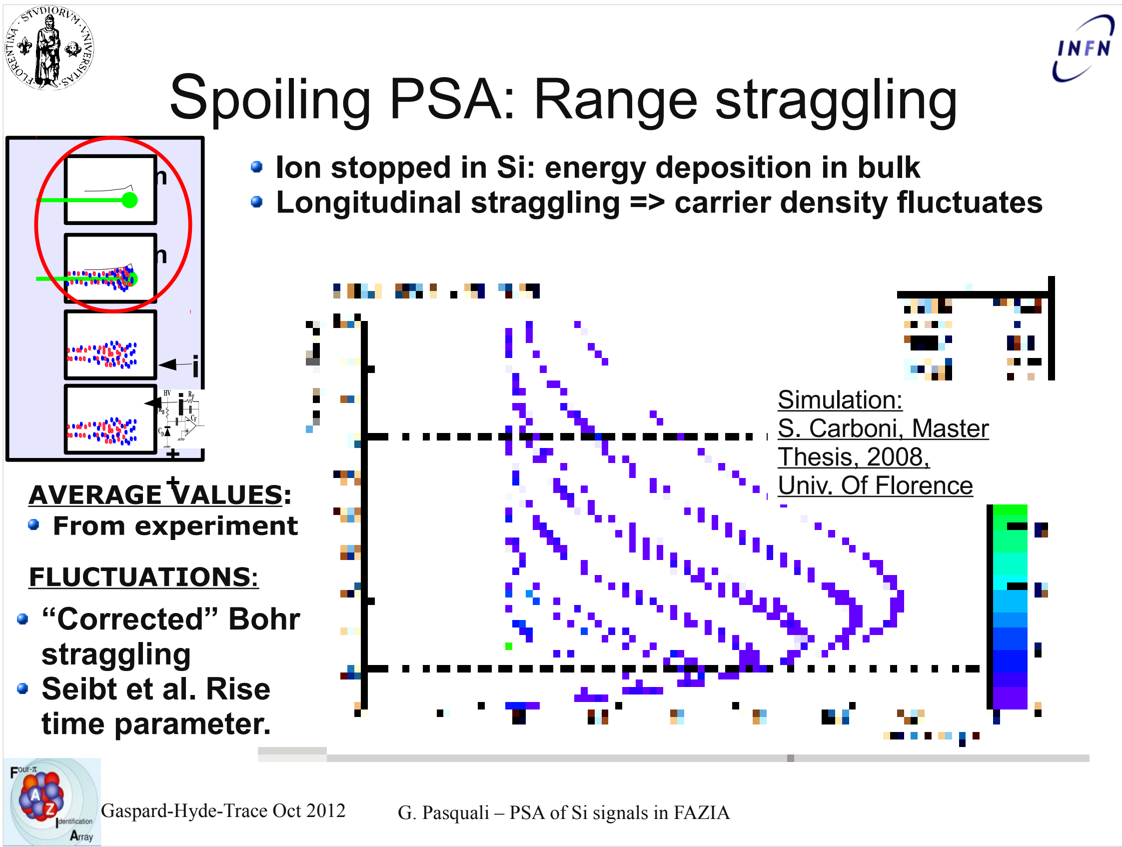


This is all expected and not particularly new. Here we can see that charge signal in reverse mounting differ the most and actually we found that they give the best PS identification, expecially when it comes to the low energy threshold for identification which is found to be sensibly lower.

I'll refer you to the paper for more details, the referee suggested a few minor changes, so we hope it'will be accepted soon.

Effects spoiling PSA

Now...what are the enemies of pulse shape identification?



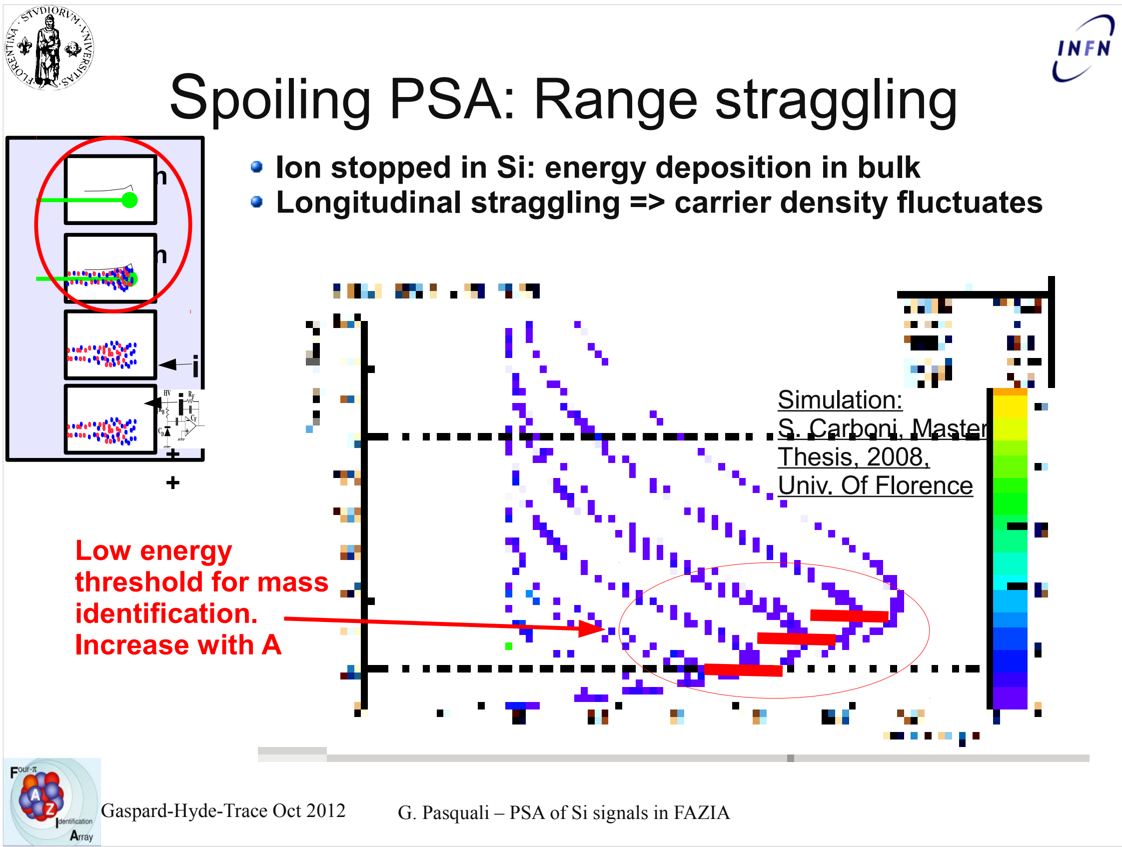
I will try to follow a logic order based on the physical process, starting from the energy deposition and ending with front end electronics issues.

The first and irreducible enemy is range straggling.

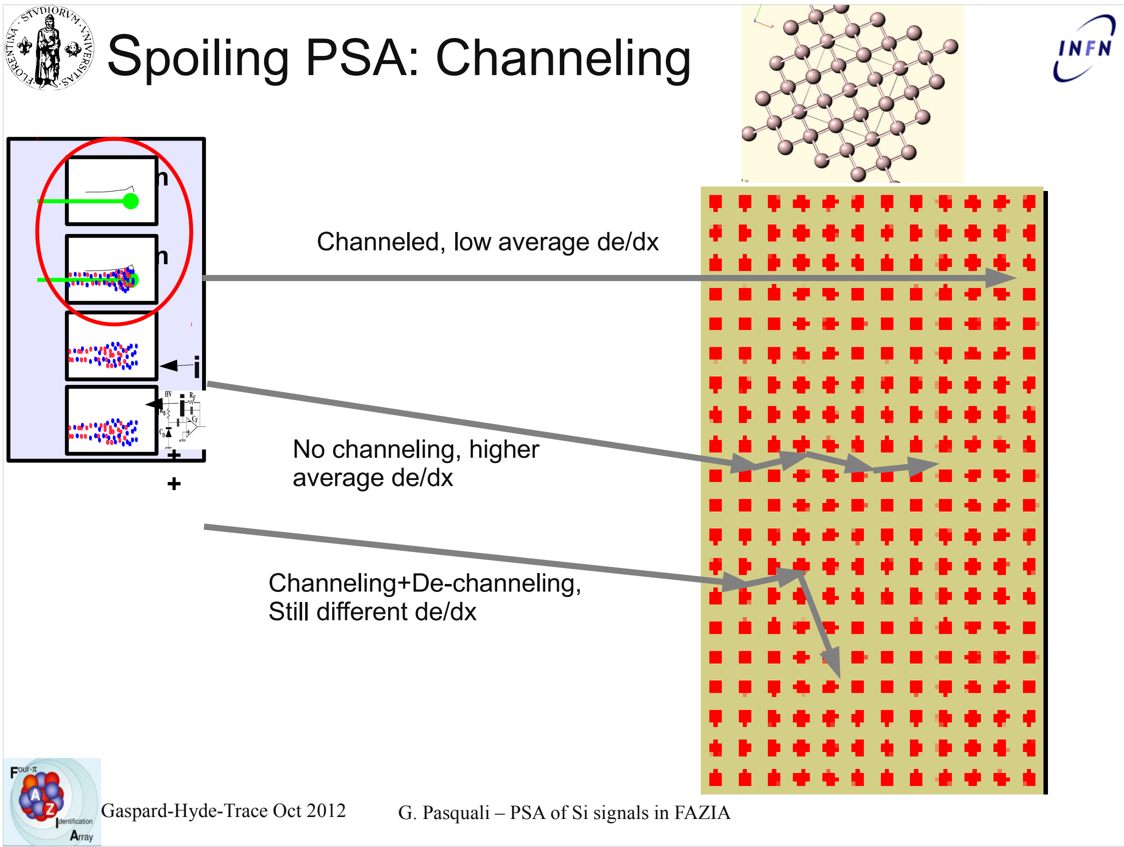
Enegy loss is a stochastic process, subject to fluctuations. Particles experiencing a lower stopping power(averaged along the track) because of fluctuations will have a longer path, even for the same impinging energy.

This will produce fluctuating carrier densities and transit times, thus producing a spread in the collection time.

There is no way to eliminate straggling, it determines the maximum achievable resolution in indentification. In the picture you can see a simulation of the effect of straggling based on a reasonable parametrization both of plasma time and range straggling.



Longitudinal straggling puts a low energy threshold on isotopic identification. The threshold in turn depends on ion mass. This is reasonable since the relative separation of adjacent isotopes decreases with increasing mass.

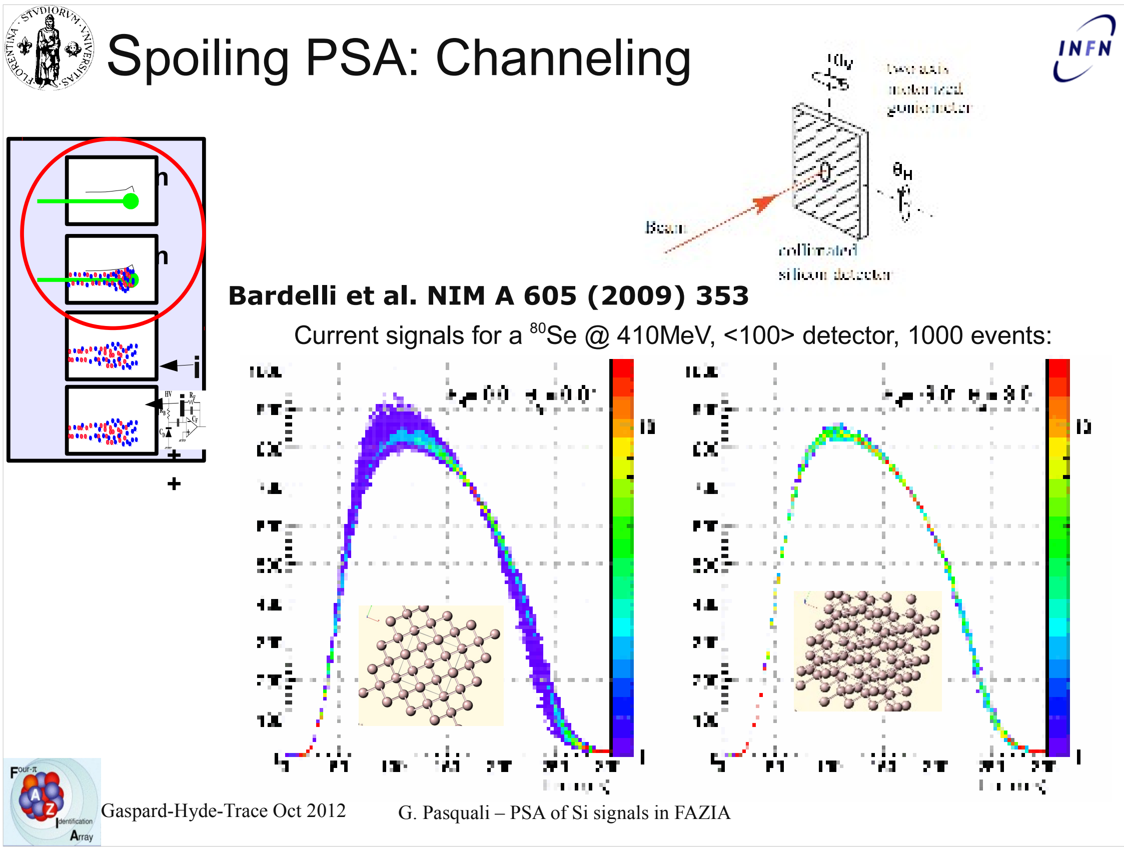


Another effect related to the energy deposition stage of the process is channeling. Channeling is a crystal orientation related effect.

A particle imping along one of the principal symmetry axis of the crystal can experience a lower stopping power and therefore it can travel a longer path.

A particle not going along such a symmetry axis will experience on the average more interactions with atomic electrons loosing all its energy after a shorter path.

Since the deposited energy is the same, the number of created carriers will be the same, on the average. Their density will thus be lower along the path of the channeled ion, thus diminshing the plasma time: we will get a faster collection time for the channeled particle. However we could also have something in between: an ion could be channeled just for part of its path.



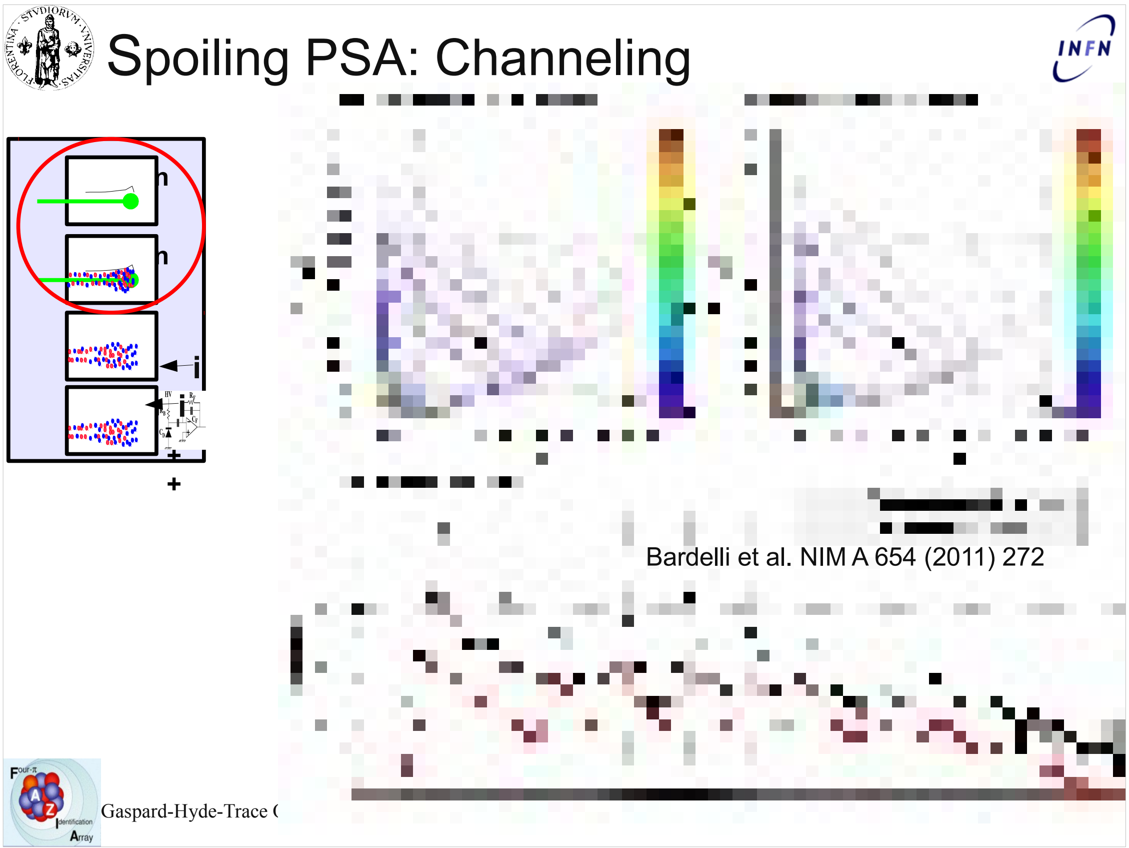
The final result is an increased variation of the possible signal shapes...as you can see in this picture.

In this experiment, elastically scattered monoenergetic selenium ions where detected on a silicon detector very narrowly collimated and mounted on a precision goniometer.

Normal incidence corresponds to incidence along one of the symmetry axis (<1 0 0>): the corresponding signal shapes are shown on the right. Here the color code is associated to the waveform intensity as you could obtain adjusting the persistency on an oscilloscope.

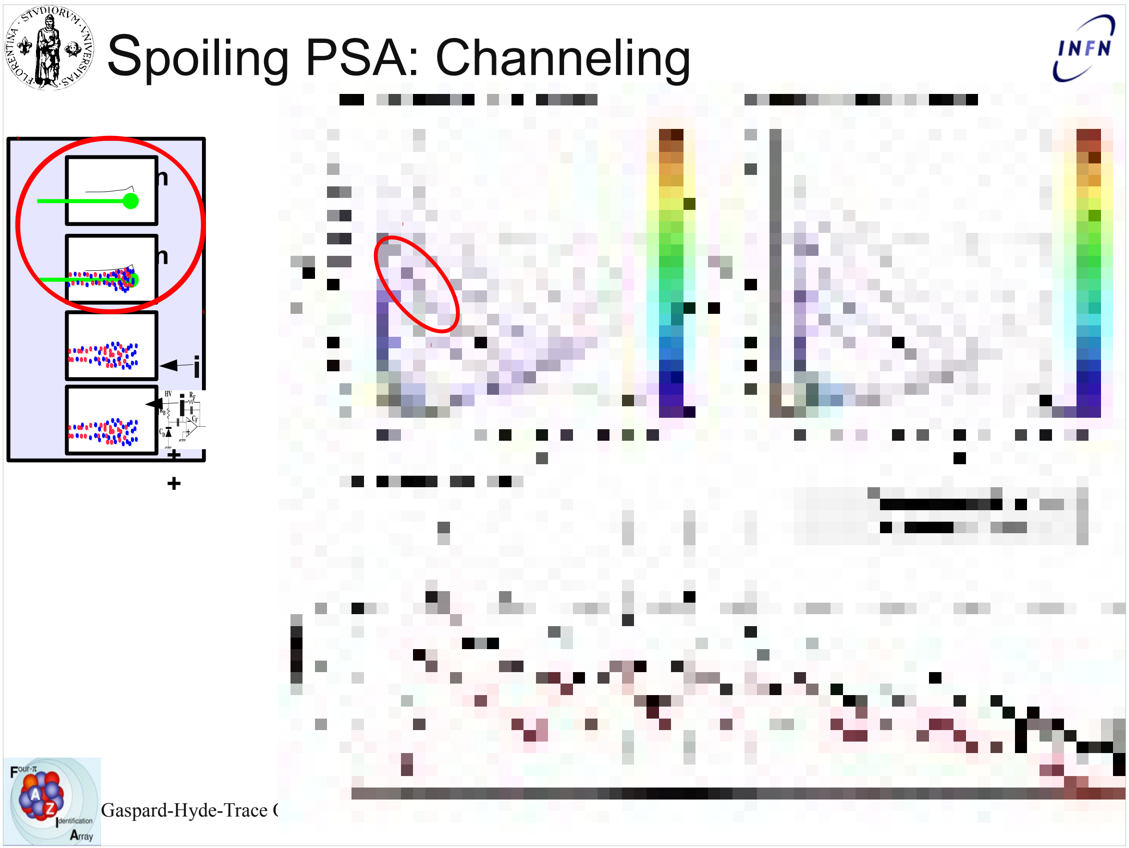
On the right we have tilted the detector a few degrees, so that particles are now seeing a much less regular atom disposition along their path.

The variation in signal shapes is reduced quite a lot!



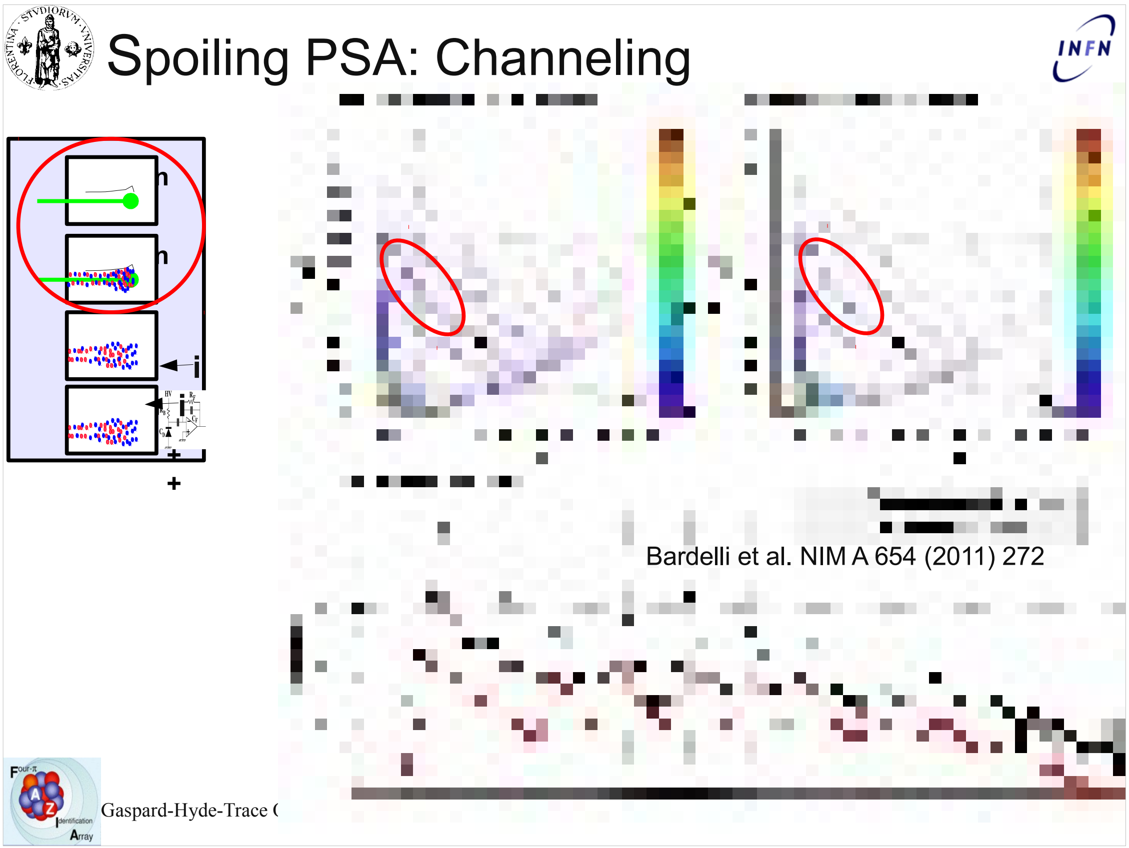
Let's see what happens to particle identification because of channeling.

Here the energy vs risetime correlation is shown on the left for incidence along the <1 0 0> direction (controlla!) and on the right for an angle called “random” since it is chosen in such a way in order to “randomize” the lattice structure as seenby the impining particle.

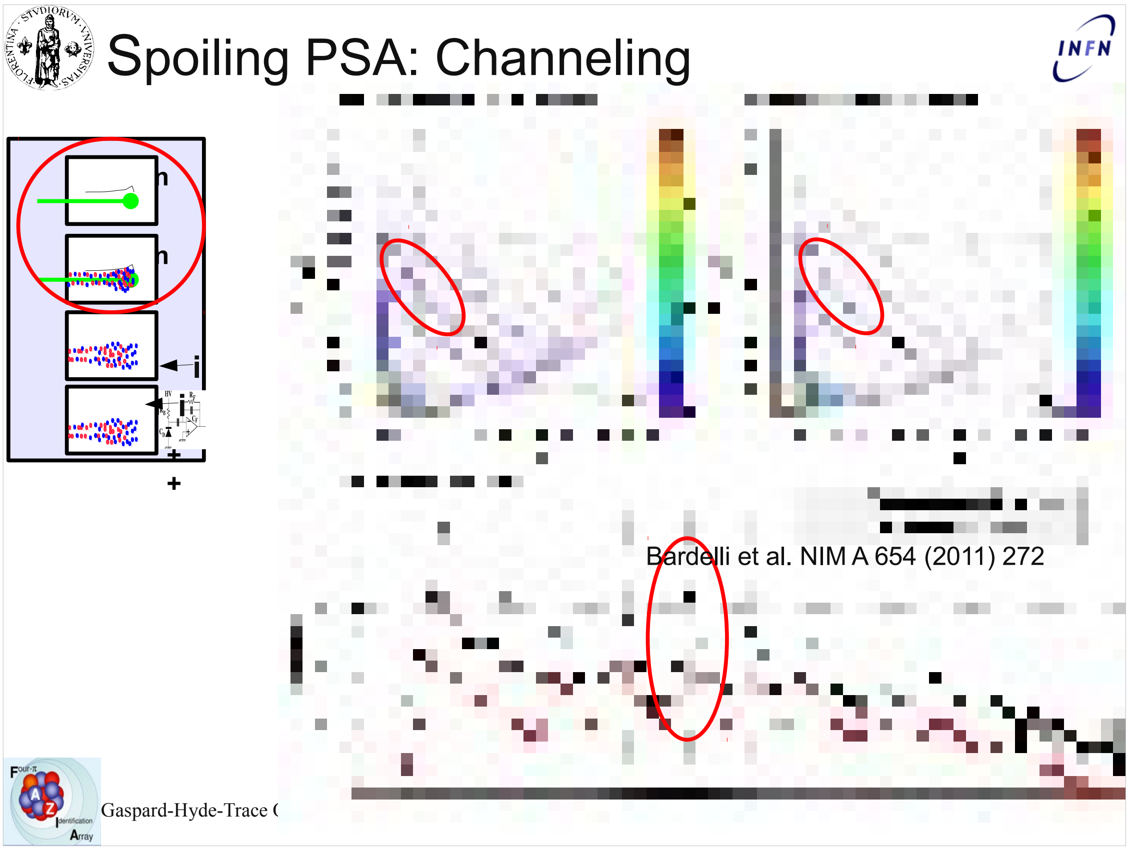


Let's choose the separation of carbon isotopes as an example.

It is clear that when channeling occurs the separation is not as good as...

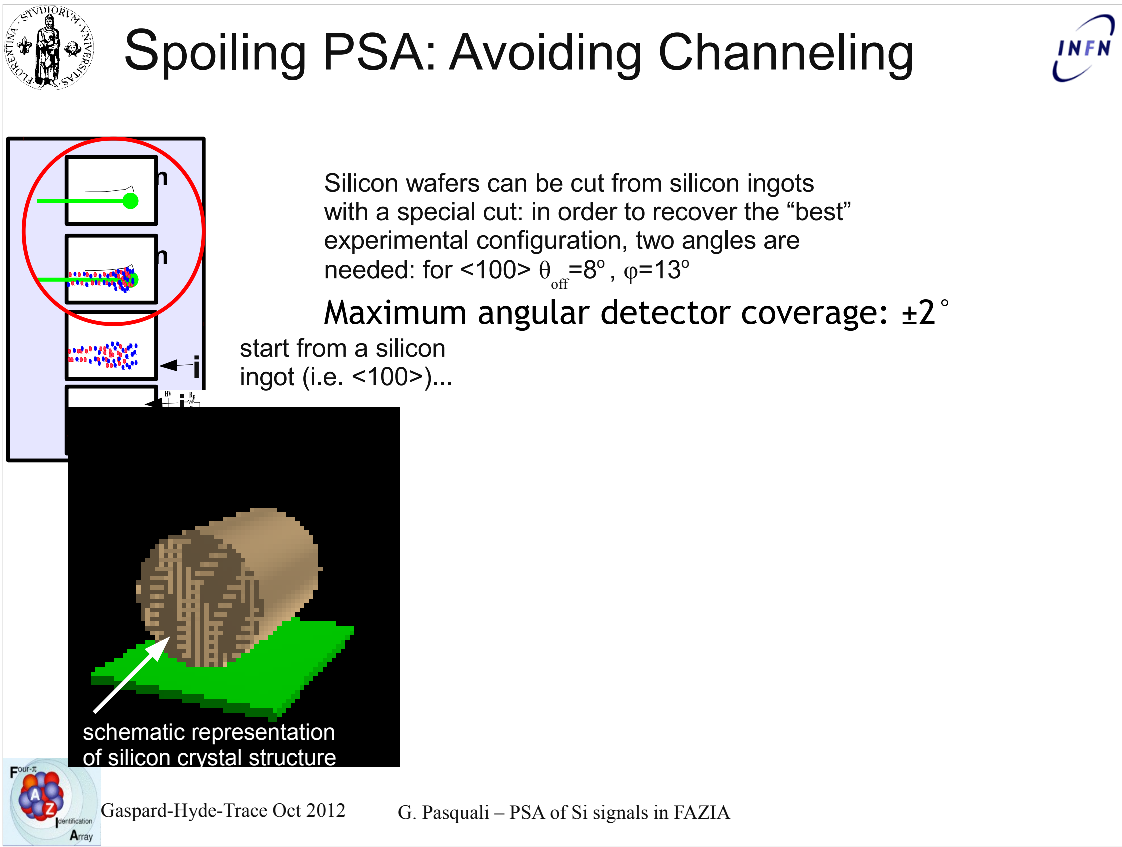


...when the random angle of incidence is chosen.



After linearization of the curves we can get a particle identification spectrum.

Here the better separation obtained for incidence along the “random” angle is confirmed.

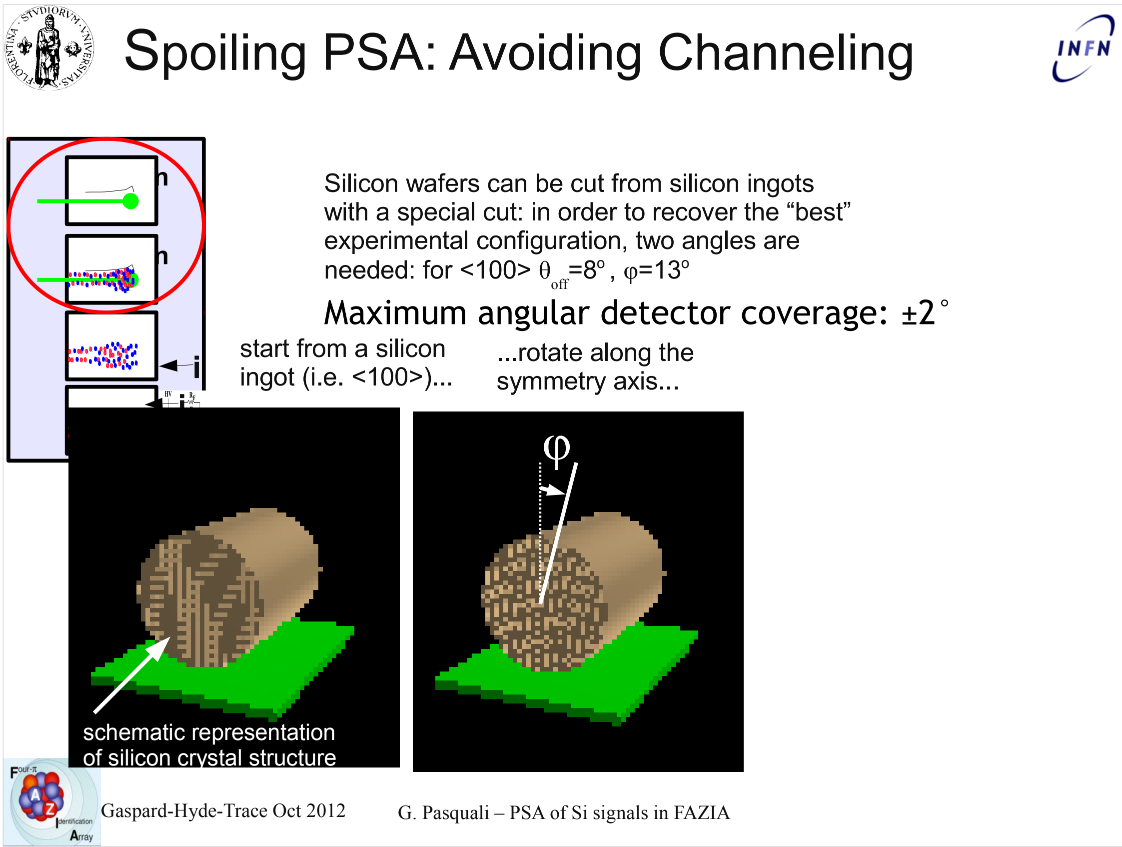


The different behaviour of channeled particles is known since a very long time. Since the fiirst studies with fission fragments and surface barrier detectors.

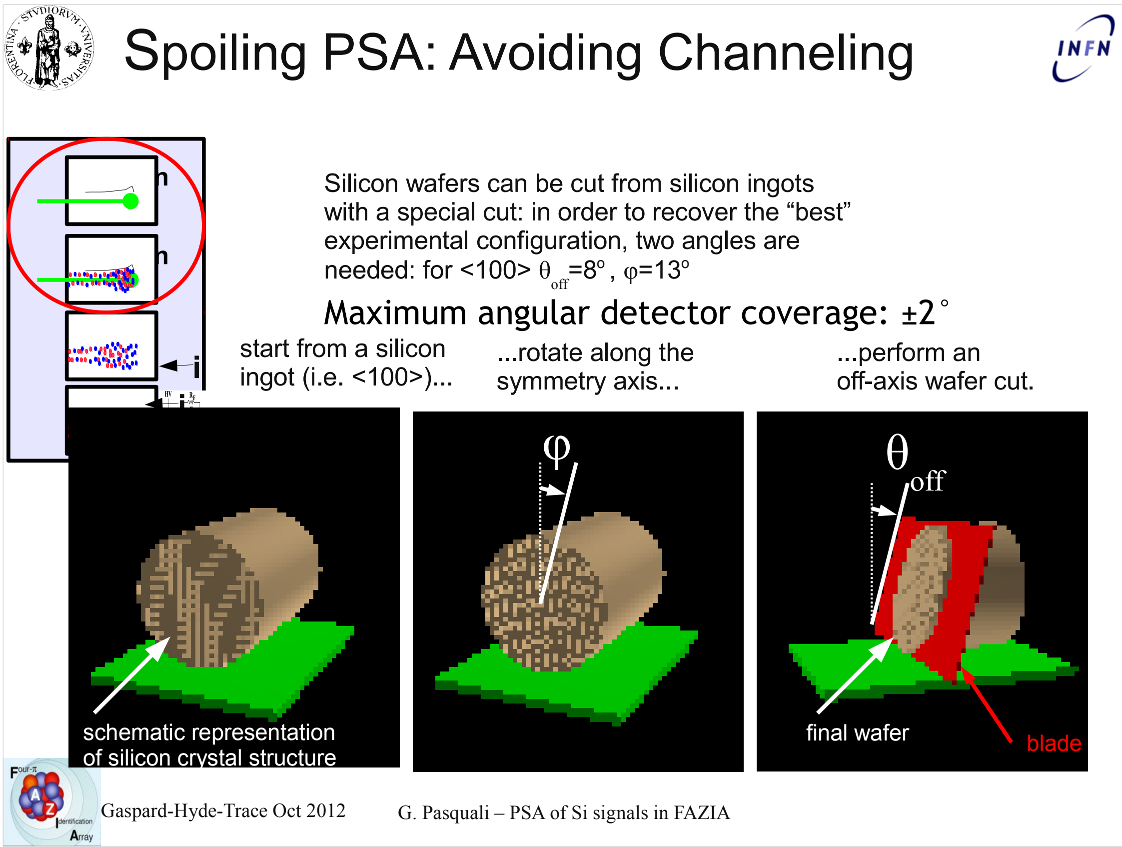
The solution devised at that time was to cut the silicon crystal not perpendicularly to a symmetry axis but at a properly selected angle.

This is not usually done in integrated circuit manufacturing due to technological constraints: the Si oxide passivation etc etc.

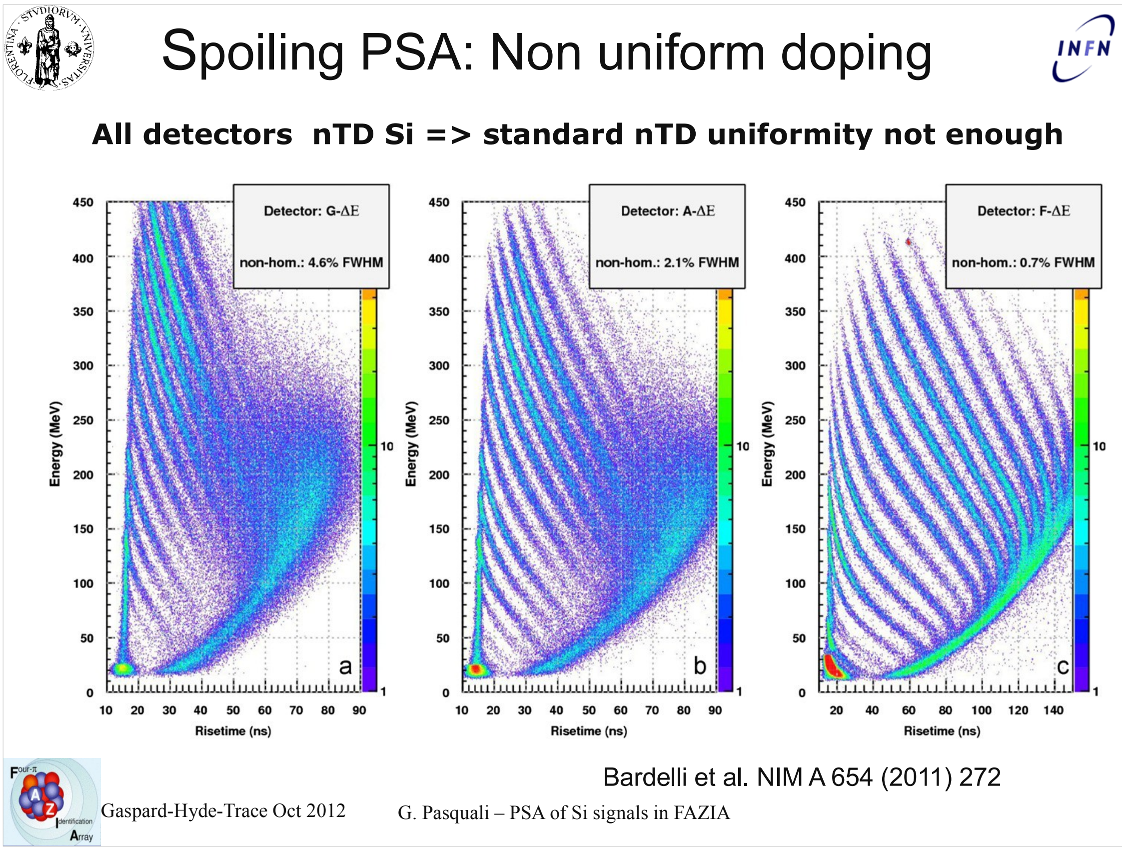
In our case we have chosen the following strategy: Starting from the silicon ingot, we asked the manufaturer to rotate it...



...by 13 degrees and then to tilt the blade at an angle of 8 degree with respect to the surface.



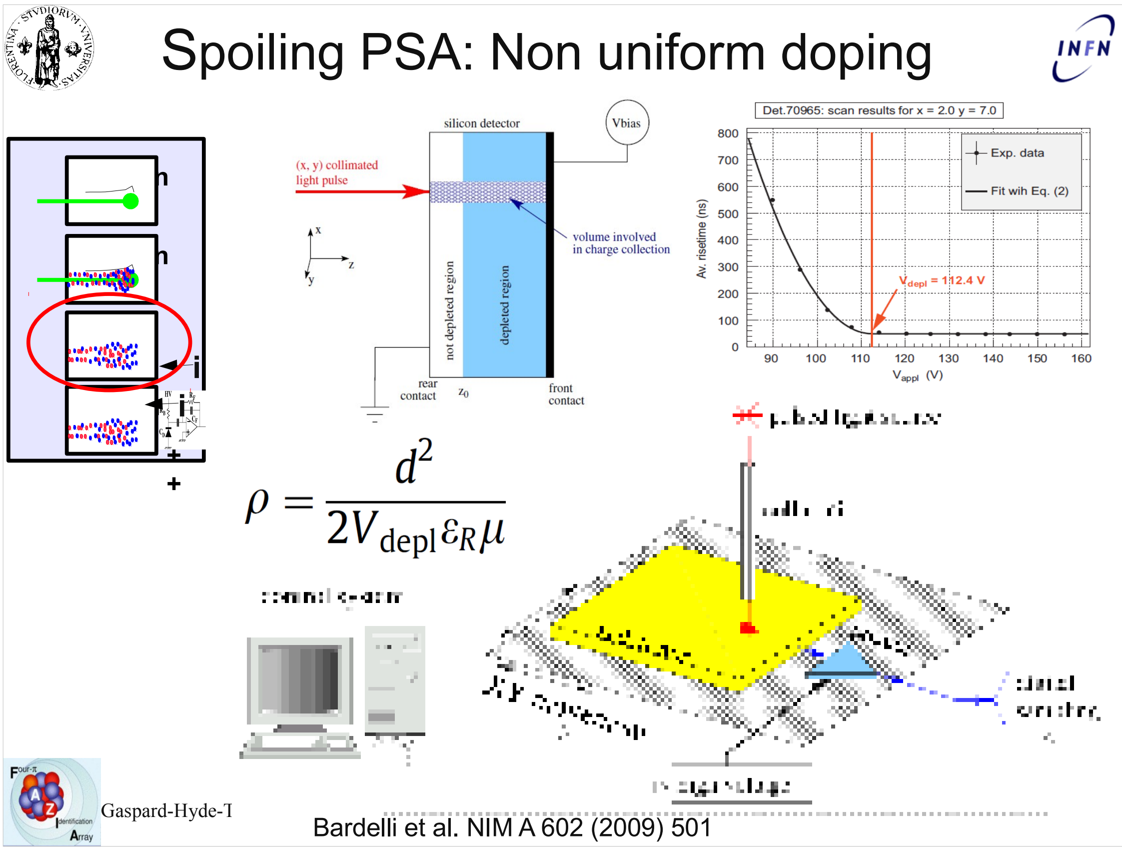
In that way when ions imping normally on the detector surface the channling probability is minimized.



We have found that an uniformity of 1% or better is mandatory for isotopic identification of IMF. This is due to the relatively small difference in risetimes for isotopes of the same ion at a given energy (~200ps on a total of tens of ns for C isotopes): a small electric field variation can thus change the rise time enough to spoil the isotopic resolution.

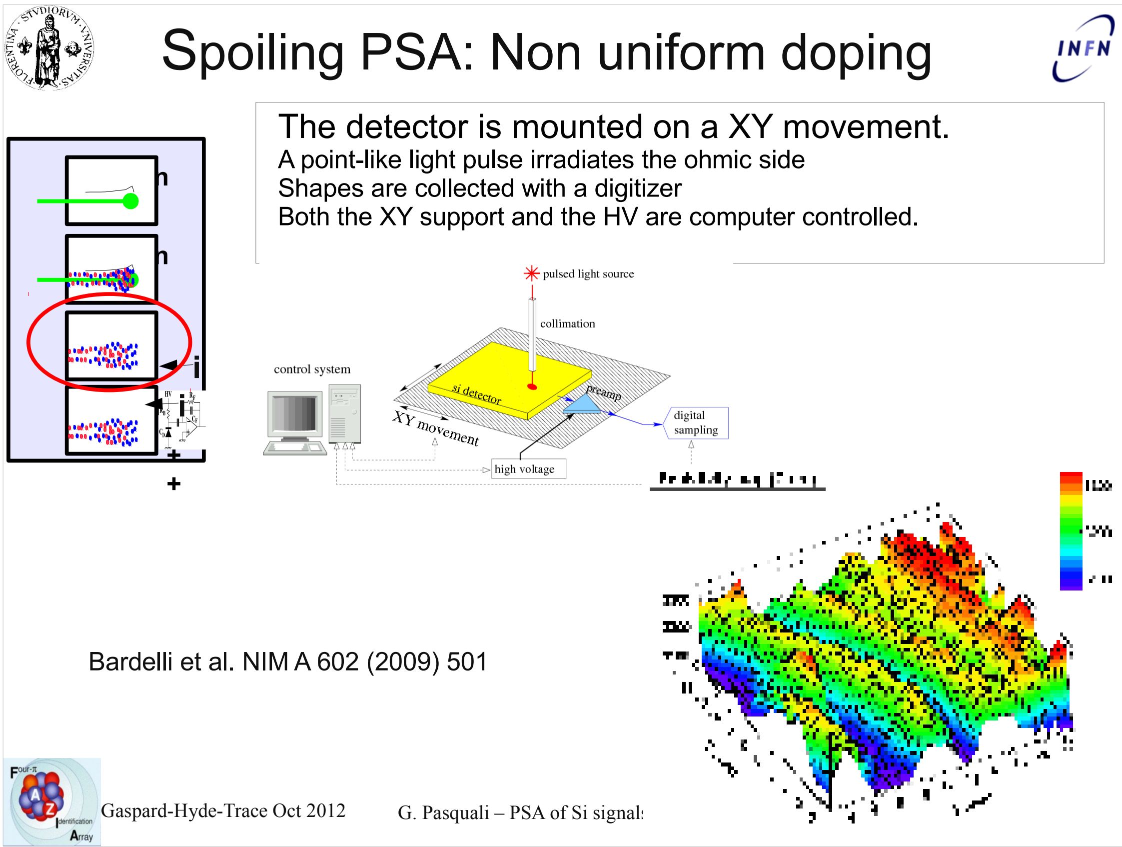
There is no much one can do to avoid this problem except selecting good uniformity ingots, which is not trivial. We use nTD silicon since it garantees the best doping uniformity but this is not enough to get 1%. Values around 3% seem easier to obtain.

Using small area detectors, or pixels, could relax the problem though sometimes we have found non-uniformities of a few % on a collimeted area of 3 mm diameter! So even a 4x4mm^2 pixel would not be small enough!



One can actually measure the detector doping uniformity in a non destructive way by scanning the detector surface with a pulsed LASER for different values of the bias voltage.

From the charge signal risetimes as a function of the applied voltage for a given position one can devise the local depletion voltage, which is related to the average silicon resistivity in the direction normal to the surface.



In that way we can build a resistivity map as a function of the entrance position and we can recognize a “bad” silicon (as the one on the left) from a “good” one, like this on the right.

On the left we can actually spot the circular striation due to the crystal manufacturing process: cylindrical ingots are grown radially so that doping fluctuations show up as growith rings on the circular wafer from which our square detectors are then cut.

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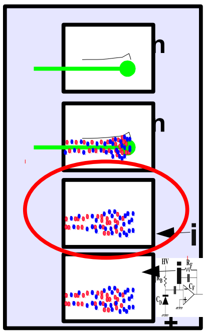
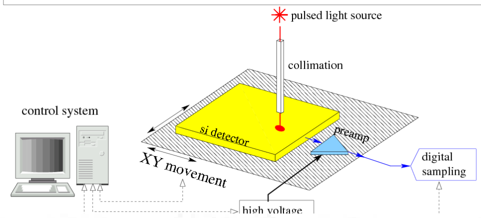
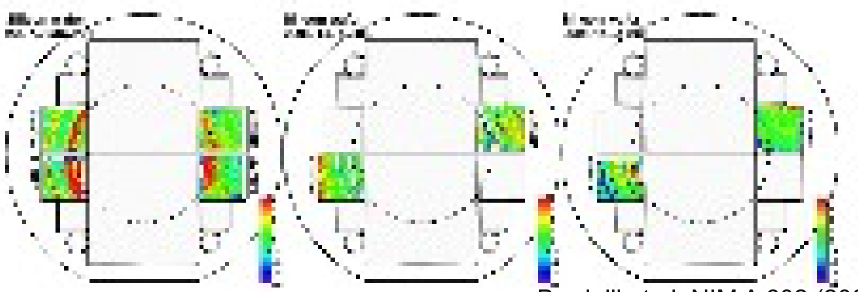
Spoiling PSA: Non uniform doping

The detector is mounted on a XY movement.
A point-like light pulse irradiates the ohmic side
Shapes are collected with a digitizer
Both the XY support and the HV are computer controlled.



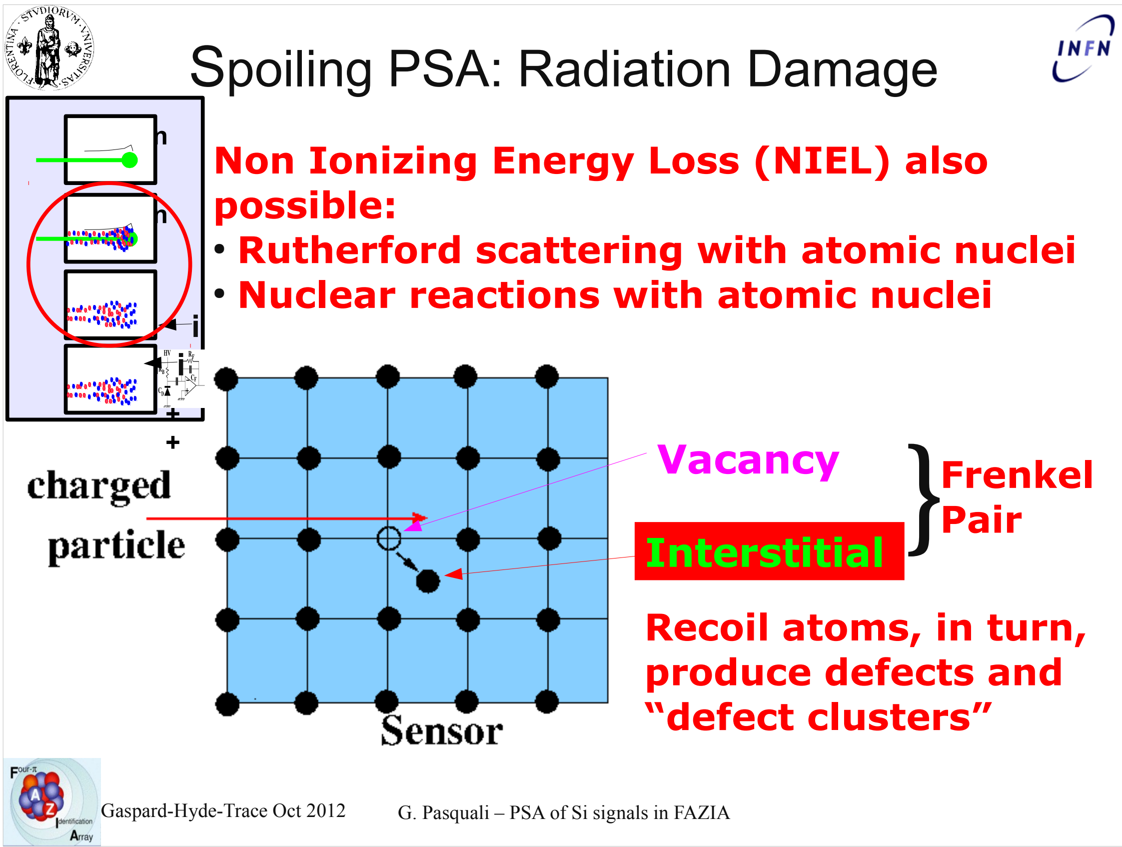




Bardelli et al. NIM A 602 (2009) 501

So here we can see just a portion of the ring.

Knowing the doping uniformity we can check its effect on pulse shape identification. Here is an example of the energy vs risetime correlation for 3 different silicon of different uniformities



Local doping can also change due to crystal damage by impinging ions. This is particularly true for heavy ions, like elastically scattered beam particles, stopped in the silicon.

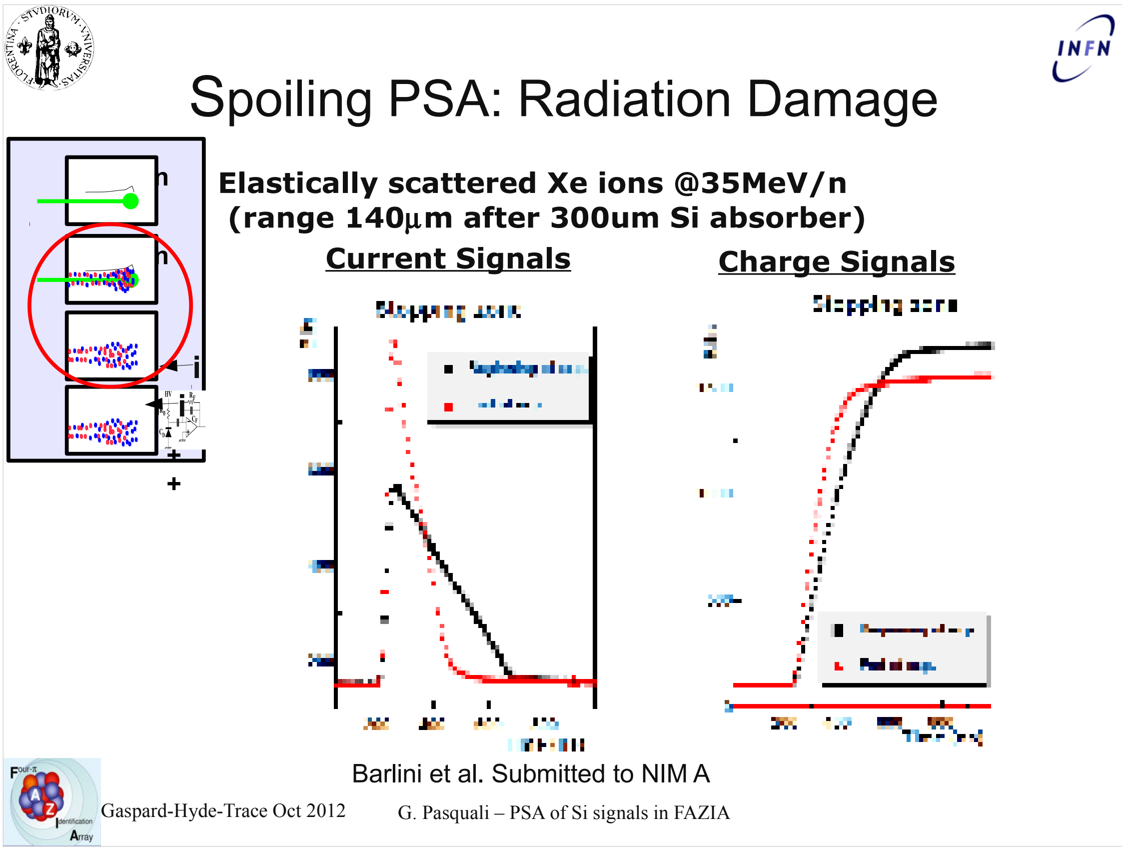
At the very end of the ion range the probability of non ionizing energy loss is high. The ion can transfer part of its energy to a silicon atomwhich recoils from its proper position formin a so called interstitial and a vacancy.

Such lattice defects can act as trapping and recombination centers.

If they are charged they affect the local space charge density, which changed the doping.

Carriers can recombine at defects, leading to a reduction in pulse amplitude.

Both space charge effects and recombination increase with fluence, the number of particles per unit area impinging on the detector.

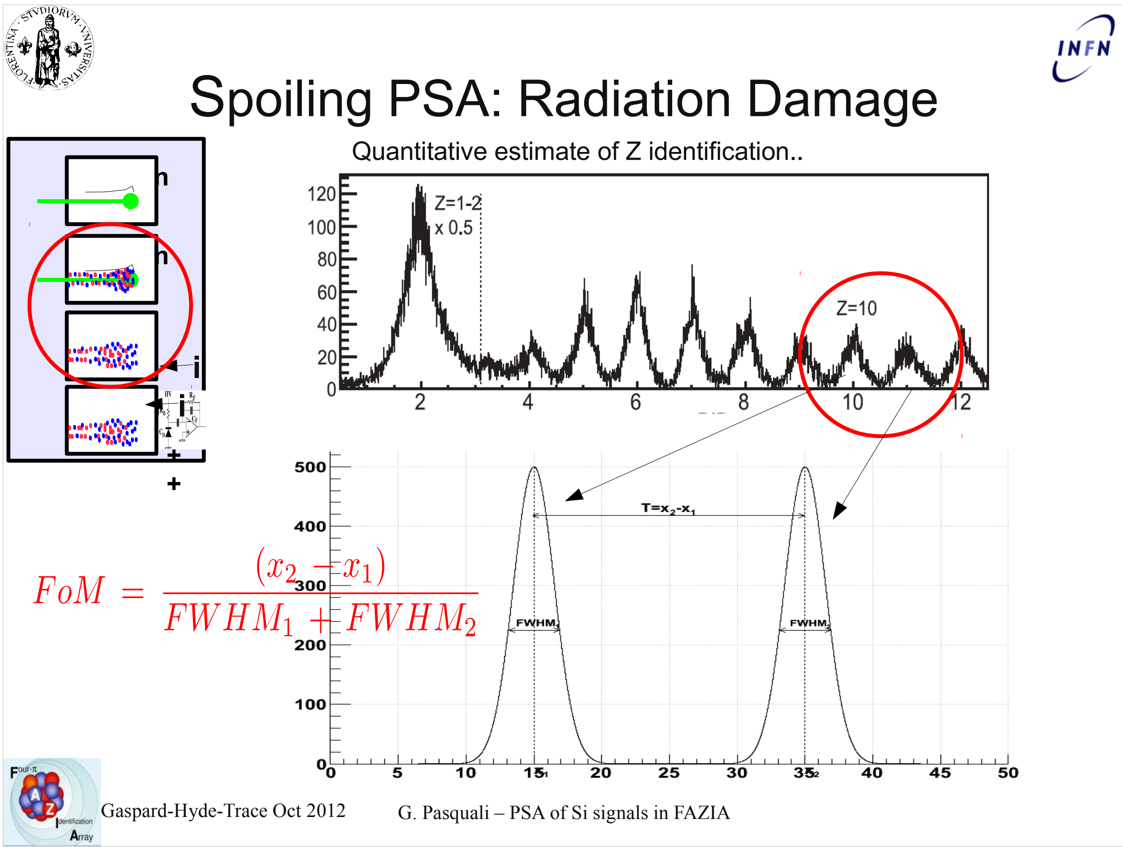


To test the effect of radiation damage on pulse shape we irradiated a 300um thick nTD silicon with elastically scattered xenon ions.

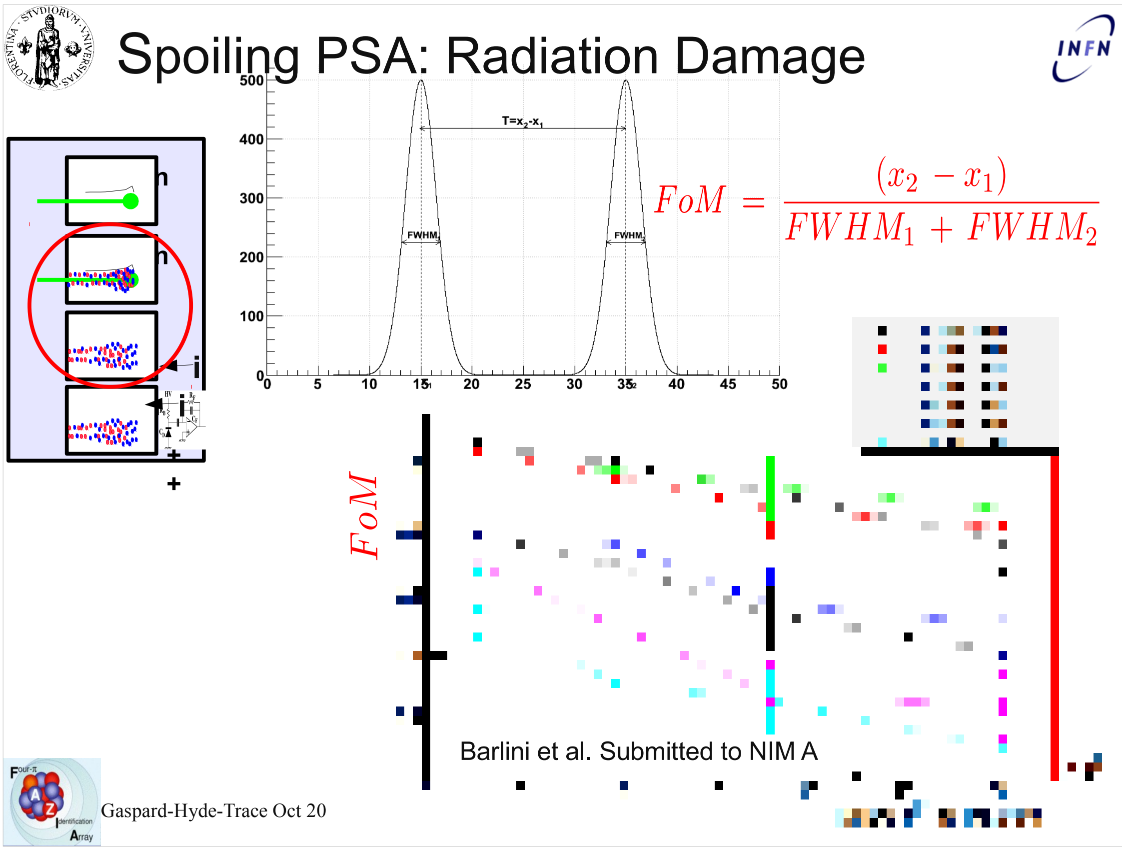
Here you can see current and charge signals produced by xenon in the silicon before and after a few days of irradiation.

You can see how the current signals duration actually gets shorter resulting in a shorter charge risetime.

Moreover, about 15% of the produced charge is lost, in the damaged detector, probably due to recombination.



An energy vs risetime spectrum shows a clear worsening of the resolution, though this picture seems bad even before irradiation...but anyway you can look at this ridge here and see how it gets wider.



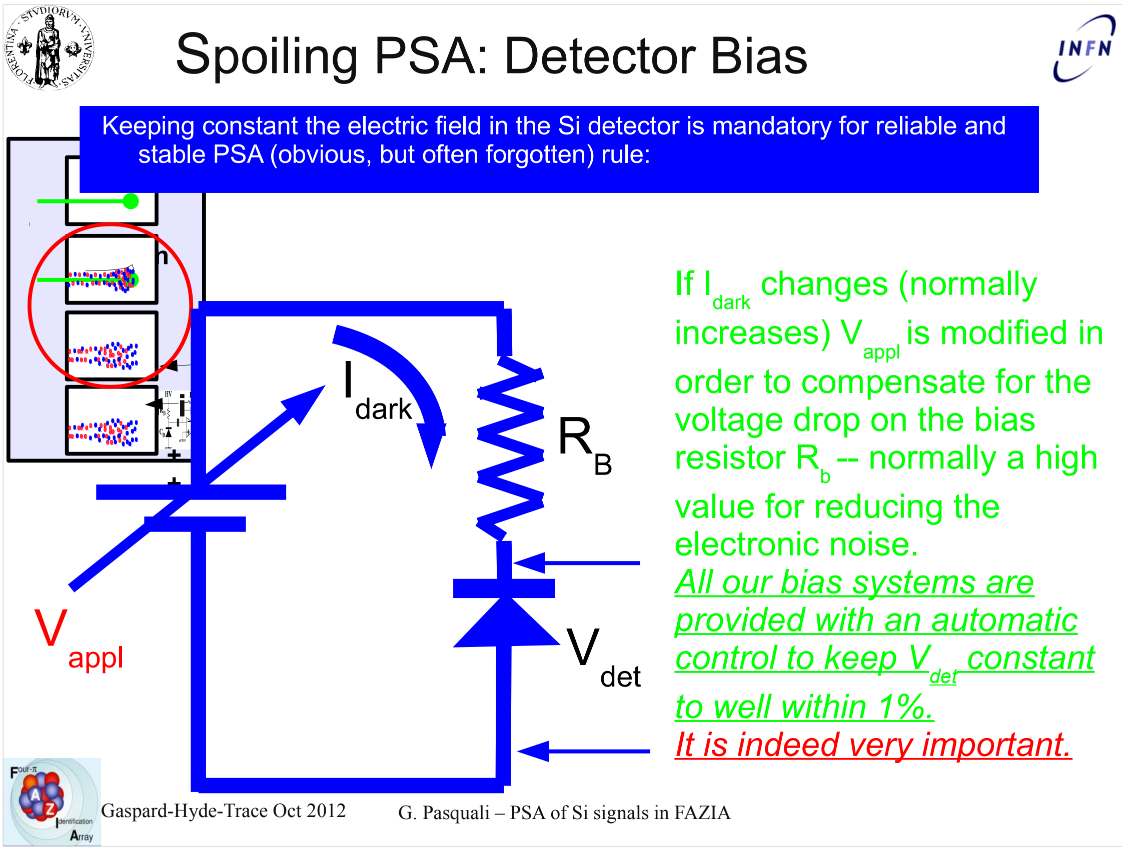
To quantitaively estimate the separation of the adjacent peaks in a particle identification spectrum one could use the so called figure of merit.

The centroid separation is compared to the FWHM of the peaks.

The higher the FoM the better the separation.

In this graph the FoM for element separation OBTAINED FROM PSA! is plotted as a function of the xenon fluence for various atomic numbers.

The separation gets in fact worse with fluence, and this is not only due to a change of the average pulse shape but also to increasing shape fluctuations around the average shape.

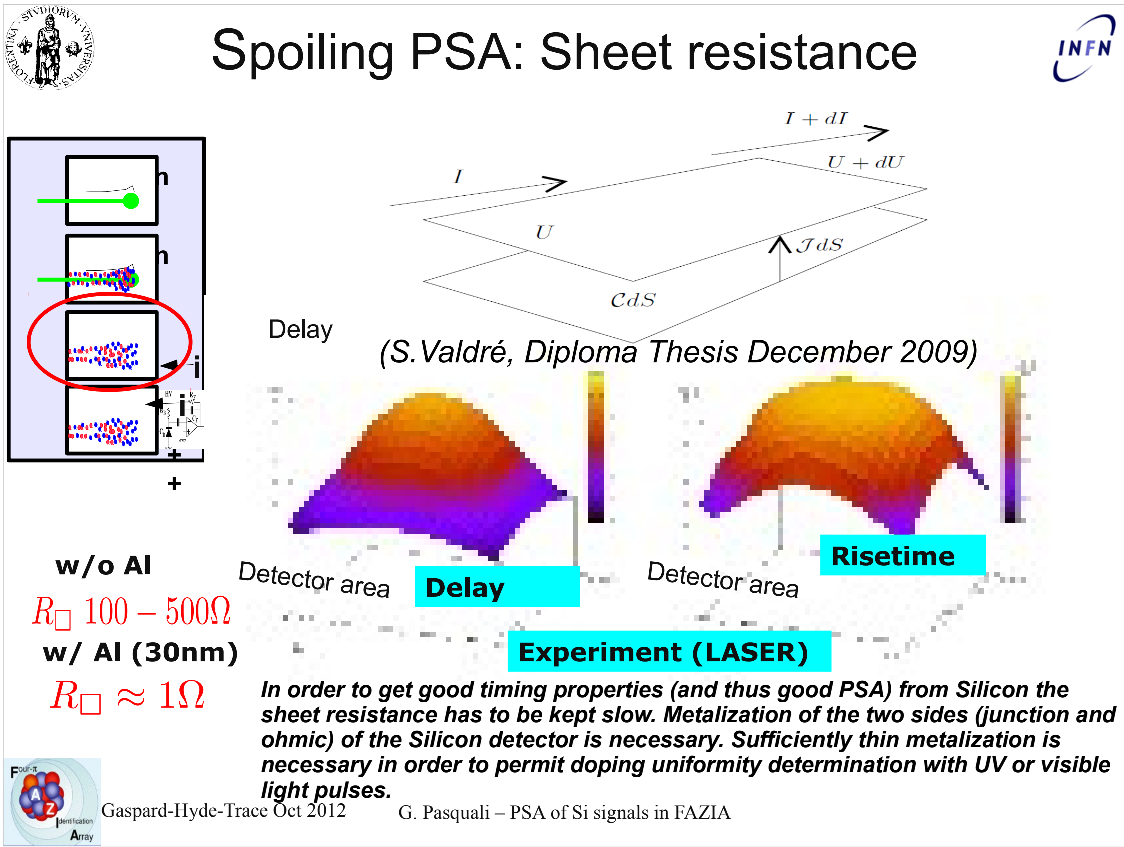


A quick remind about a very obvious fact.

Since the charge collection times changes with the electric field present in the bulk, this field must not change during measurments.

However, the bias voltage is usually connected to the detector through a large resistor of the order of 10MOhms or more.

If the dark current passing through the diode changes with time, as it does because of radiation damage for instance, the voltage drop accross Rb will change and so the voltage applied to the detector.
One must continuously monitor the dark current and correct the applied voltage accordingly, in order to keep the voltage on the detector constant.



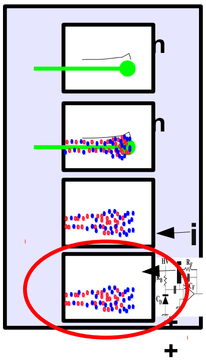
Finally, a curiousity: with the aim of using short light flashes to calibrate time delays, we planned to use silicon detector with non alumination, sensible to visible light.

What was not completely expected was the effect of the sheet resistance of the implanted electrodes on pulse shape.

Both experiments and calculations have confirmed that the electrodes behaves like a two dimensional transmission line, so that a signal produced in the center gets delayed and slowed down more than a signal produced near the border, thus spoiling pulse shape identification.

Front End Electronics

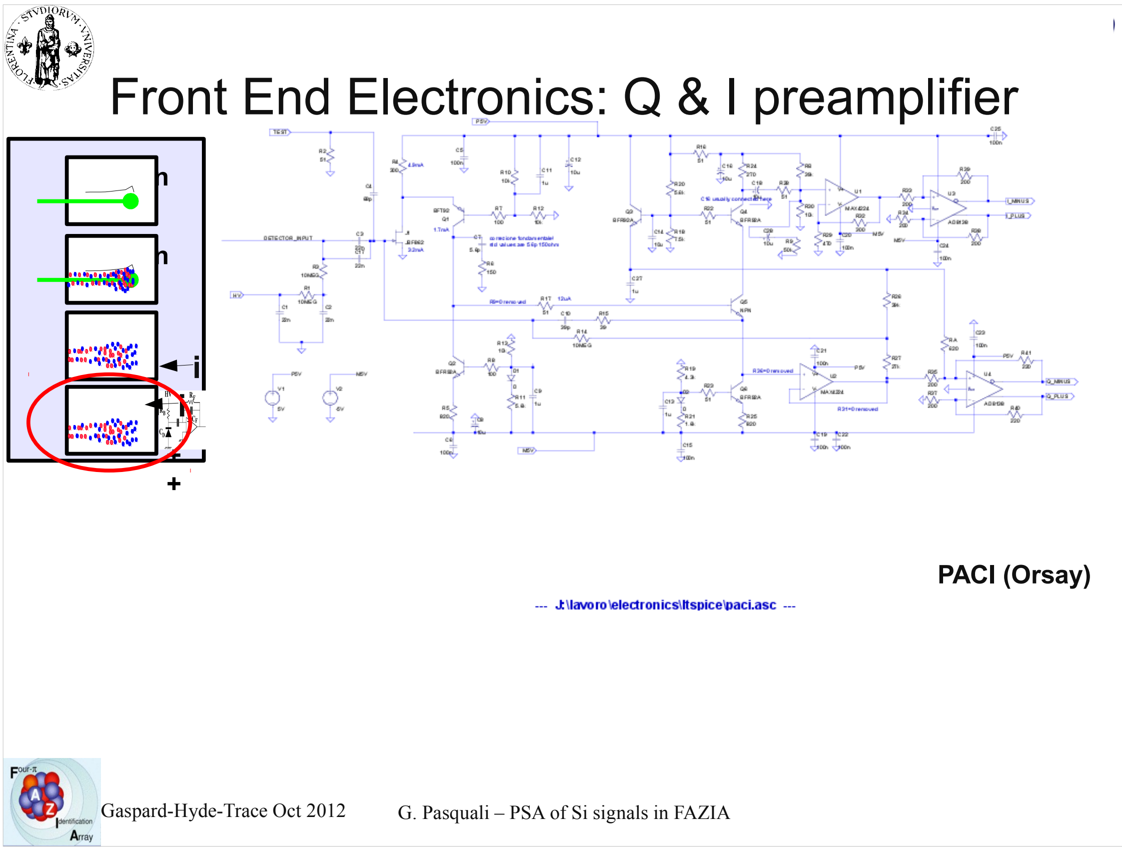
Front End Electronics: General Requirements



- **FEE must digitize the charge and/or current signal(s) preserving most of the relevant info!**
- **Amplitude (energy) is not enough**
- **Info is coded in shape => e.g. Leading edge of charge signal**
- **Minimize signal distortion**
- **Minimize noise**

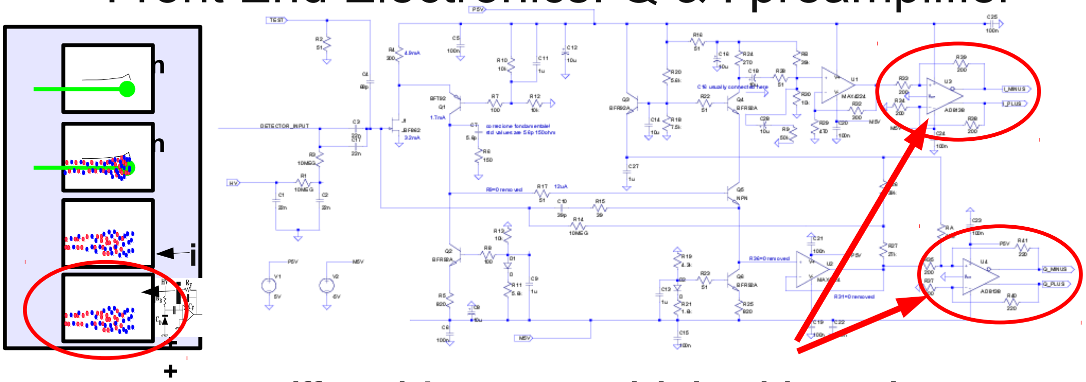
All efforts must be done in order to preserve the information contained in signal pulse shape.
The info must not be spoiled in the patch between the detector and the ADC.
The ADC must be choosen properly etc.

We have to remember that the info is coded in the time evolution of the signal. A system optimized for measuring the signal amplitude is not enough...we have to minimize signal distortion.



The first element of the FEE is the read out circuit of the current pulse: the so called preamplifier.

Front End Electronics: Q & I preamplifier

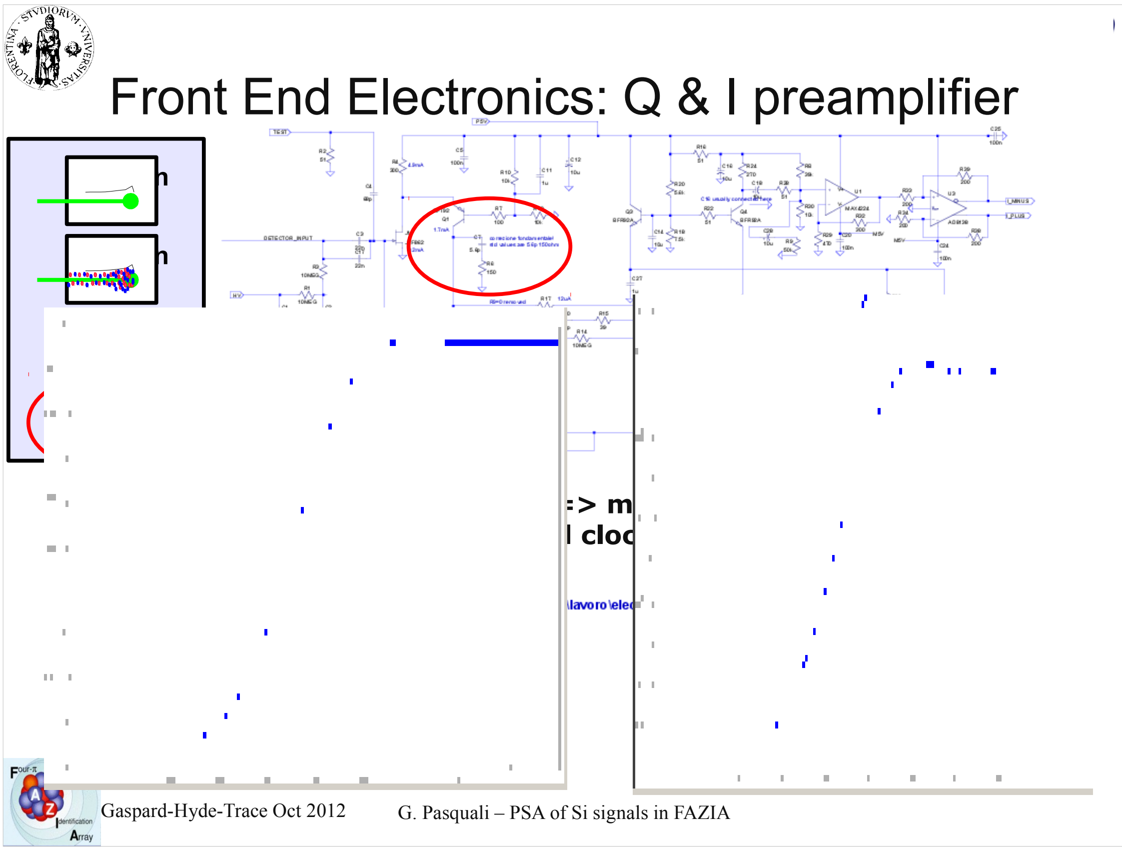


Differential outputs=> minimize pick up noise (e.g. Digital clocks) and cross talk

PACI (Orsay)

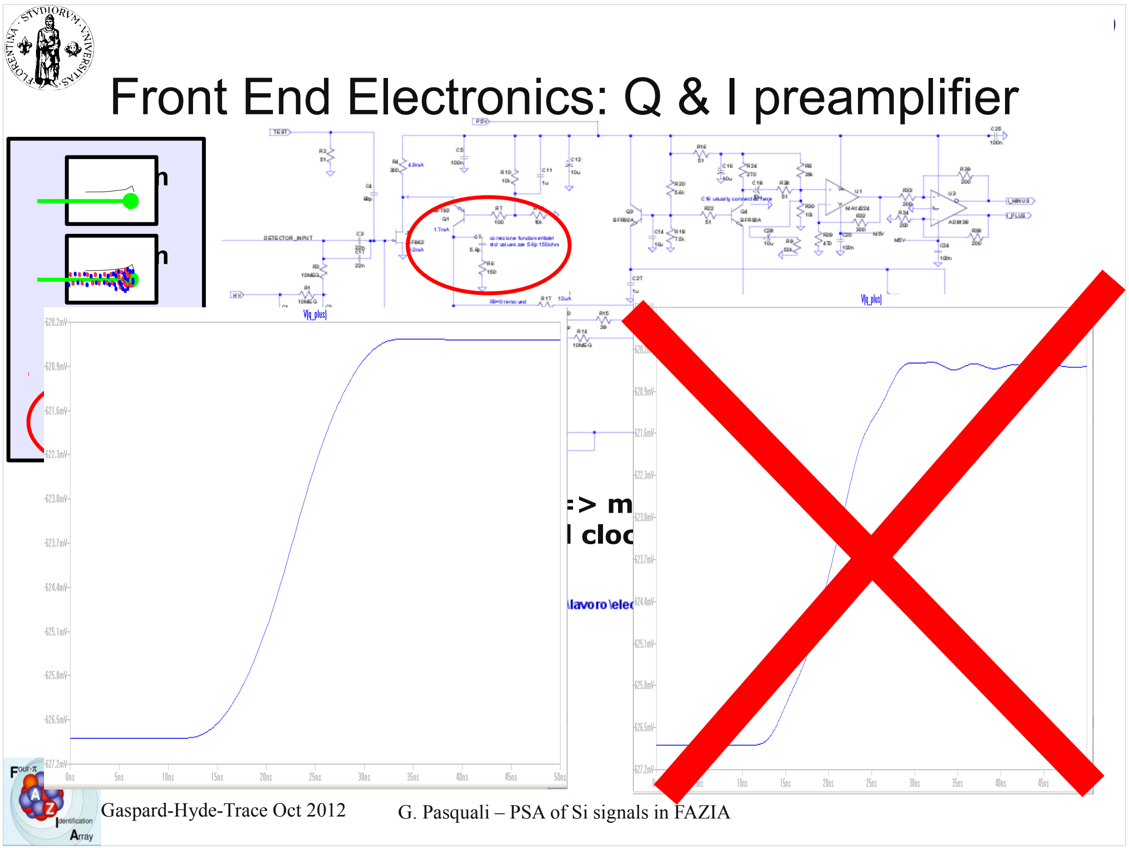
--- J:\lavoro\electronics\ltspice\paci.asc ---

In order to reduce as much as possible pick up noises and distortion, FAZIA has adopted a completely differential tranmission line from the preamplifier up to the sampling ADC.

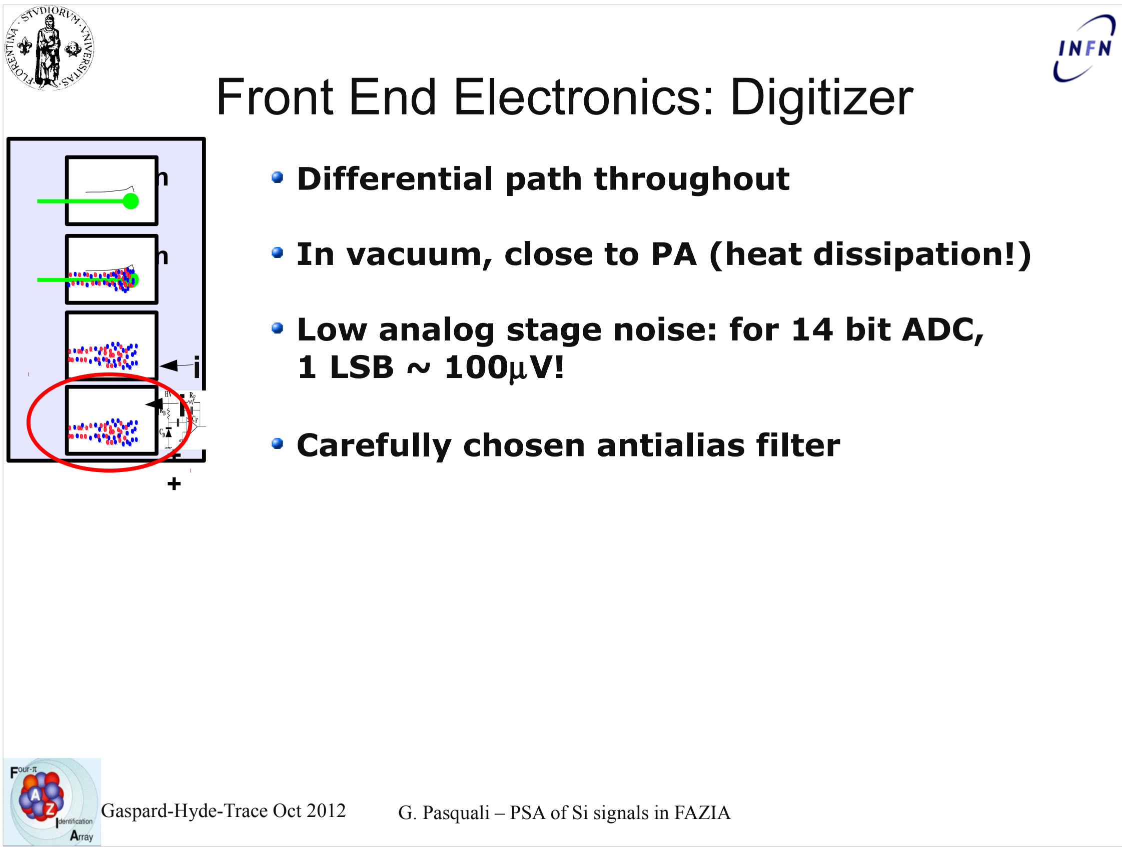


Moreover, care has been taken to preserve a clean leading edge, avoiding the damped oscillator behaviour that is often acceptable for amplitude measurements.

We can safely accept a charge signal of the shape shown on the left.



The signal on the right is surely modified by the tendency of the preamplifier to oscillate, so we can't accept such a response.



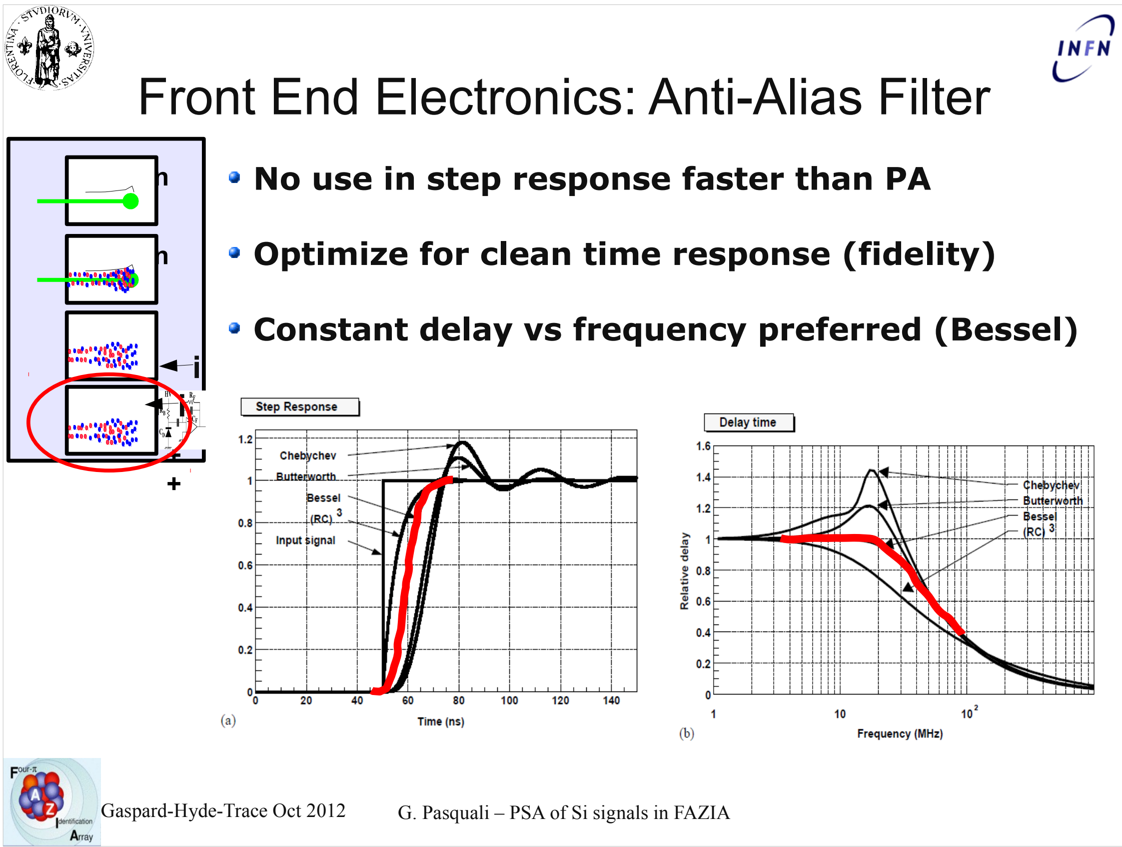
After the preamplifier, here comes the digitizing electronics.

During the R&D phase, we had to put the digitizers outside the vacuum chamber, using long differential cables to take the signals out.

This produced a slowing down and some distortion, expecially in the final part of the leading edge of charge signals.

In the FAZIA demonstrator the signal path will be made as short as possible by putting also the digitizers in vacuum on the same board as the preamps. That means we have to remove the heat generated by the ADCs and FPGA.

Maybe the main interesting topic here is the choice of the antialias filter, a low pass filter which you put before the ADC in order to attenuate frequencies greater than half the sampling rate. A compromise must be done between time response and frequency response...a so called Bessel response...



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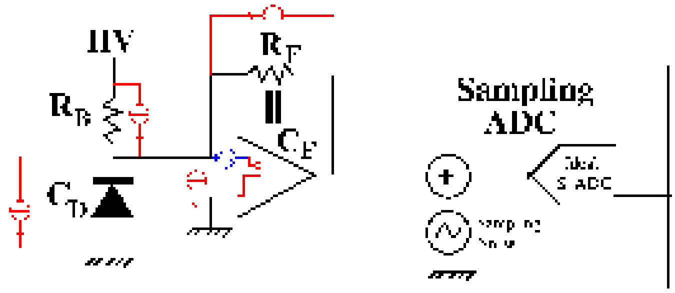
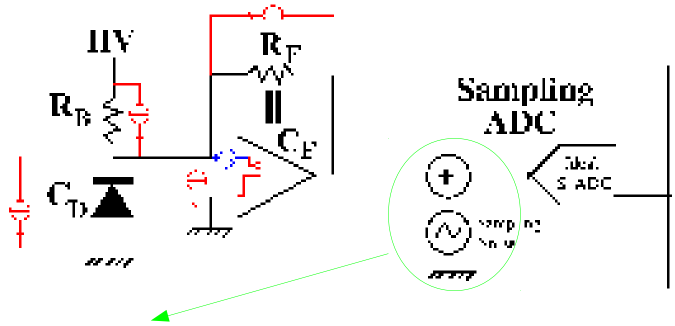
Front End Electronics: sampling ADC noise



Front End Electronics: sampling ADC



$$\sigma_n = \frac{2^{N_{bit}-ENOB}}{\sqrt{12}}$$

ENOB=effective number of bits

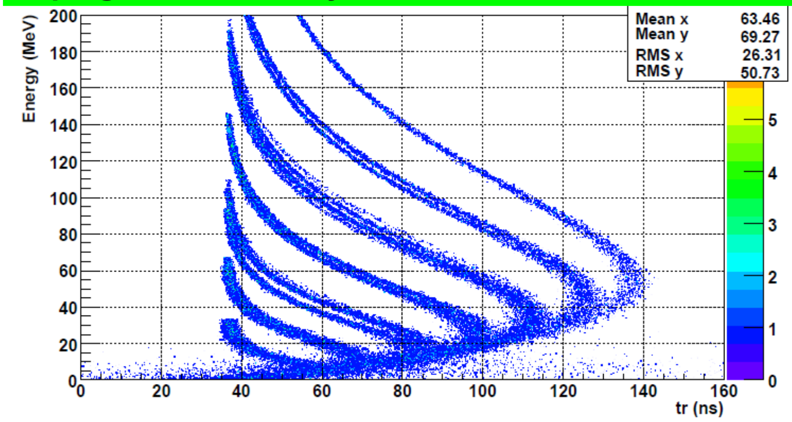
ENOB limits the obtainable Time and max{I} resolution =>limit on PS identification.

Straggling, noise, doping: which is the main culprit?

Now , which is main factor limiting PS identification?

Range straggling, noise, doping

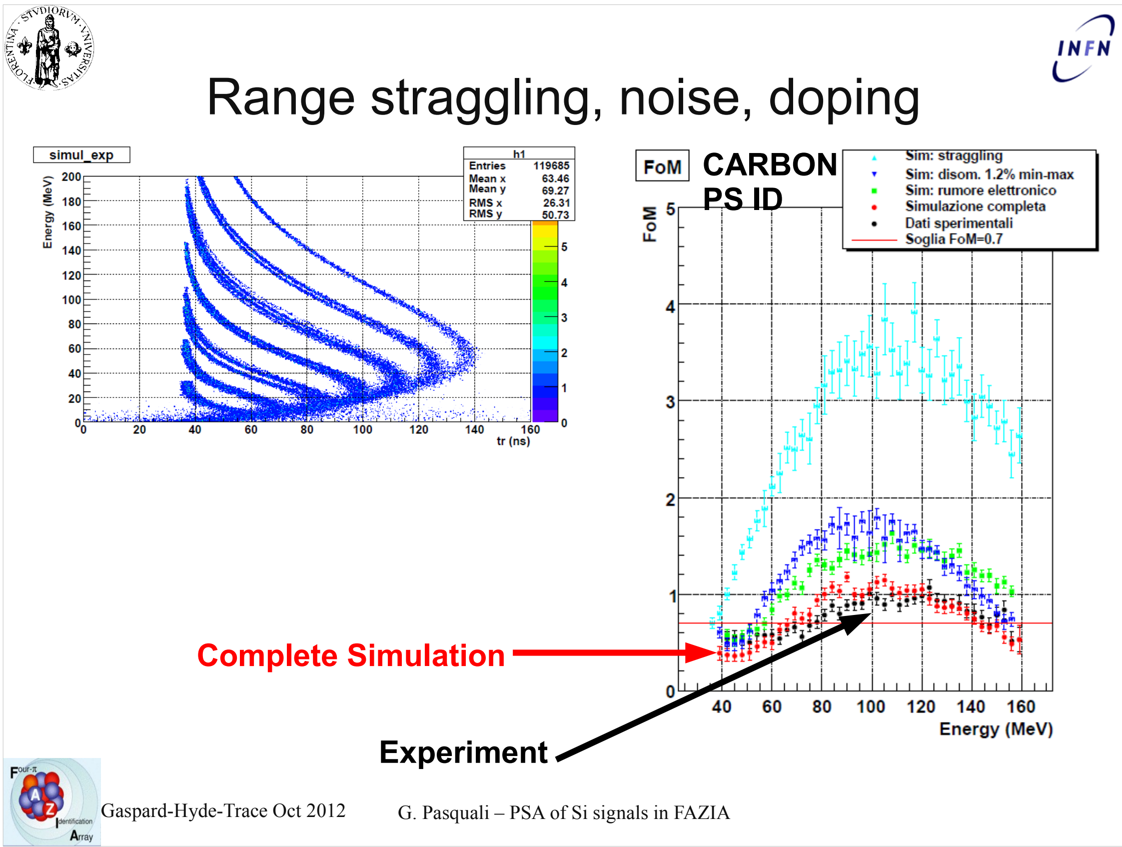
Average behaviour of curves: experimental data.
Fluctuations: simulations including range straggling, noise and doping non-uniformity



Stefano Carboni Master's Thesis – A.A. 2007/2008 University of Florence

I have already shown a simulation showing how straggling puts a unavoidable lower threshold for particle identification.

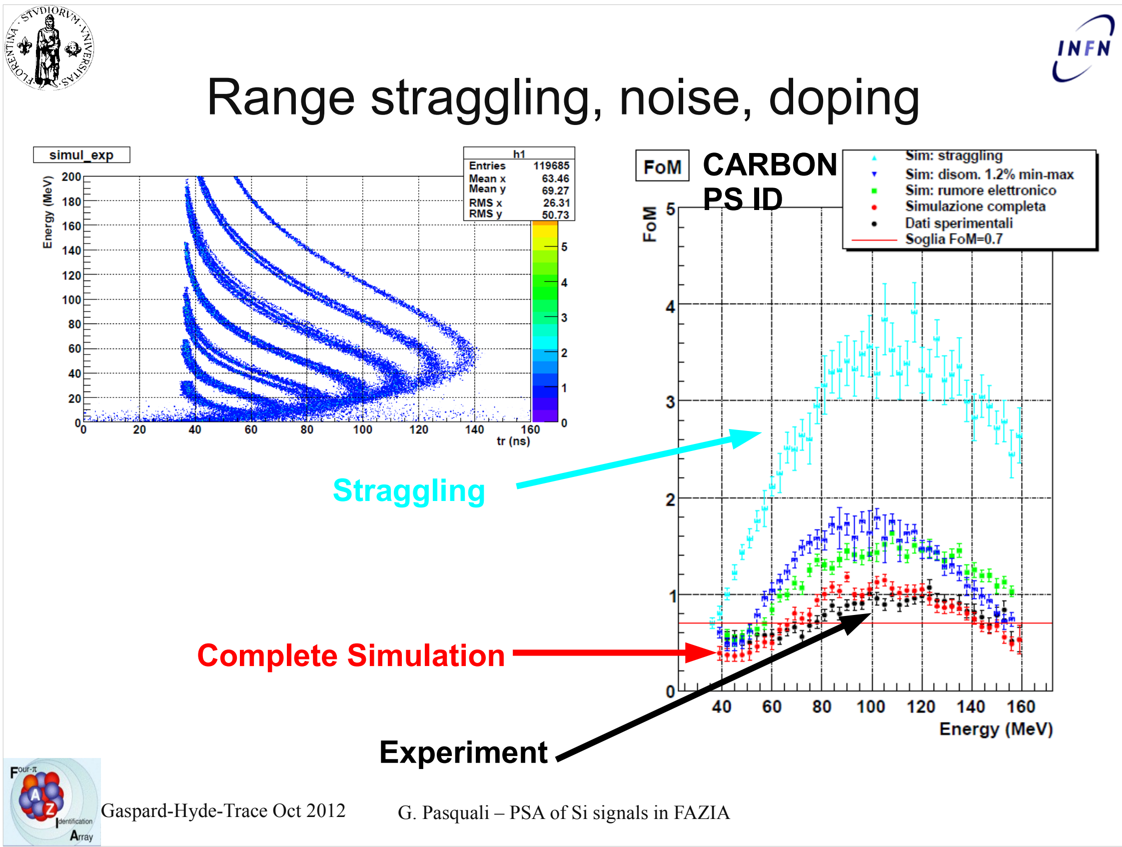
When we add electronic noise and doping non uniformity to the simulation, risetime resolution gets even worse as you can see in this plot.



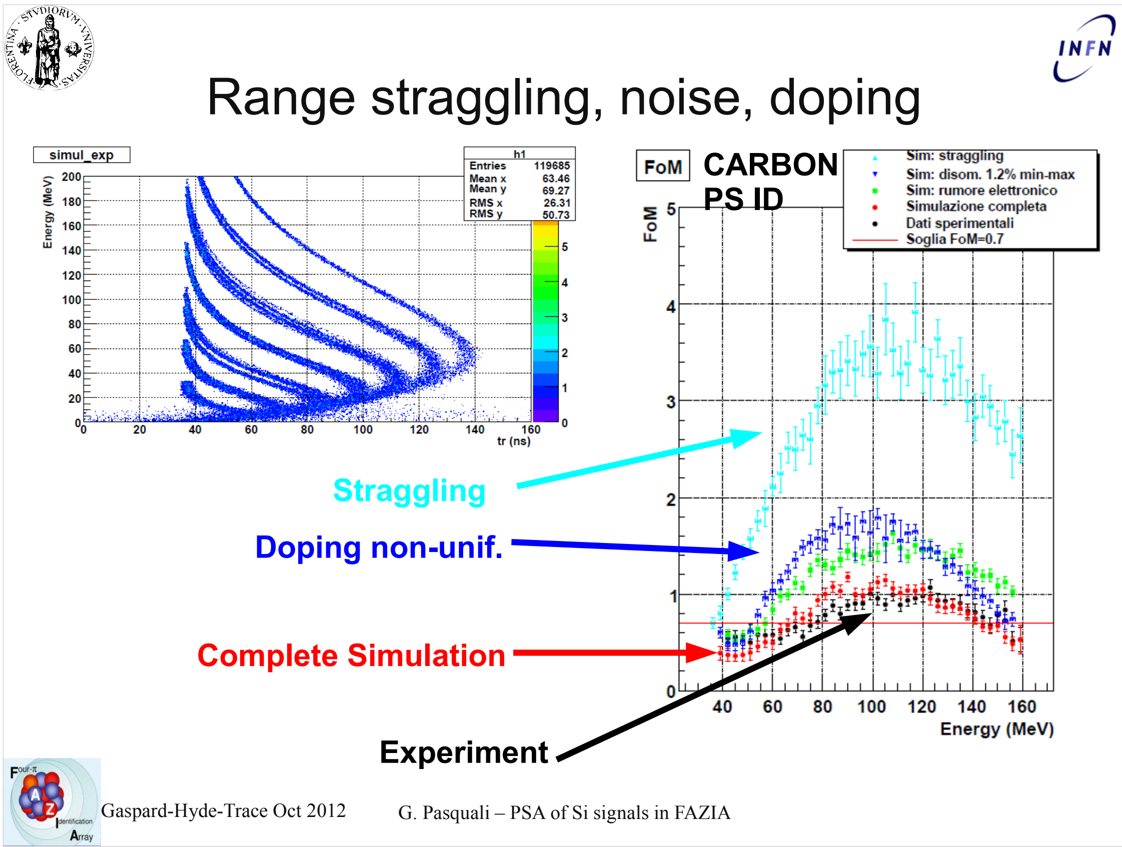
Being it a simulation, we can disentangle the various contribution to some quality estimator.

Let's take the figure of merit calculated from the linearized correlations for carbon isotopes.

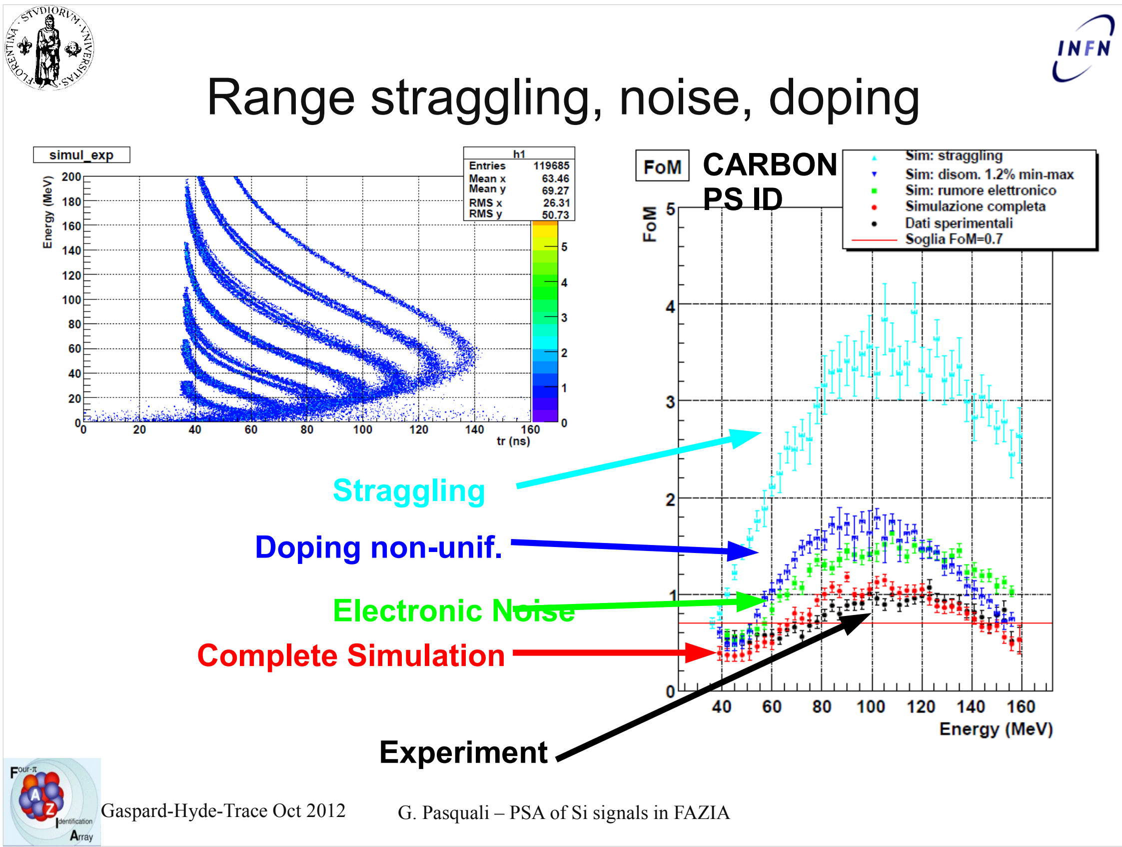
The full simulation is plotted in red and it compares reasonably well with the experiment which is in black.



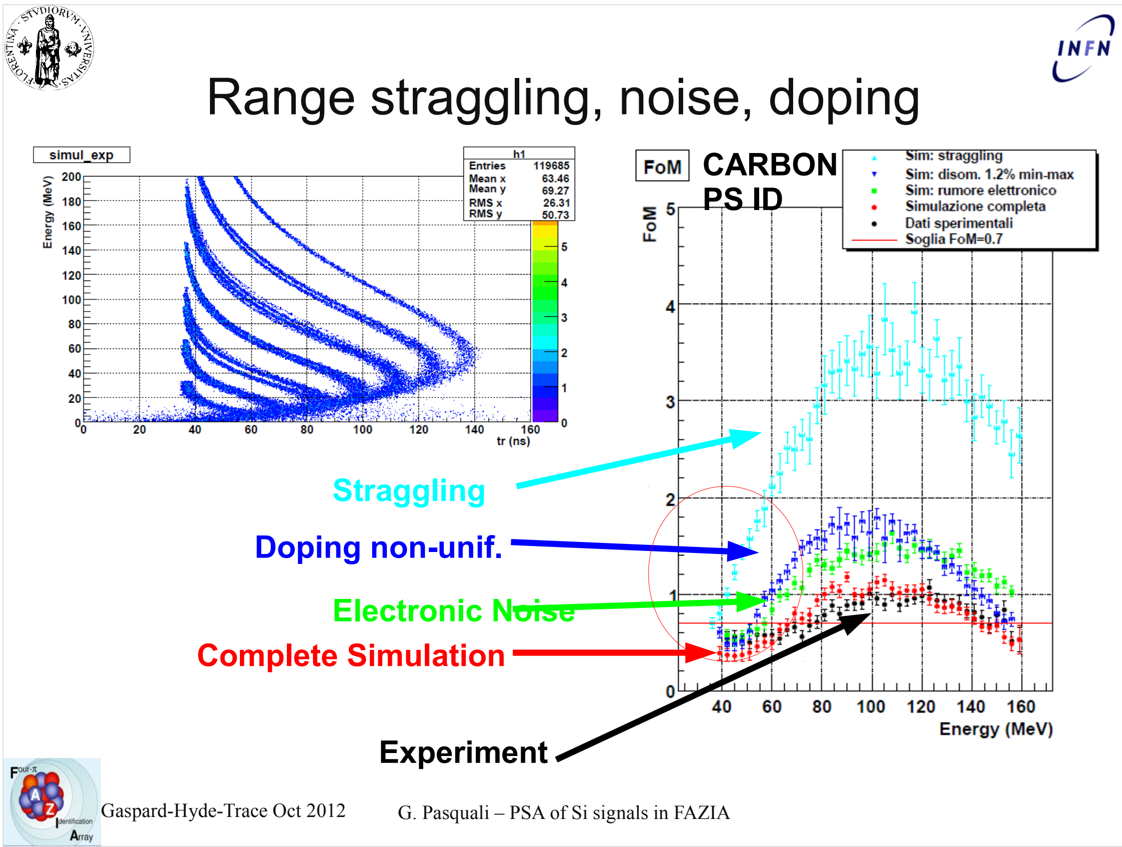
The longitudinal straggling contribution has been estimated using a corrected Bohr formula, also estending it to thick absorbers.



Being it a simulation, we can disentangle the various contribution to some figure of merit



Being it a simulation, we can disentangle the various contribution to some figure of merit

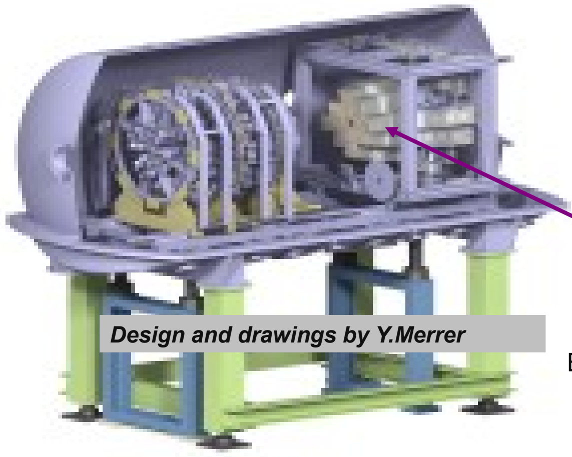


Being it a simulation, we can disentangle the various contribution to some figure of merit

FAZIA demonstrator

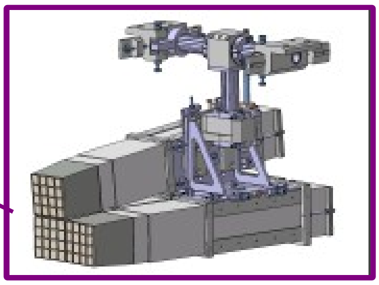
FAZIA demo: Mechanical setup

Demonstrator together with **INDRA at GANIL**

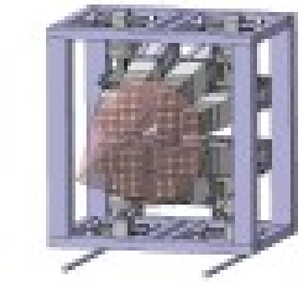


Design and drawings by Y.Merrer

Schedule: **fall 2013 to 2016**

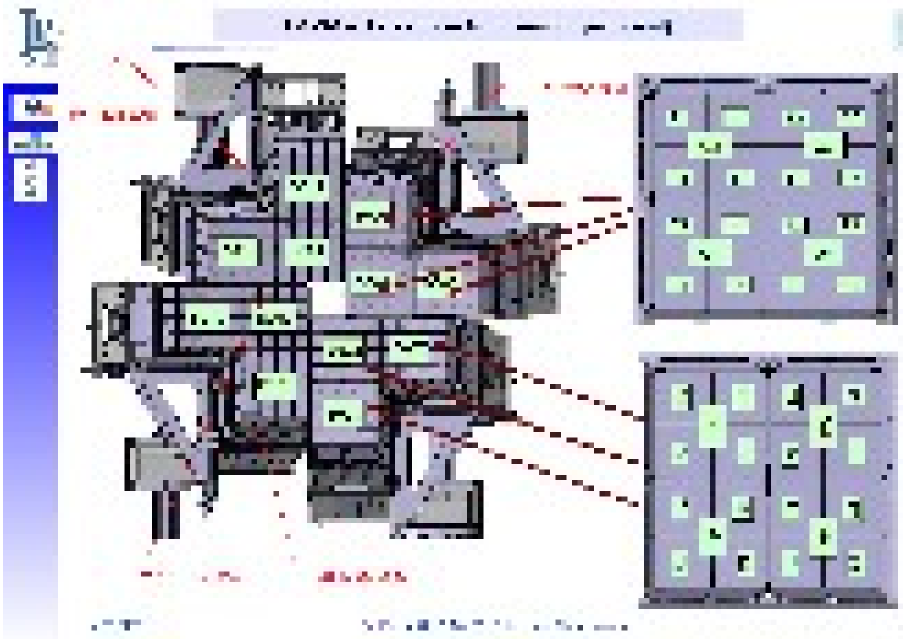


Block held by supports in group of three



- **192 telescopes organized in 12 blocks, mounted at 100cm from target**

FAZIA demo: Mechanical setup



FAZIA demo: Front End Electronics (Orsay)

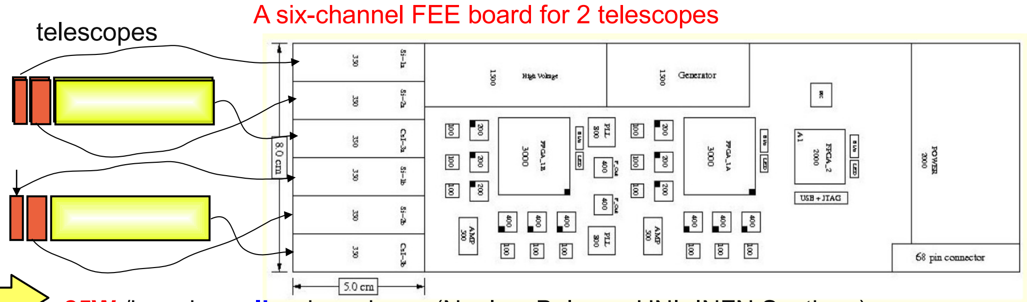
- Stage 1 (silicon 300 μm)
  - Charge 250 MeV full scale 250 Ms/s 14 bit
  - Charge 4 GeV full scale 100 Ms/s 14 bit
  - Current 250 Ms/s 14 bit
- Stage 2 (silicon 500 μm)
  - Charge 4 GeV full scale 100 Ms/s 14 bit
  - Current 250 Ms/s 14 bit
- Stage 3 (CsI + photodiode)
  - Charge 4 GeV full scale 100 Ms/s 14 bit

Services to the detectors

- Single low voltage power supply 48 V
- High voltage bias production/monitoring
  - 30_000 individually monitored voltages
- Temperature monitoring
- Pulser and other calibration facilities
- In-situ, in-vivo configuration of the FPGAs
- Software dowload (slow control, calibration)

Everything under VACUUM

A six-channel FEE board for 2 telescopes

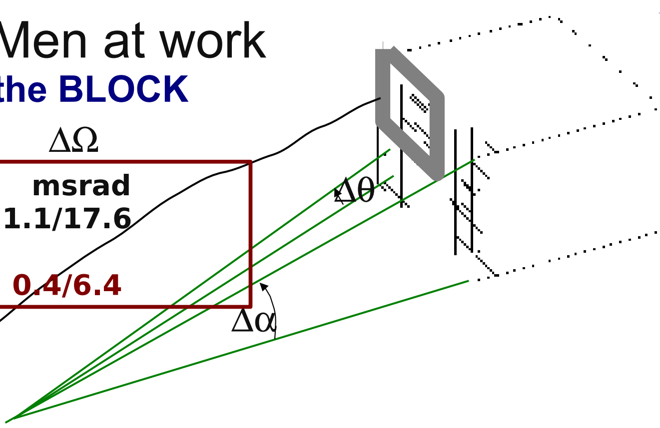


25W /board: **cooling** is an issue (Naples, Bologna UNI+INFN Sections)

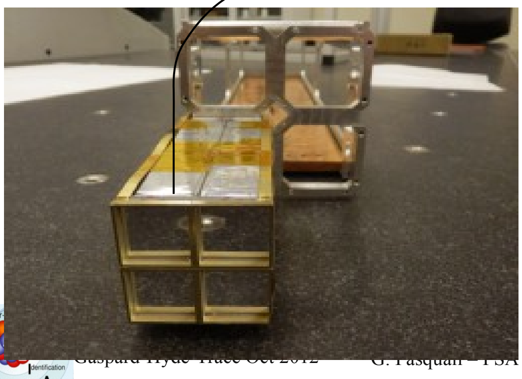
FAZIA demo: Men at work

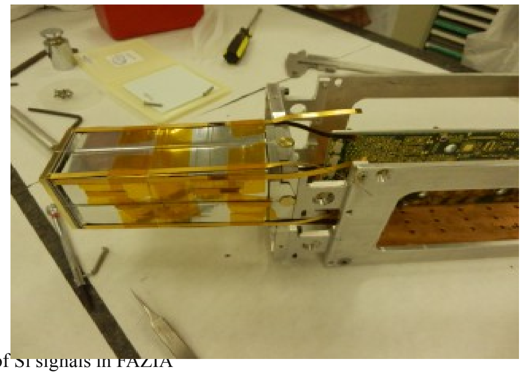
The Quartets and the BLOCK

distance from target	$\Delta\alpha$	$\Delta\theta$	$\Delta\Omega$
mm	deg	deg	msrad
600	8.4	1.9	1.1/17.6
1000	5.0	1.1	0.4/6.4



Mounting tests in FLORENCE
March to May 2012





Conclusions (1)

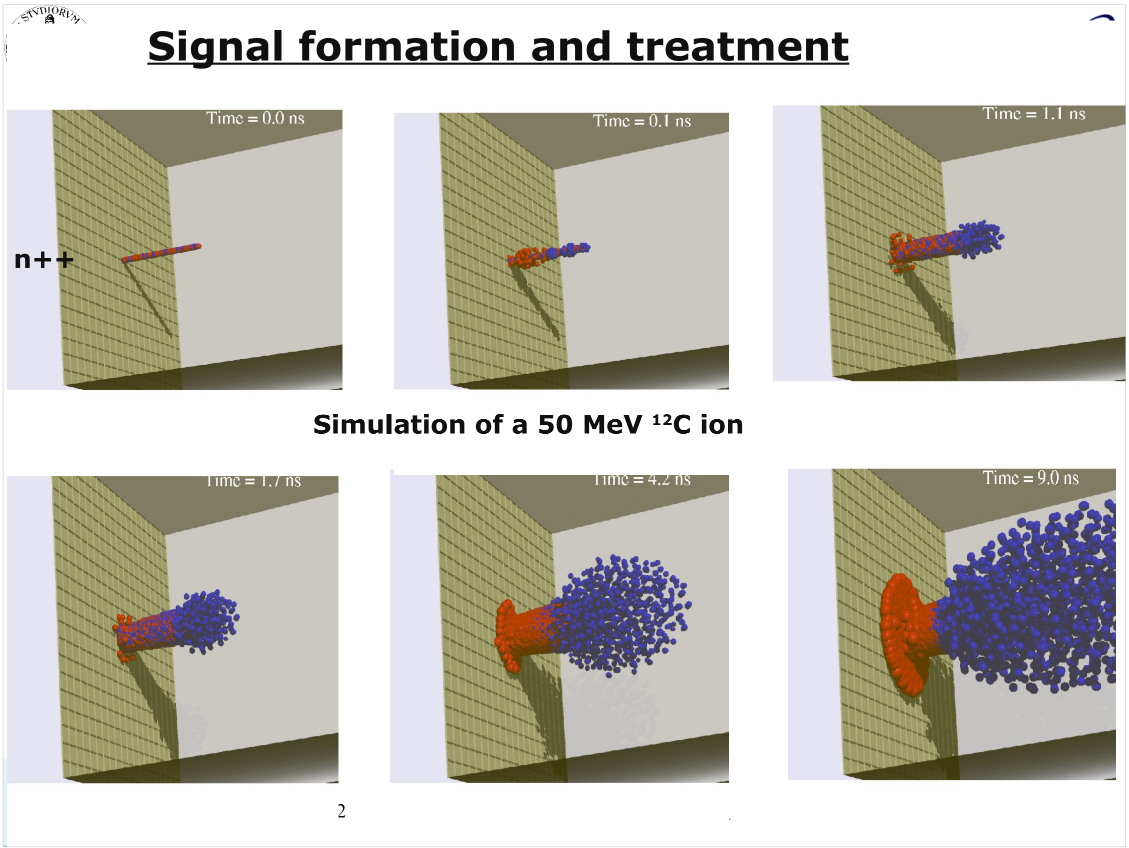
Many effects limit PS identification...

- Energy deposition and e-h creation:
  - longitudinal straggling, channeling,
- Signal formation:
  - non unif. doping, rad. Damage, Vbias instab., sheet resistance
- Signal treatment:
  - Noise and pick up
  - FEE response (pa, cables, antialias filter...)
  - Sampling noise

Conclusions (2)

- Long. Straggling=> unavoidable low energy threshold for A identification (for a given Z)
- In FAZIA: doping and sampling noise=> similar contribution, straggling important only at low E
- Solutions:
  - Double gain to get better SNR for LCP id and for IMF mass id.
  - select better unif. Ingots! Cut wafers at an angle
  - Higher sampling rate (not comprimising ENOB) to get better time resolution for LCP

Thanks!



As soon as they are created,they start to diffuse in the bulk due to their concentration gradient. They also assume a drift velocity towards the electrodes, a velocity proportional to the local electric field...unless their density is so high that the charge column behaves like a charged plasma: the electric field inside the column is either zero or at least reduced and the column must be eroded by the head and the sides, thus slowing down charge collection.

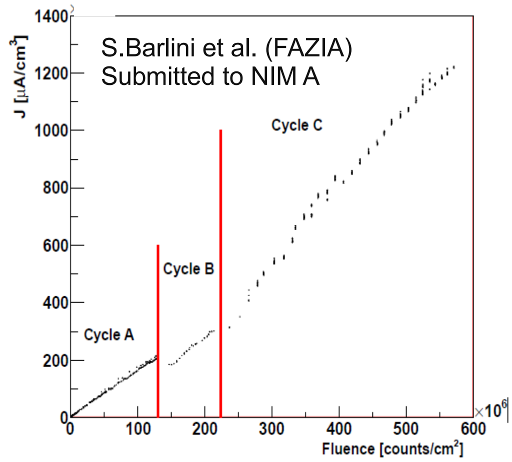
The plasma lifetime will be greater the lower the electric field in the track region.

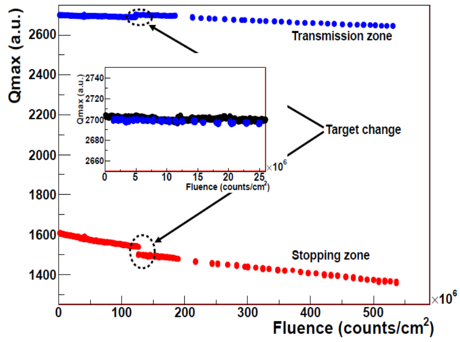
Moreover, different energy means different range and different range means a different transit time of the charge carriers towards the electrodes.

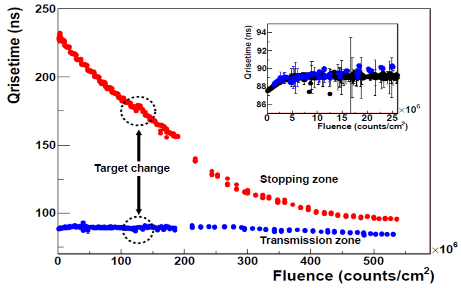
Plasma time and transit time will depend on deposited energy and particle range.

Sensor: Effects of RD

Effects of RD in Si detectors vs. fluence (ions/cm²)

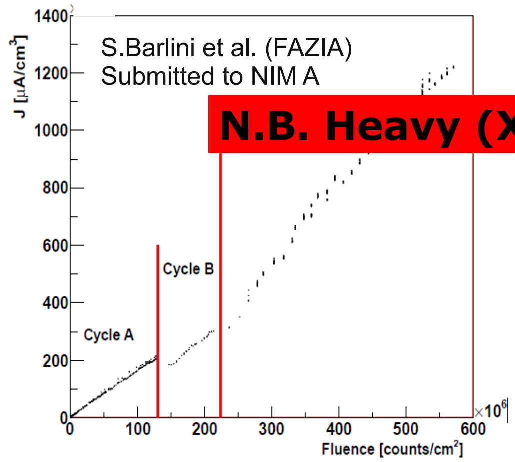




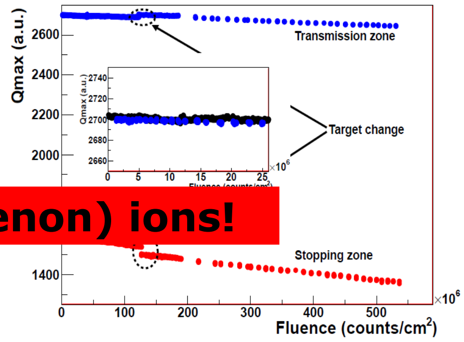


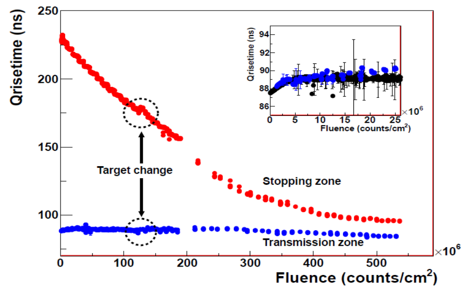
Sensor: Effects of RD

Effects of RD in Si detectors vs. fluence (ions/cm²)



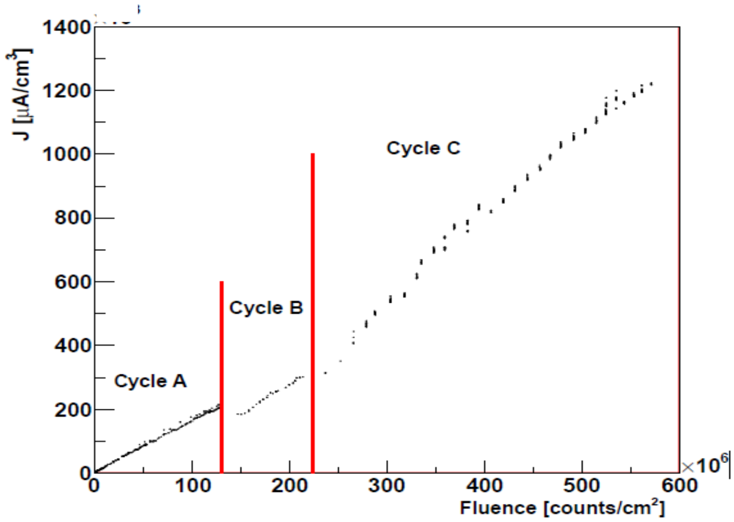
N.B. Heavy (Xenon) ions!

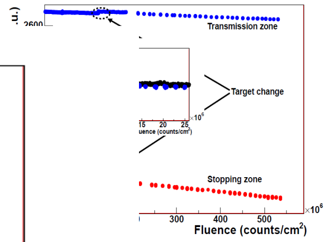


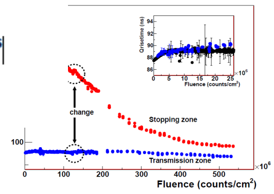


Sensor RD: leakage current

Effects of RD in Si detectors vs. fluence (ions/cm²)

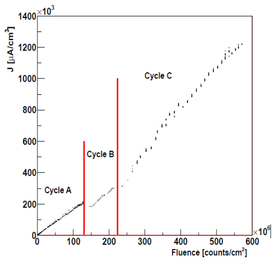






Sensor RD: collection efficiency

Effects of RD in Si detectors vs. fluence (ions/cm²)



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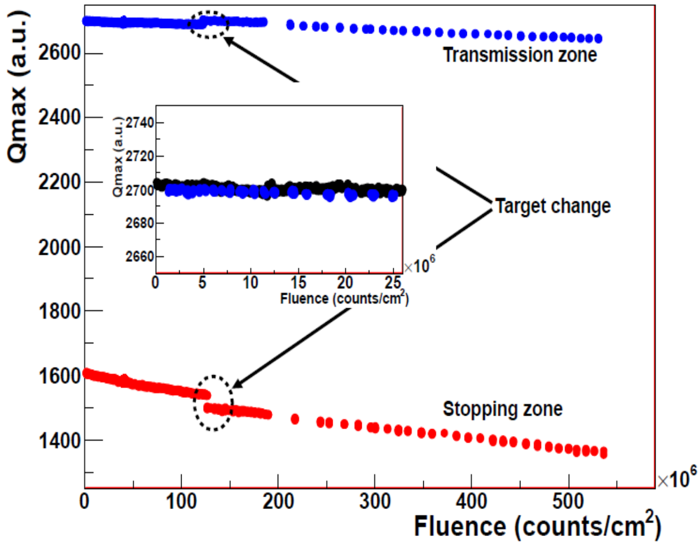
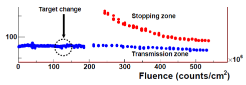
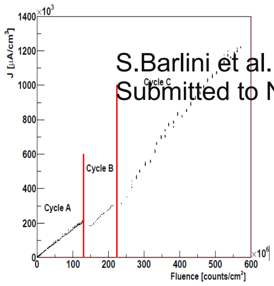
Submitted to NIM A





Sensor RD: collection time

Effects of RD in Si detectors vs. fluence (ions/cm²)



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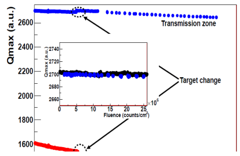
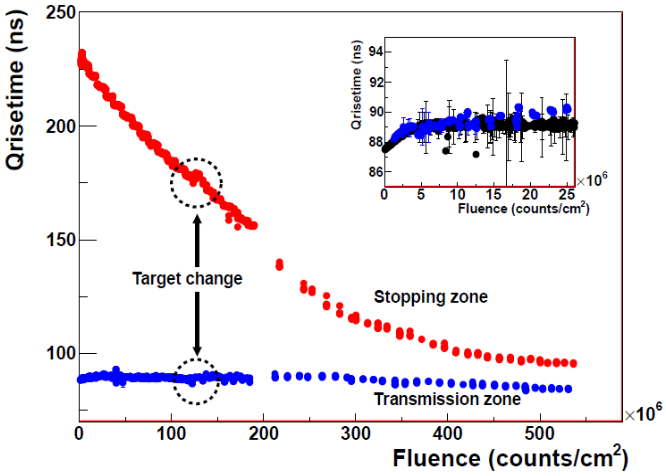
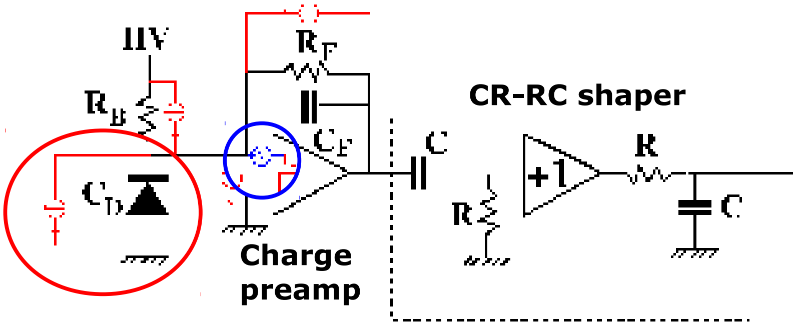




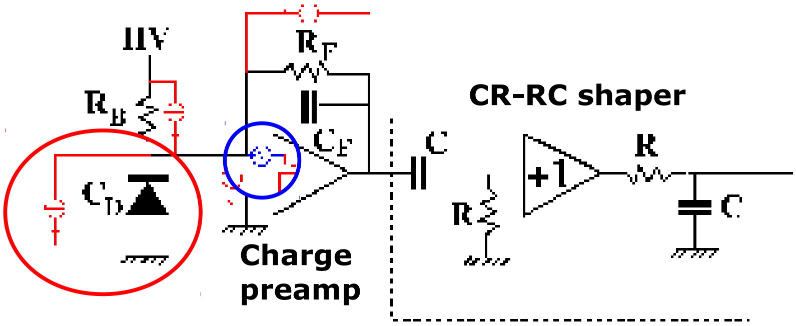
FEE: Electronic noise



Charge signal variance Q_n^2 (measured, e.g., in squared Equivalent Noise Charge, ENC²)

ENC: input charge giving an output voltage signal equal to the rms voltage noise.

FEE: Electronic noise



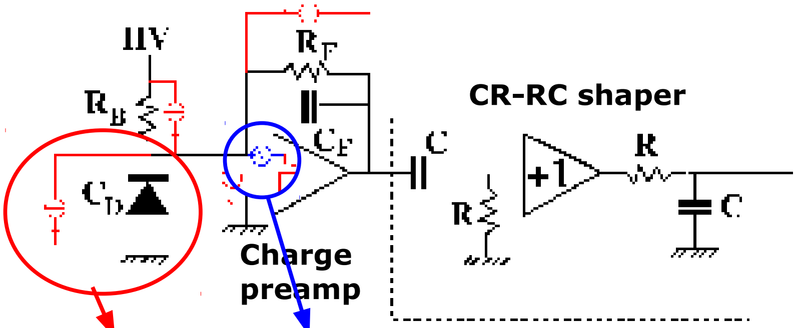
$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s}$$

T_s : measure time (e.g. CR – RC shaper : $T_s = RC$)
T : absolute temperature

Long T_s => current noise dominates

Short T_s =>voltage noise dominates

FEE: Electronic noise



$$Q_n^2 = i_n^2\, \mathcal{F}_i\, T_s + e_n^2\, \mathcal{F}_v\, \frac{C_{in}^2}{T_s}$$

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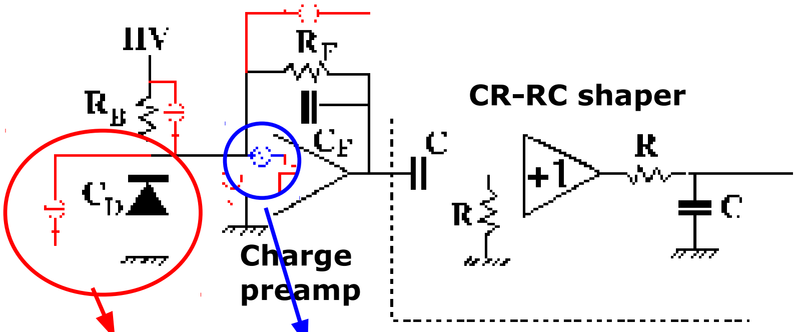

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FEE: Electronic noise

$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s}$$

i_n^2 $\quad i_n^2 \approx 2\, e\, I_D \quad I_D(T) \propto T^2 e^{-E/k_B T}$

- **increases linearly with leakage current**
- **leakage current increases with damage**

FEE: Electronic noise

$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s}$$

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e_n^2 $\quad e_n^2 \approx \frac{2.7\,k_B\,T}{g_m} \propto \frac{2.7\,k_B\,T}{I_{FET}}$

- **increases w/ decreasing input transistor transconductance => decreasing power**
- **"amplified" by input capacitance squared**

FEE: Electronic noise

$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s}$$

$$i_n^2 \qquad i_n^2 \approx 2\, e\, I_D \qquad I_D(T) \propto T^2 e^{-E/k_B T}$$

- **increases linearly with leakage current**
- **leakage current increases with damage**

$$e_n^2 \qquad e_n^2 \approx \frac{2.7\, k_B\, T}{g_m} \propto \frac{2.7\, k_B\, T}{I_{FET}}$$

- **increases w/ decreasing input transistor transconductance => decreasing power**
- **"amplified" by square on input capacitance**

FEE: Electronic noise

$$Q_n^2 = i_n^2 F_i T_s + e_n^2 F_v \frac{C_{in}^2}{T_s}$$

$$i_n^2 \qquad i_n^2 \approx 2\, e\, I_D \qquad I_D(T) \propto T^2\, e^{-E/k_B T}$$

- increases linearly with leakage current
- leakage current increases with damage

$$e_n^2 \qquad e_n^2 \approx \frac{2.7\, k_B\, T}{g_m} \propto \frac{2.7\, k_B\, T}{I_{FET}}$$

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FEE: Electronic noise

$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s}$$

$$i_n^2$$

$$i_n^2 \approx 2\, e\, I_D \qquad I_D(T) \propto T^2\, e^{-E/k_B T}$$

- **increases linearly with leakage current**
- **leakage current increases with damage**

$$e_n^2$$

$$e_n^2 \approx \frac{2.7\, k_B\, T}{g_m} \propto \frac{2.7\, k_B\, T}{I_{FET}}$$

- **increases w/ decreasing input transistor transconductance => decreasing power**
- **"amplified" by input capacitance squared**

Both increase with temperature!

Some ASIC specific issues

- relatively low bias voltage=>need bigger feedback capacity for the same dynamic energy range with respect to discrete of higher bias voltage
- big capacity => occupy large area on ASIC chip
- low voltage noise needs high transconductance, i.e. Large JFET bias current => needs large area for JFET
- taking out preamp signal for digitizers problematic
- slow (sequential) readout. Sparse readout faster though it needs some timing logic (CFD,...). Dead time after sample/hold.

Performances

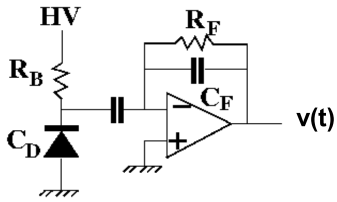
Deposited energy => collected charge

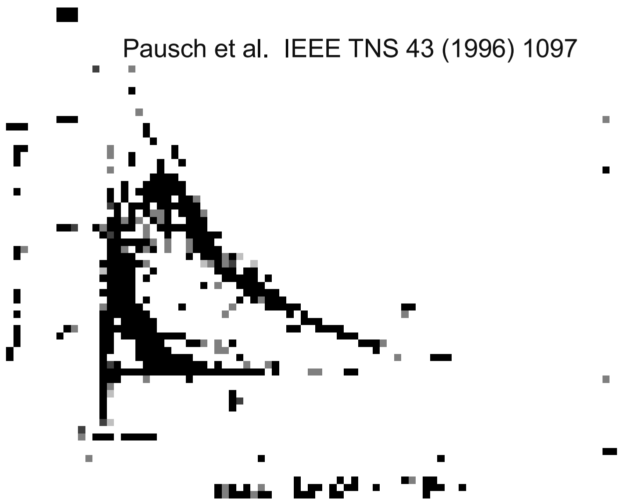
Fluctuations in carrier number, electronic noise etc => finite resolution in determining charge (energy).

Collection time=>timing and resolving time.

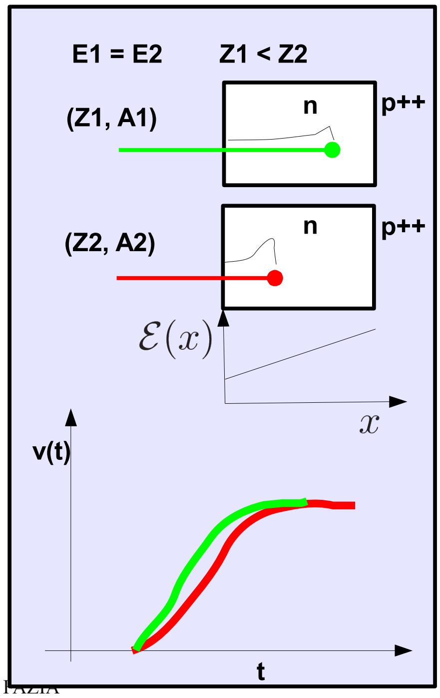
	Scintillator	Gas	Solid State
Energy/carrier	100−500 eV	20−40 eV	~3 eV
Energy resol. @ 1 MeV	100−500 keV	20−50 keV	1−10 keV
Timing resol. @ 1 MeV	~0.03−1 ns	0.1−1 ns	0.1−2 ns
Detectable particle charge	1−6	>20	all
pulse shape	y	n	y/n
Area limits	100 cm^2	m^2	cm^2
Easy to handle	y	y/n	y
Cost/cm^2	medium	medium	high

Particle ID: Pulse Shape Ident. in Silicon



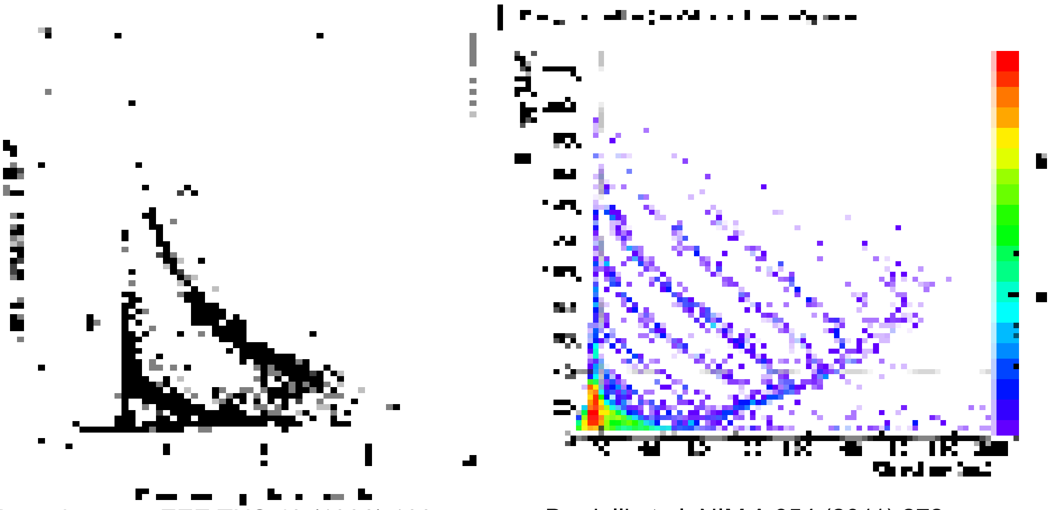


Pausch et al. IEEE TNS 43 (1996) 1097



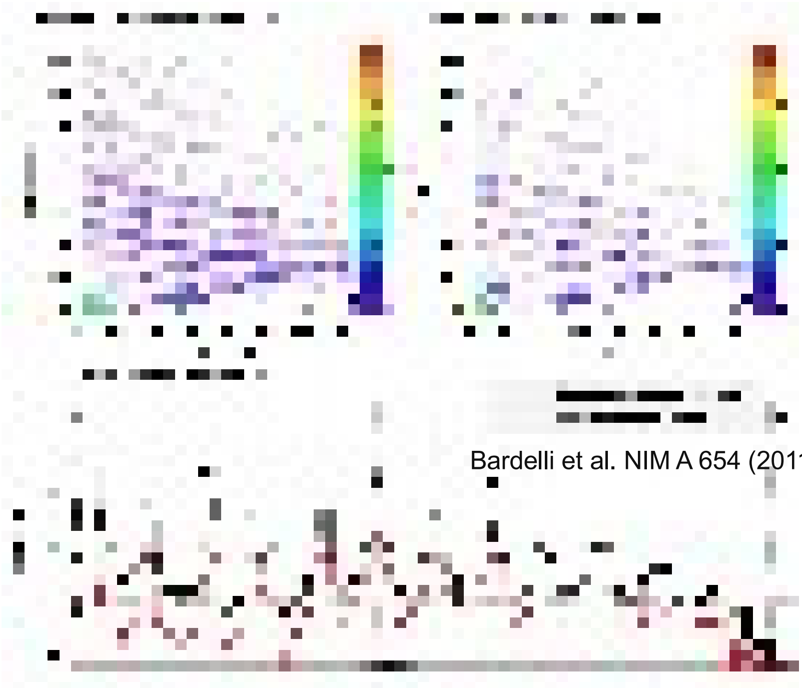
Particle ID: Pulse Shape Ident. in Silicon

Pausch image rotated and flipped for easier comparison.



Pausch et al. IEEE TNS 43 (1996) 1097   Bardelli et al. NIM A 654 (2011) 272

Particle ID: ΔE-E and Channeling



Bardelli et al. NIM A 654 (2011) 272