Charged particle detectors for high intensity beams: some thoughts and open problems

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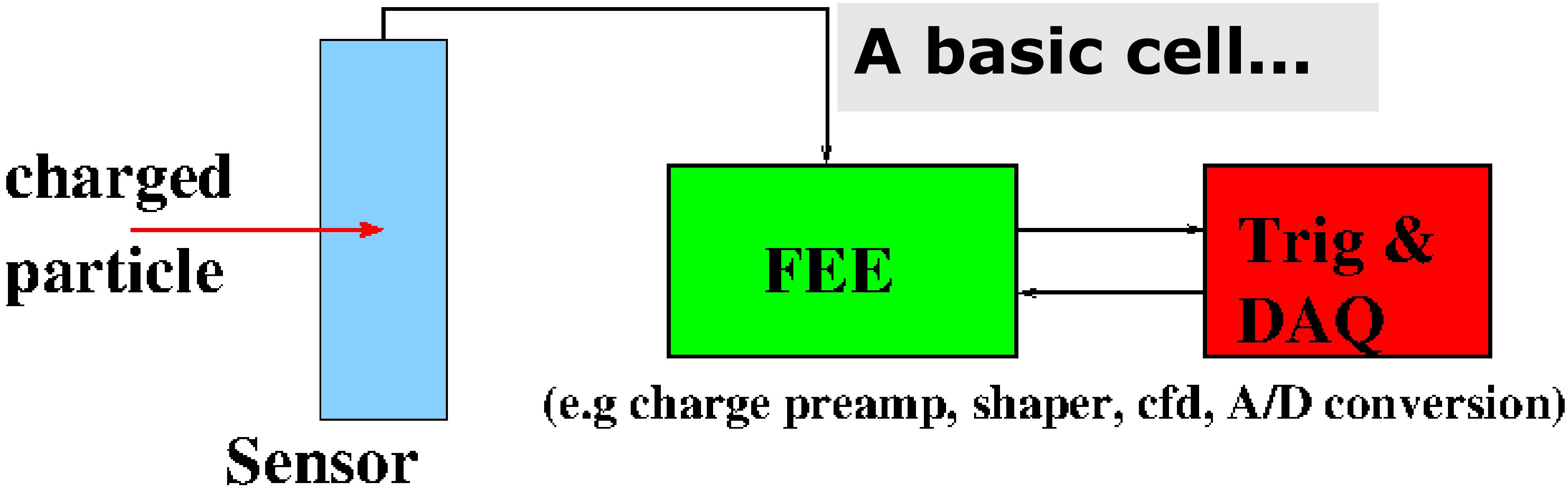
Outline

- **Introduction**
  - **Applications of Charged Particle Detectors (CPD)**
  - **Basic detection principles**
- **Particle Identification**
  - **Delta E-E technique**
  - **Pulse Shape Analysis in Silicon**
- **Limits to detector performance**
  - **Radiation Damage in Silicon**
  - **Multiple hits and Pile-Up**
  - **Noise, power consumption and their interplay with noise and pile-up, Segmentation**
- **Study case**
  - **Ancillary detector for LCP's for new generation gamma arrays**
- **Conclusions**

Charged part. detection basics

CPD: Detection basics

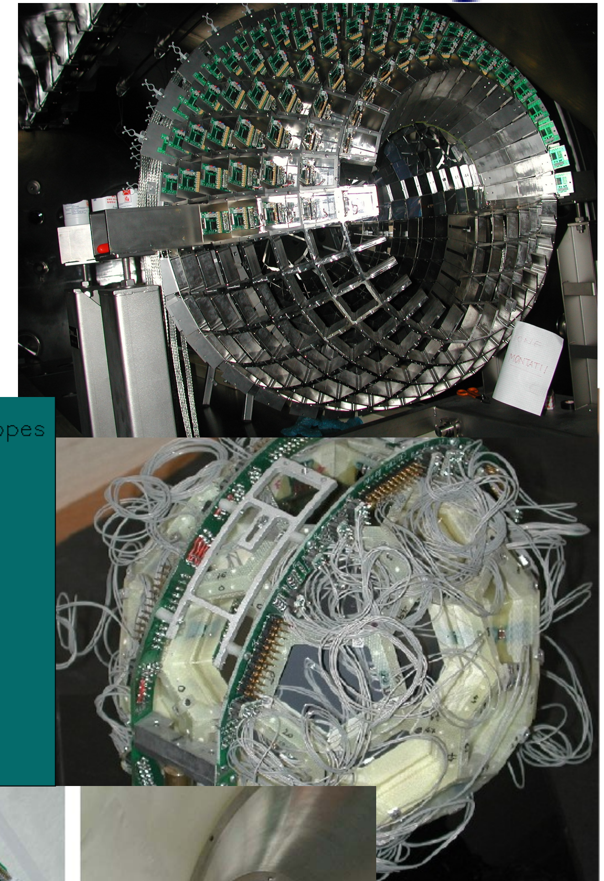
- Detection via energy loss in an absorber
- Absorbed energy => current/charge signal
- Signal => Timing/Energy/Type information

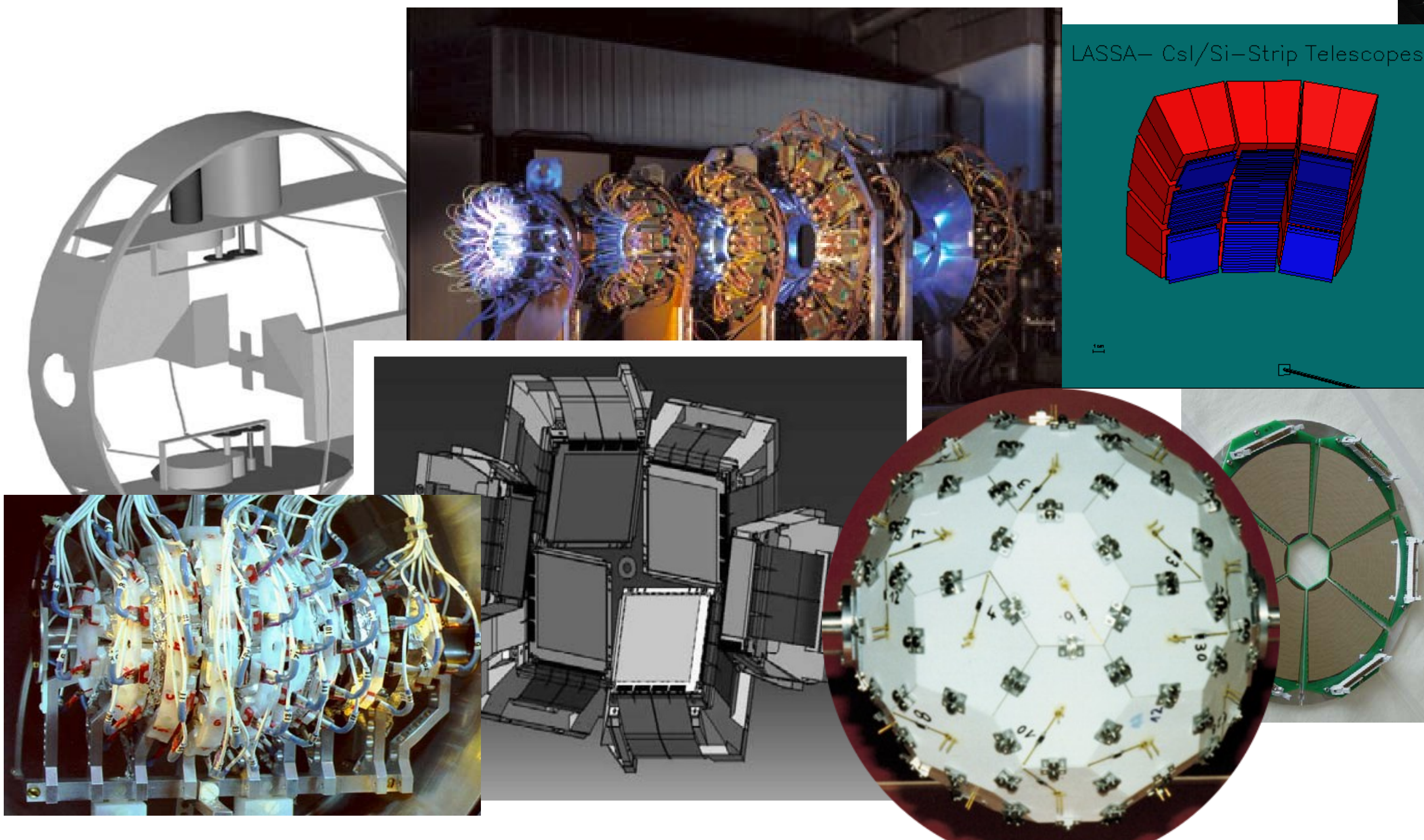


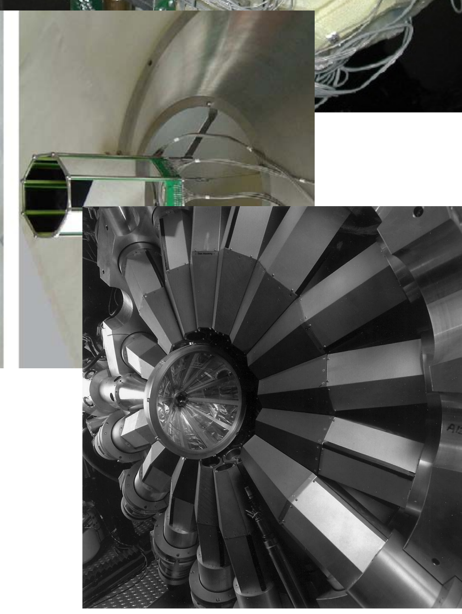
Sensor: active volume+electrodes

CPD: Applications

- Ancillary detectors for gamma arrays
- Large solid angle telescope arrays
- Focal plane detectors for spectrometers

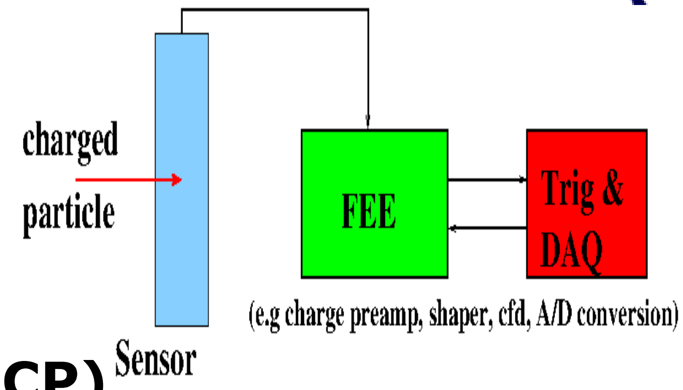






CPD: Sensor material

- **Gas detectors (IC, MWPC, PPAC, etc.)**
- **Semiconductor detectors (Si)**
- **Scintillators (CsI(Tl), plastics, etc..)**
- **Conversion foils + electron mult (e.g. MCP)**



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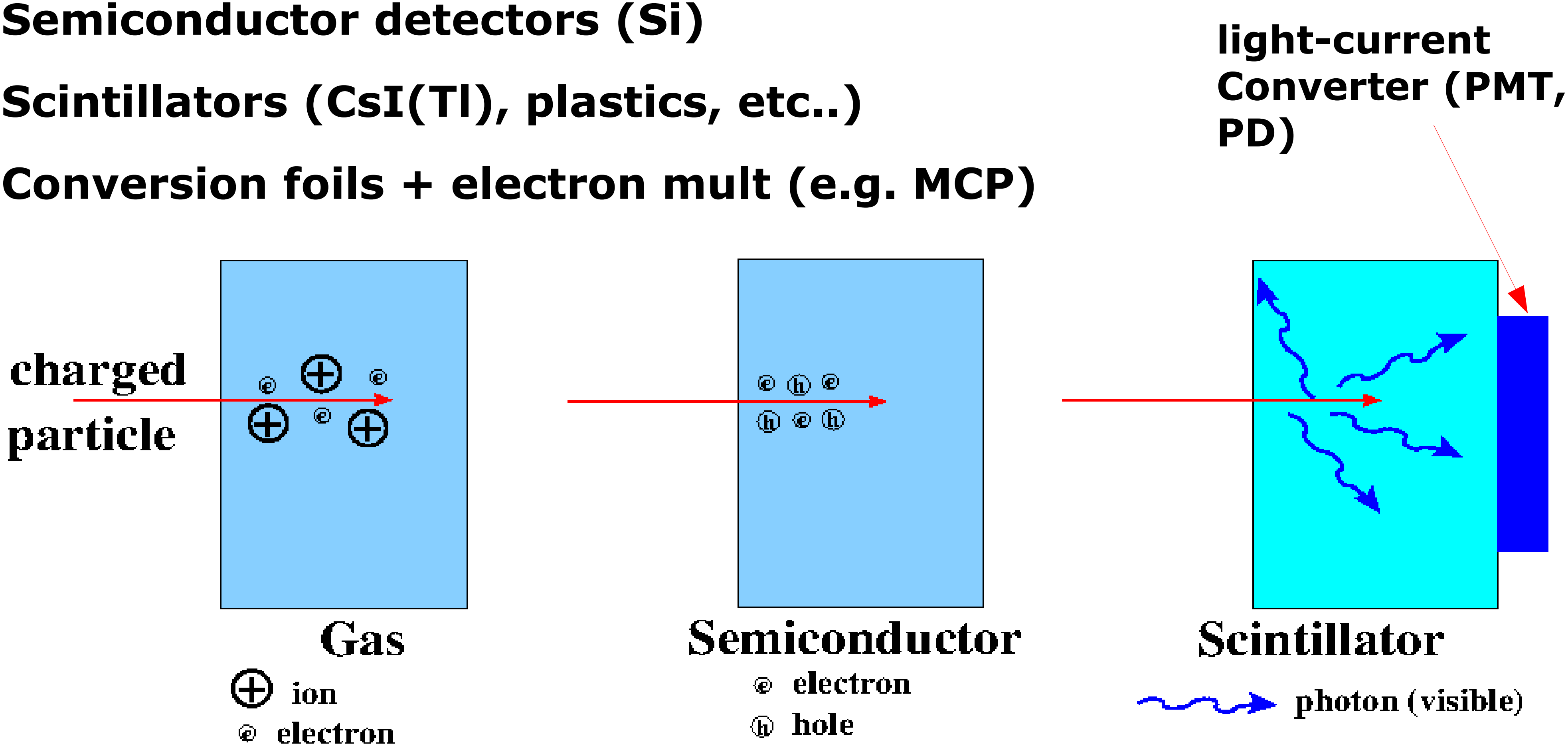

Main interaction: electrostatic with atomic electrons (ionization, excitation).

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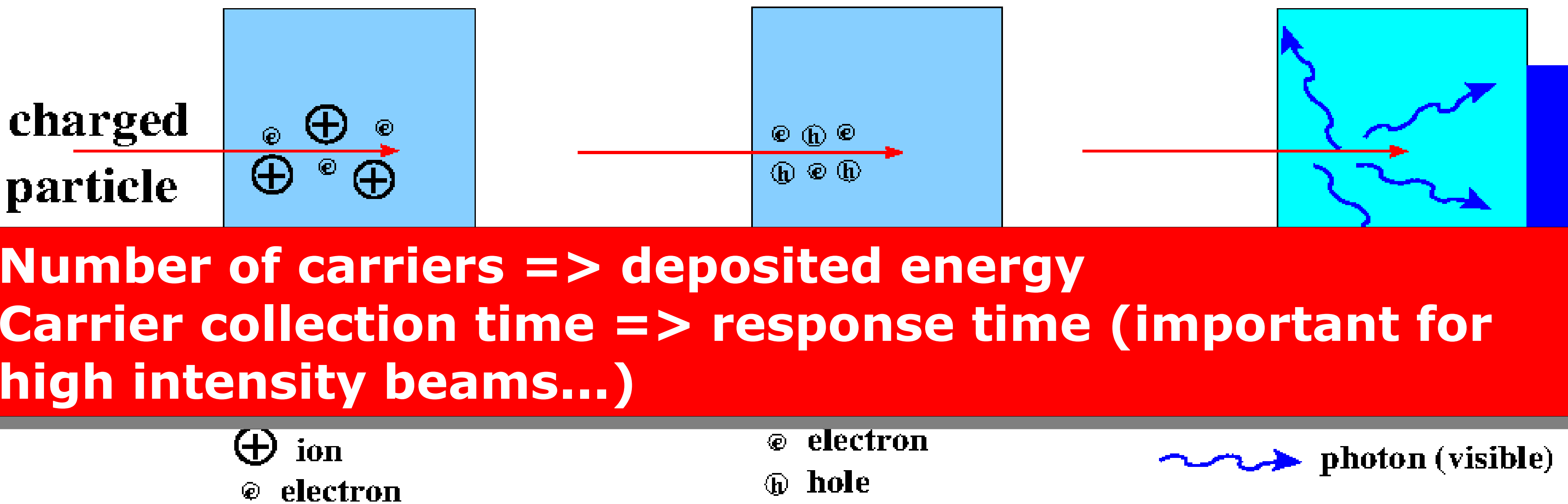

Number of carriers => deposited energy
Carrier collection time => response time (important for high intensity beams...)

Main interaction: electrostatic with atomic electrons (ionization, excitation).

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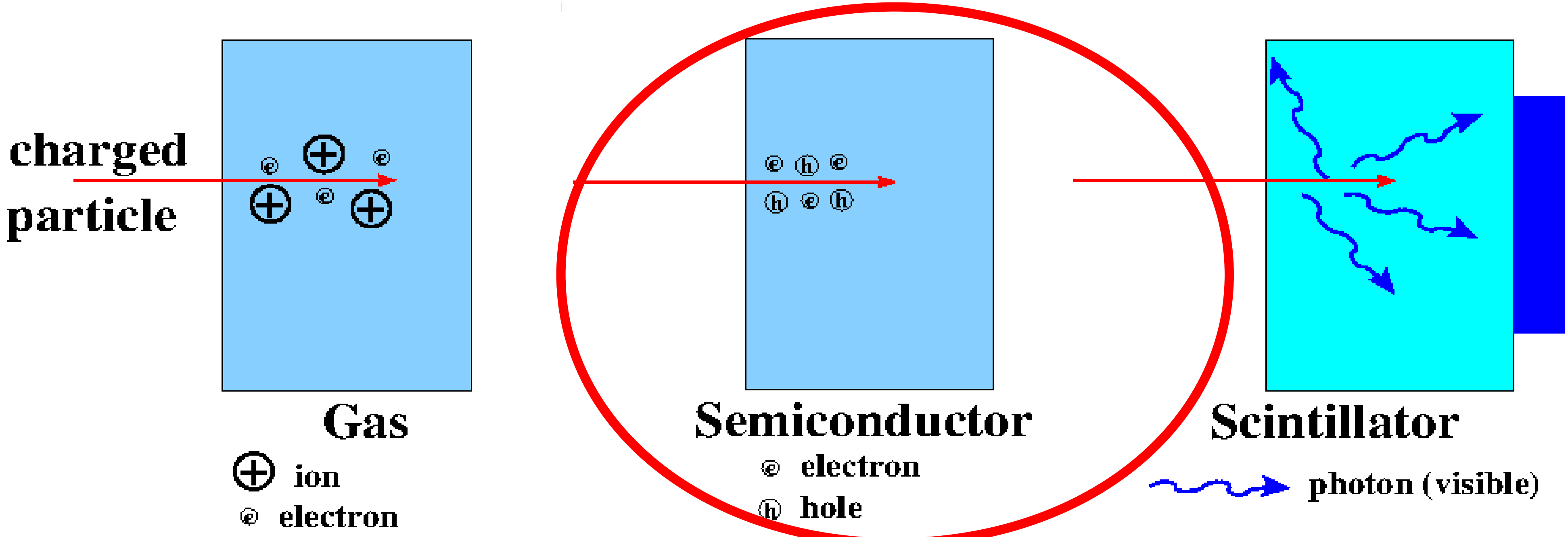

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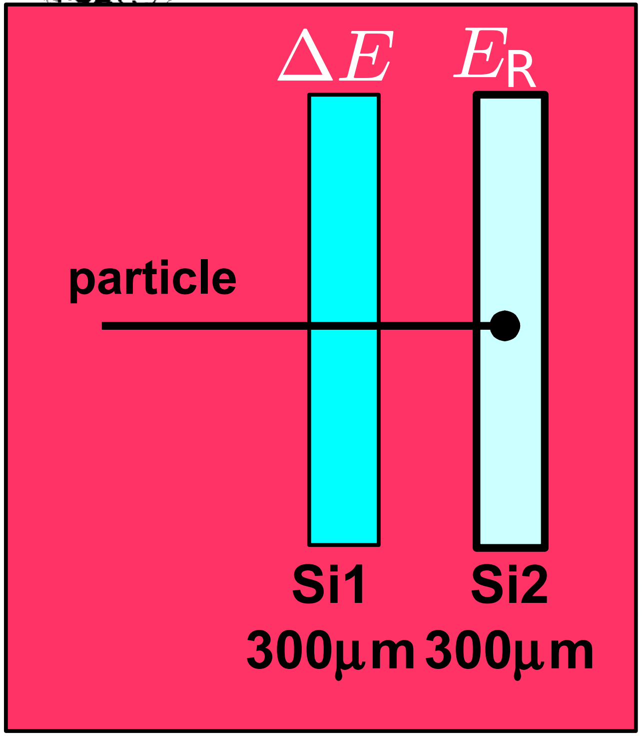
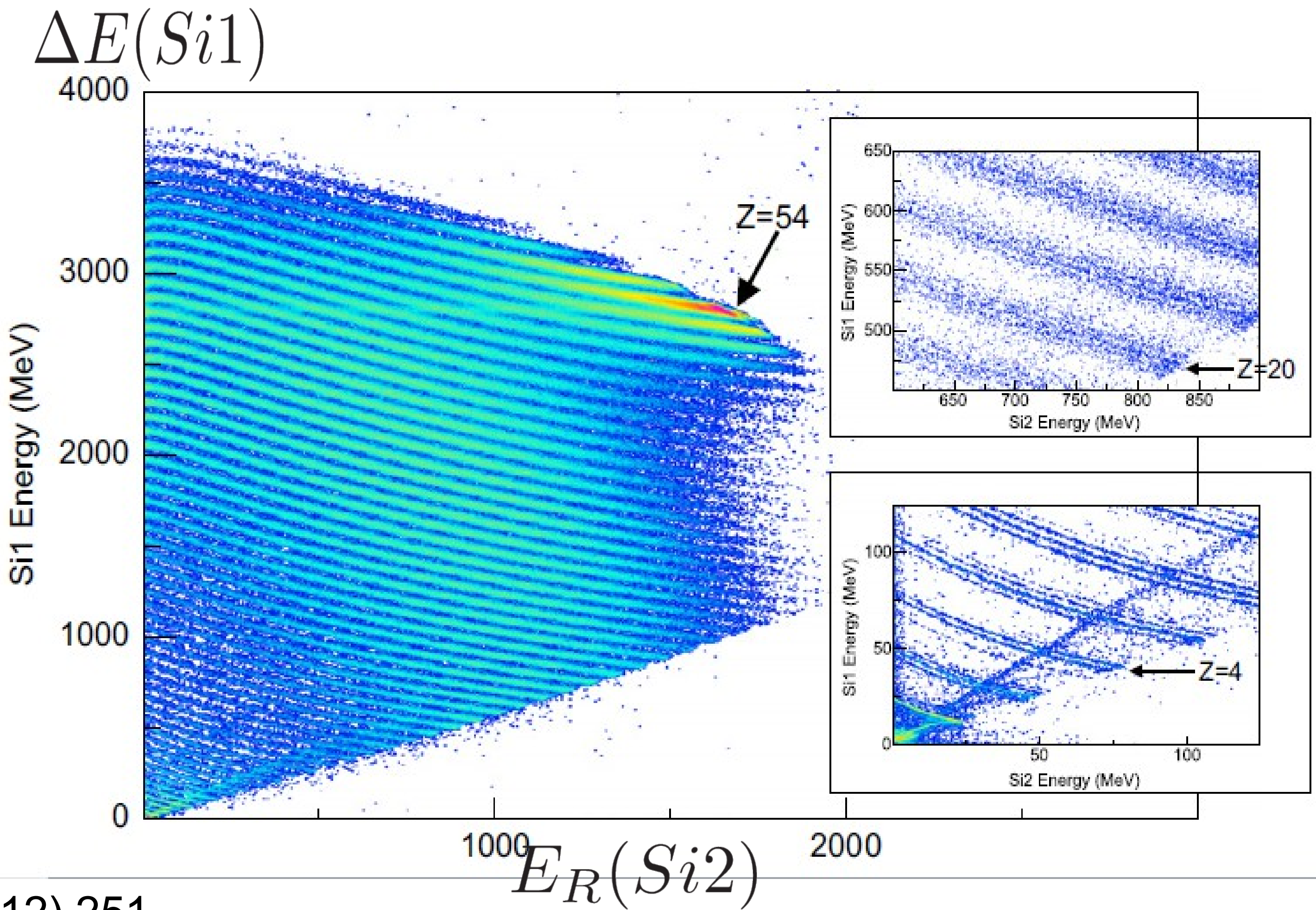
Particle Identification

Particle ID: ΔE-E telescope



$$\Delta E \times (\Delta E + E_R) \propto Z^2 A$$



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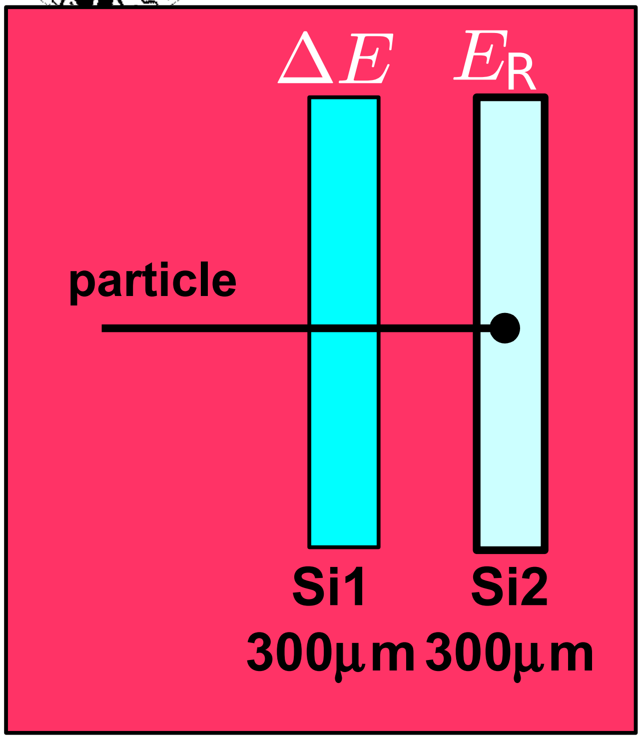
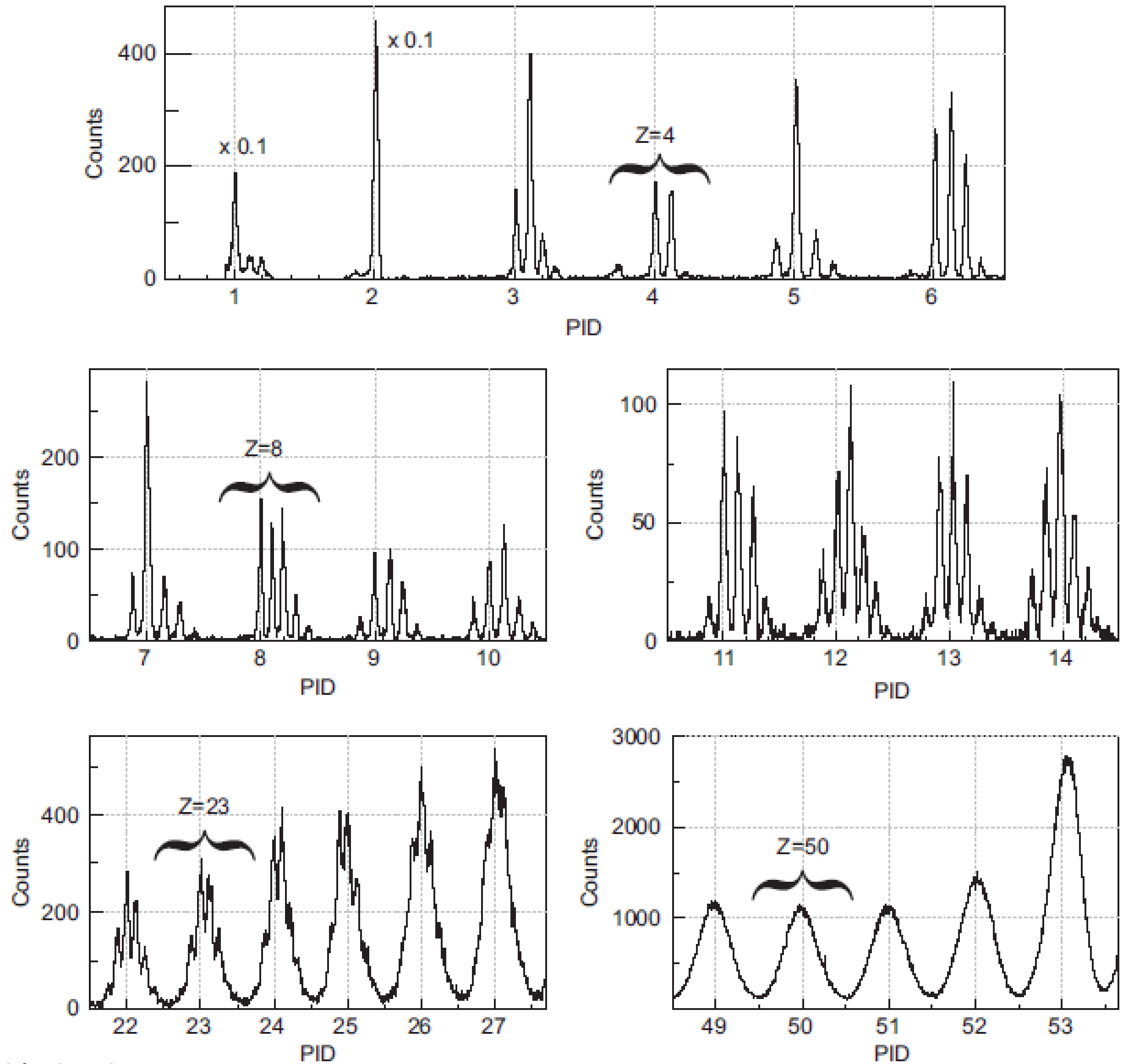
Particle ID: ΔE-E and PID





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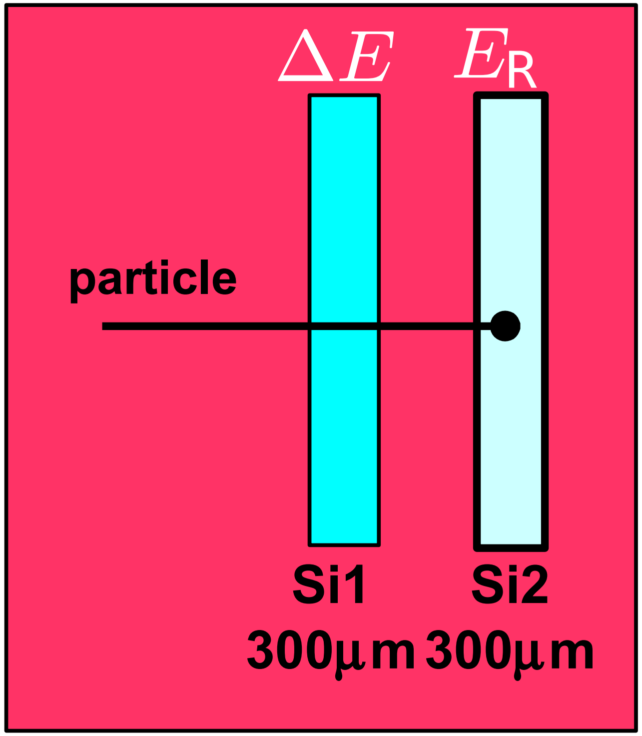

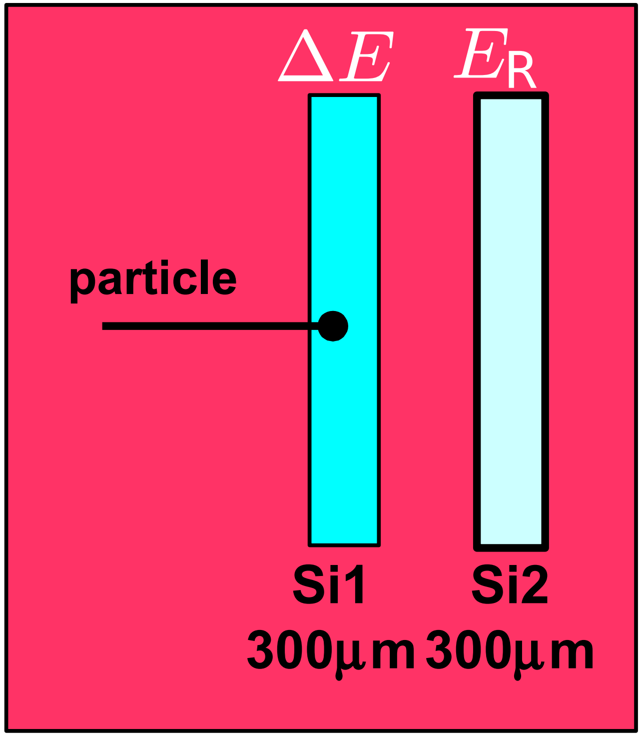

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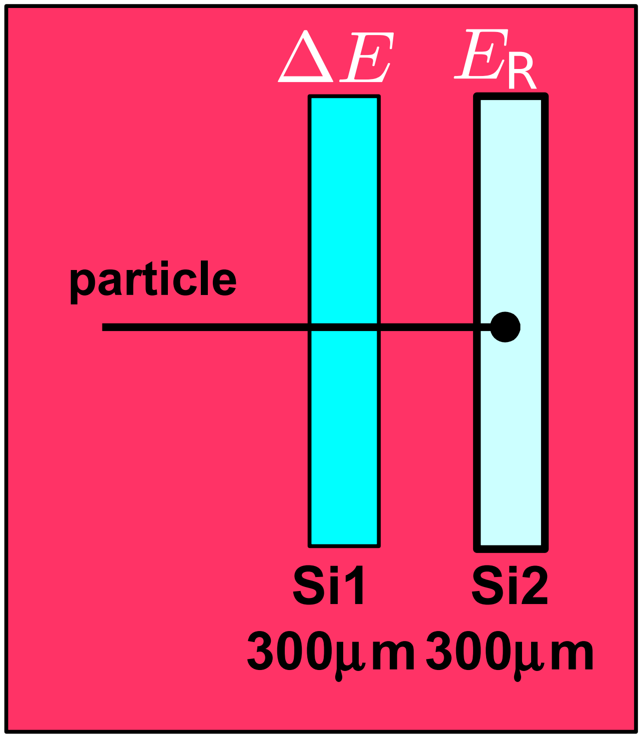
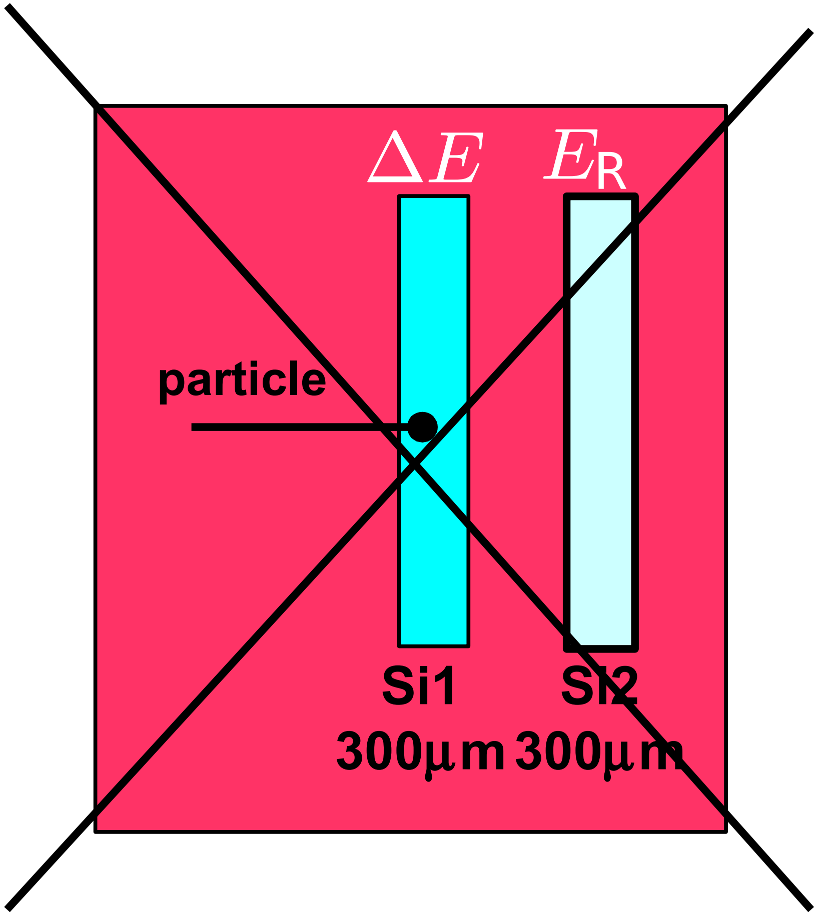
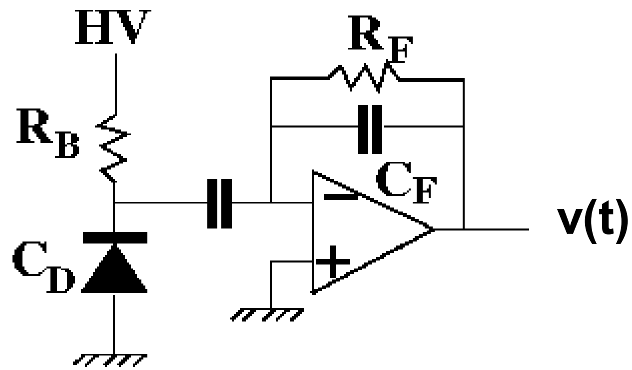
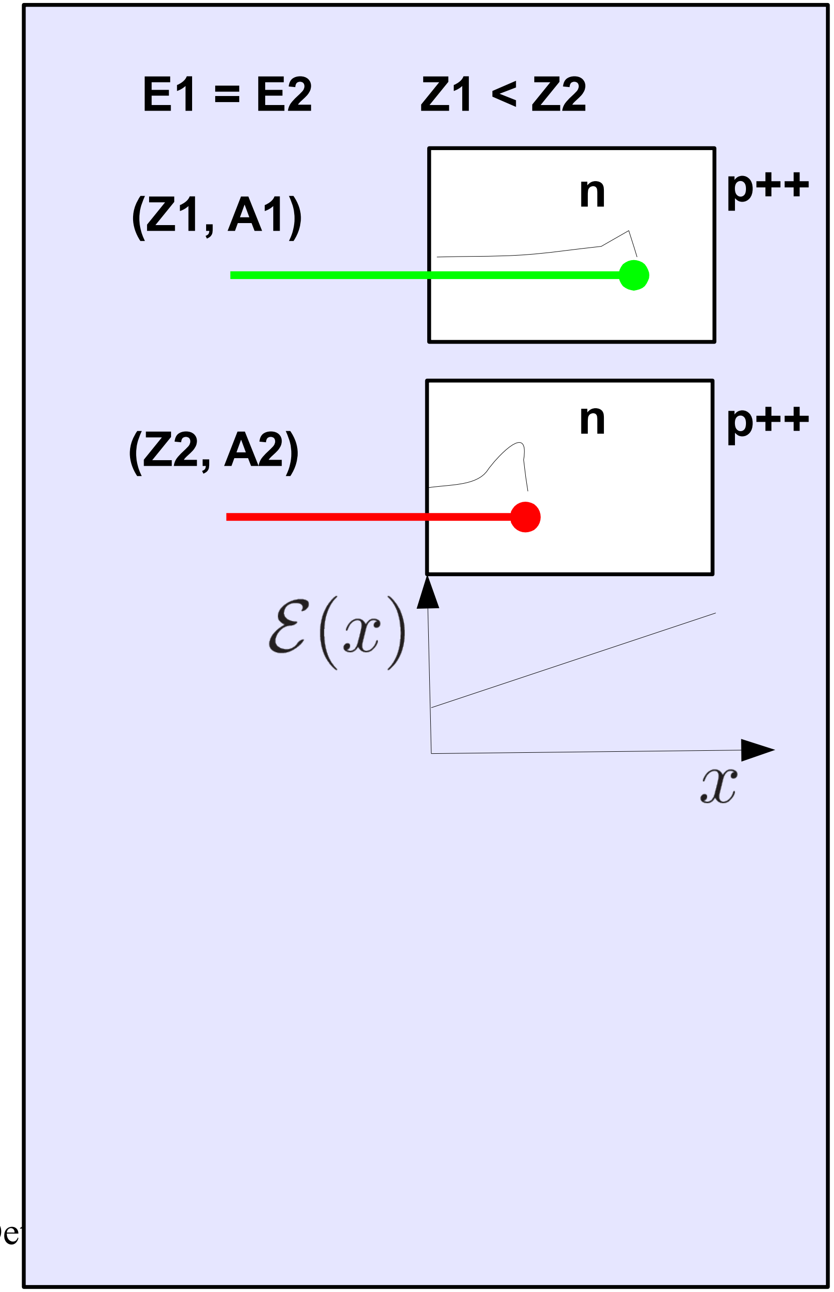




Particles stopped in first detector: no identification!

Particle ID: Pulse Shape Ident. in Silicon





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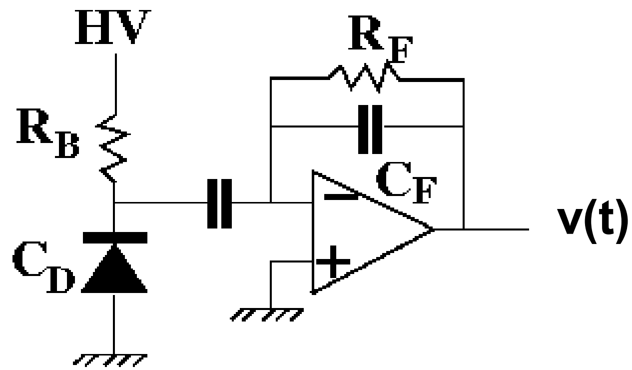

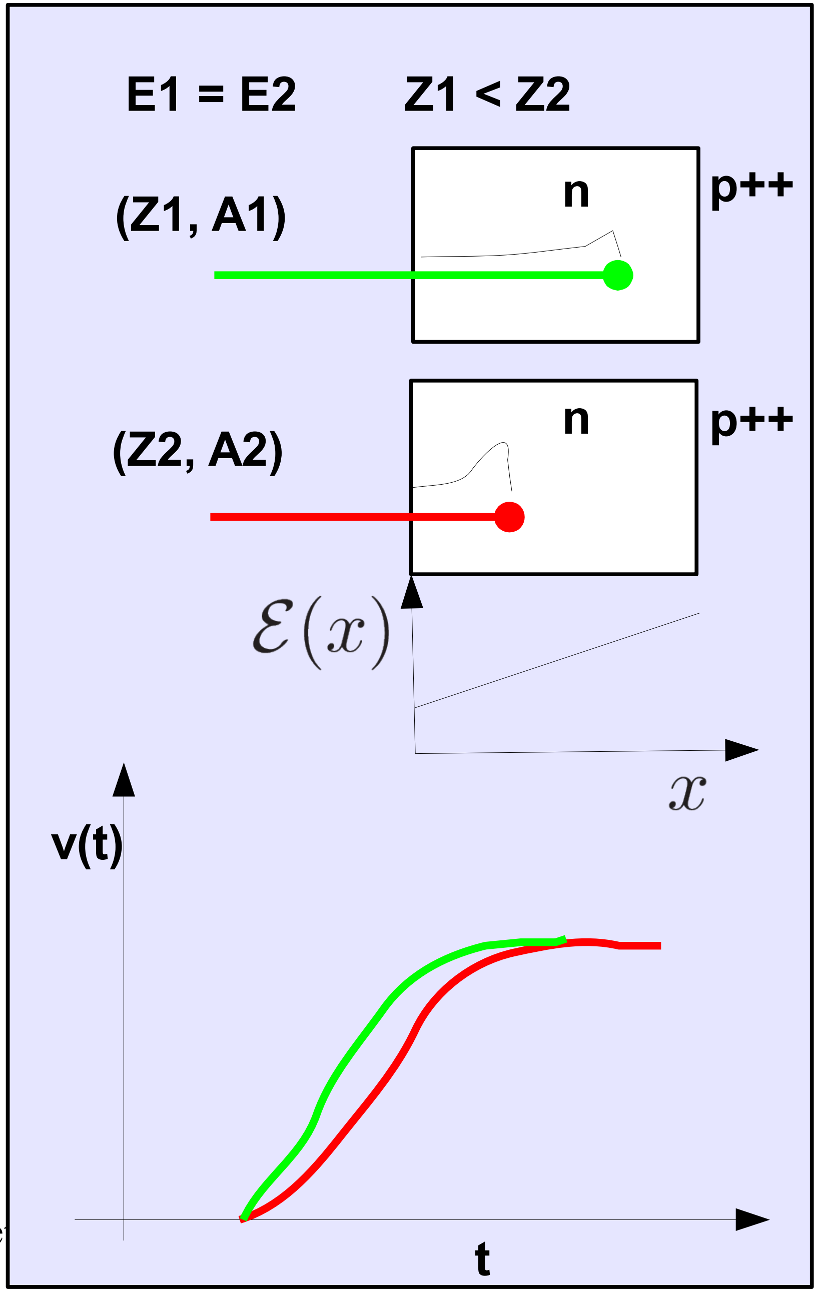

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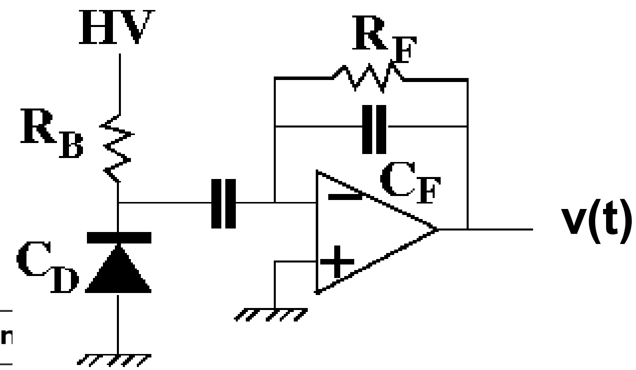

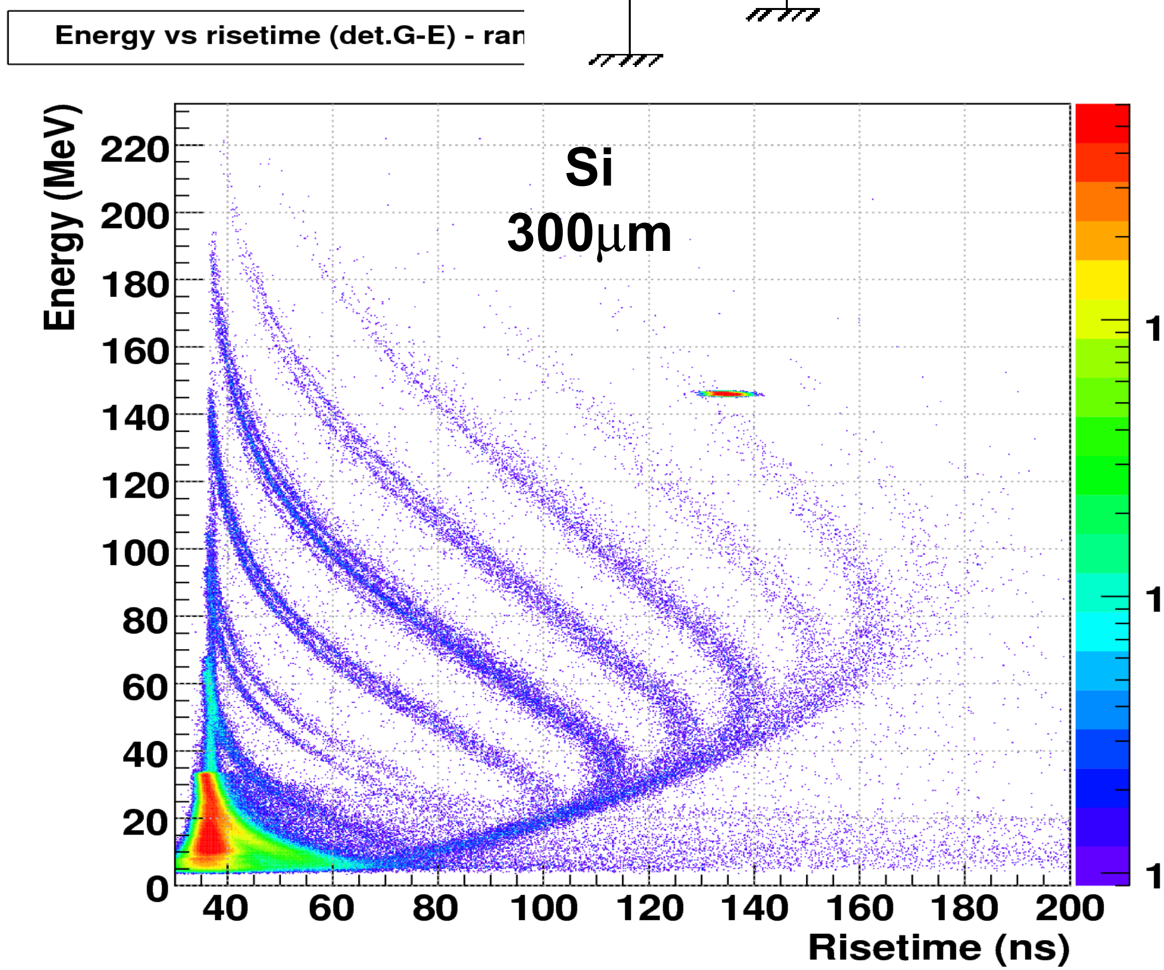

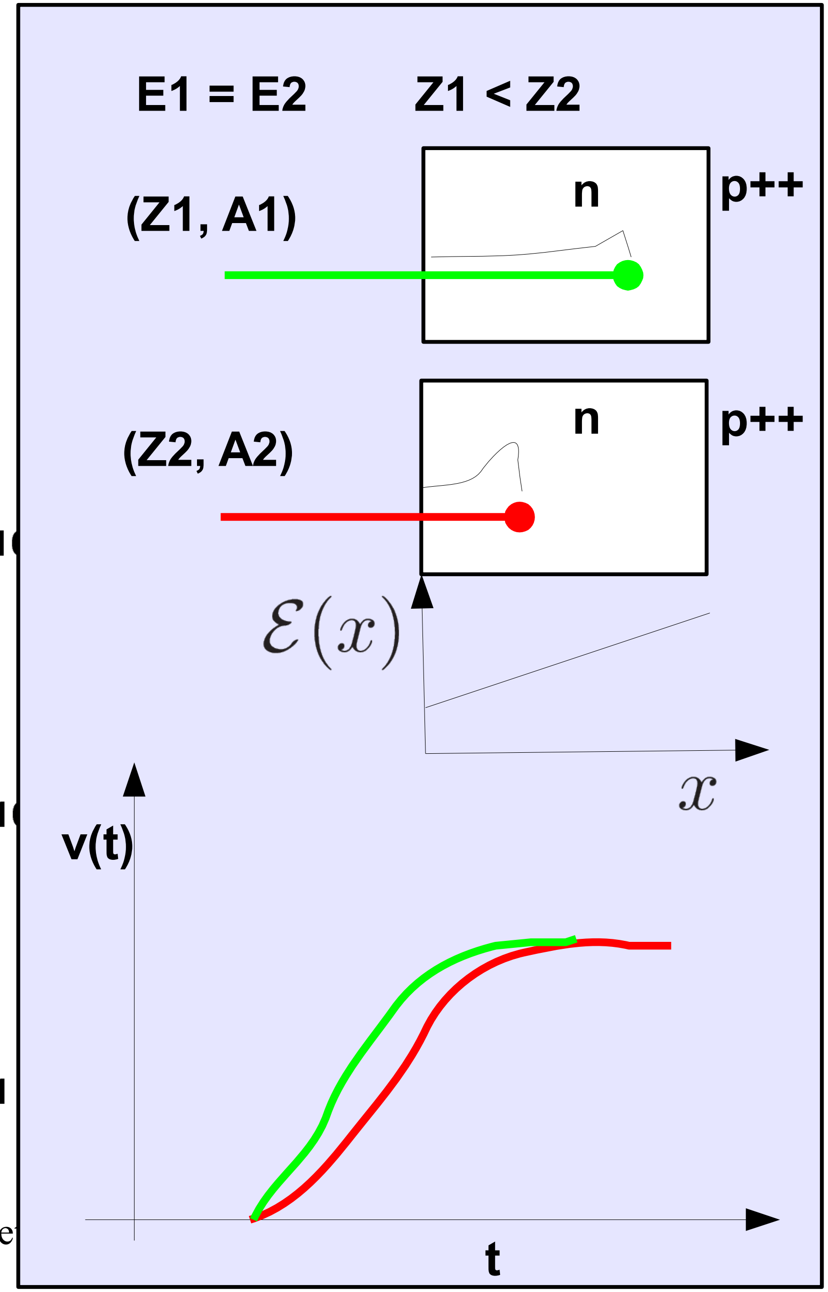

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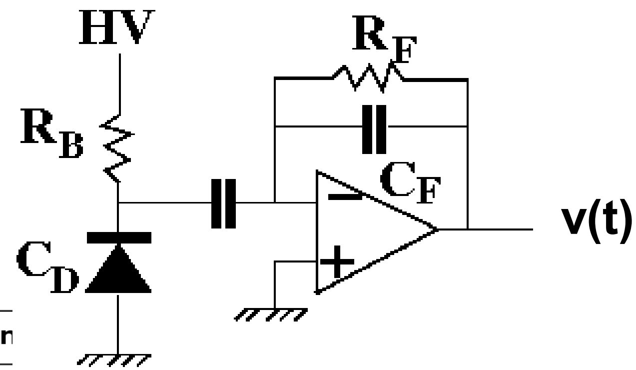
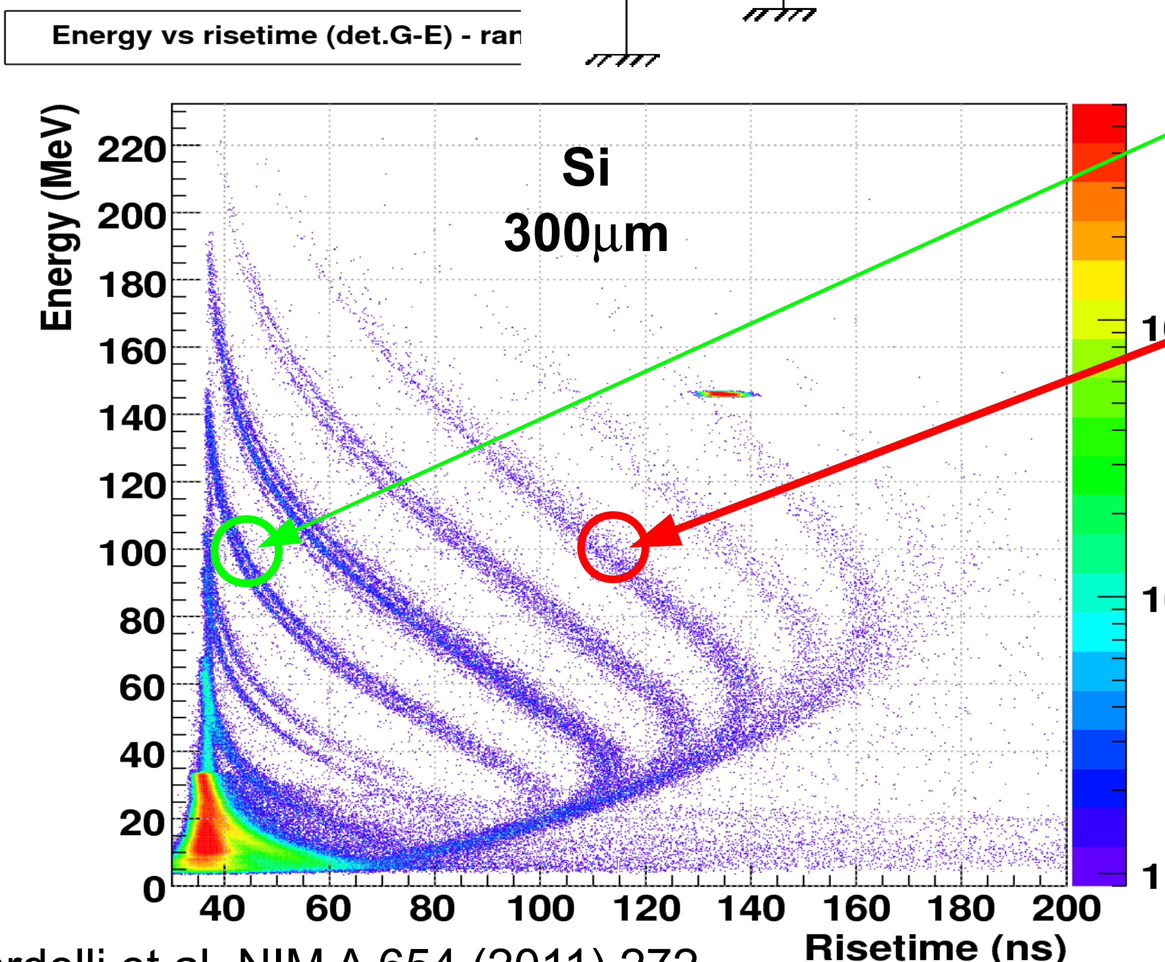
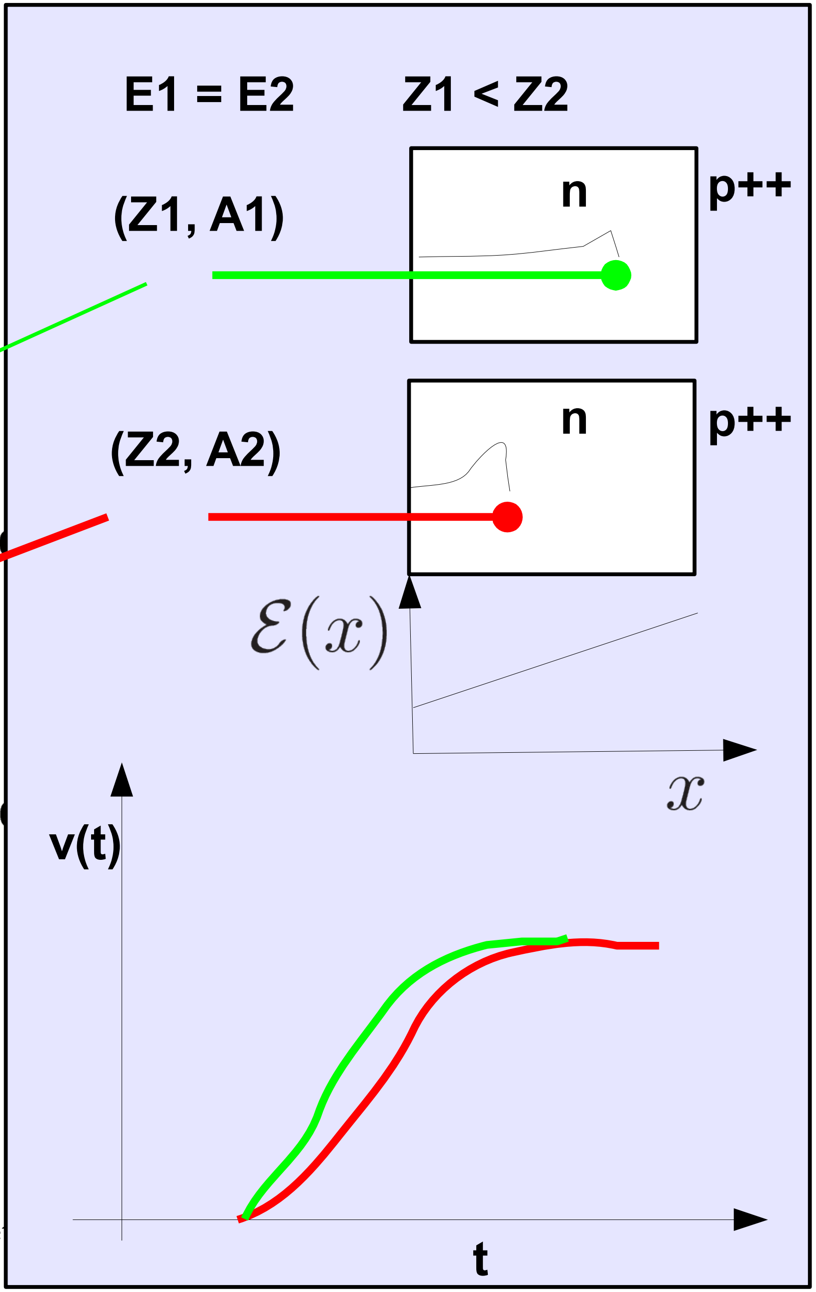






Bardelli et al. NIM A 654 (2011) 272

Limiting and degrading factors

Sensor: Energy deposition

Main interaction: electrostatic with atomic electrons (ionization, excitation).

However: NIEL also possible

Non Ionizing Energy Loss (NIEL):

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

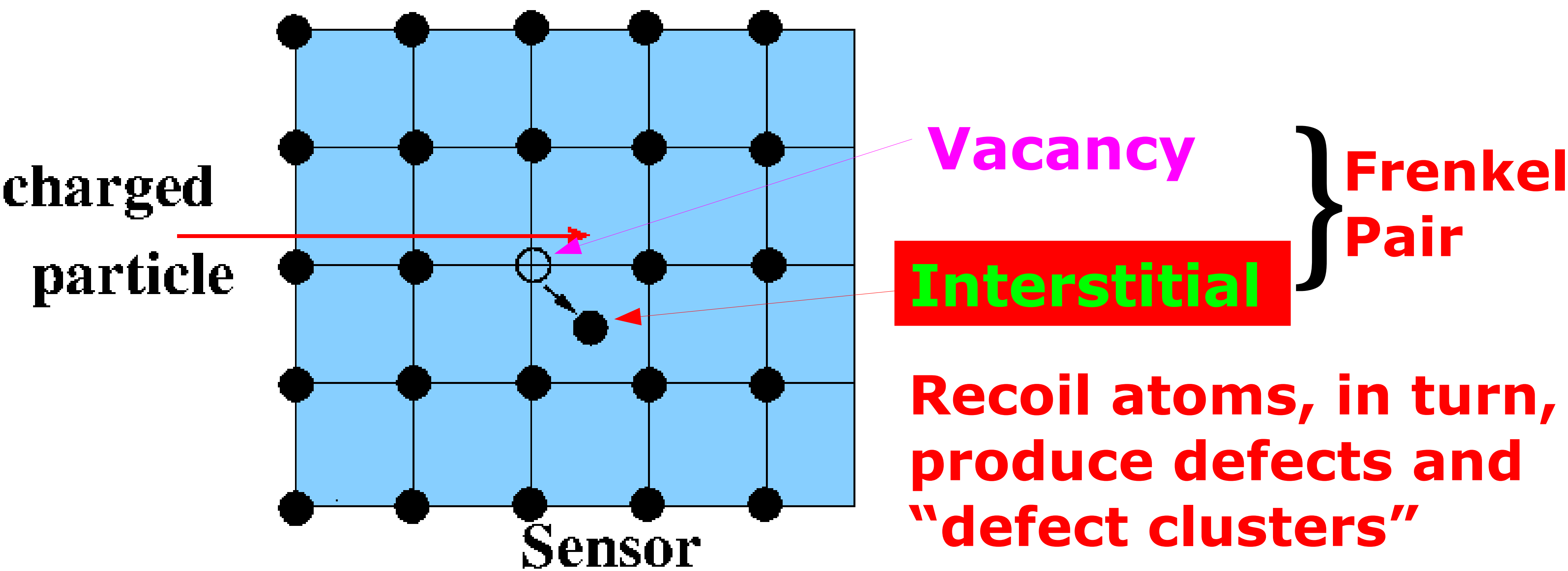
↕

Radiation Damage in lattices (e.g. silicon)

Sensor: Radiation Damage(RD)

Non Ionizing Energy Loss (NIEL) also possible:

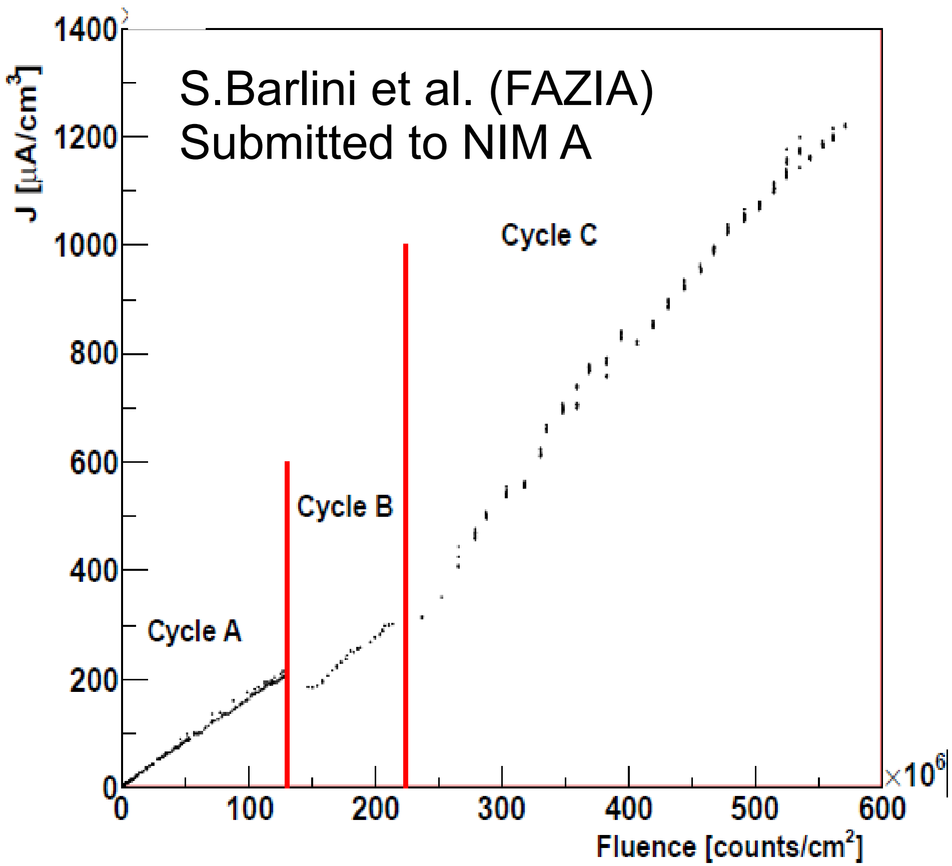
- **Rutherford scattering with atomic nuclei**
- **Nuclear reactions with atomic nuclei**

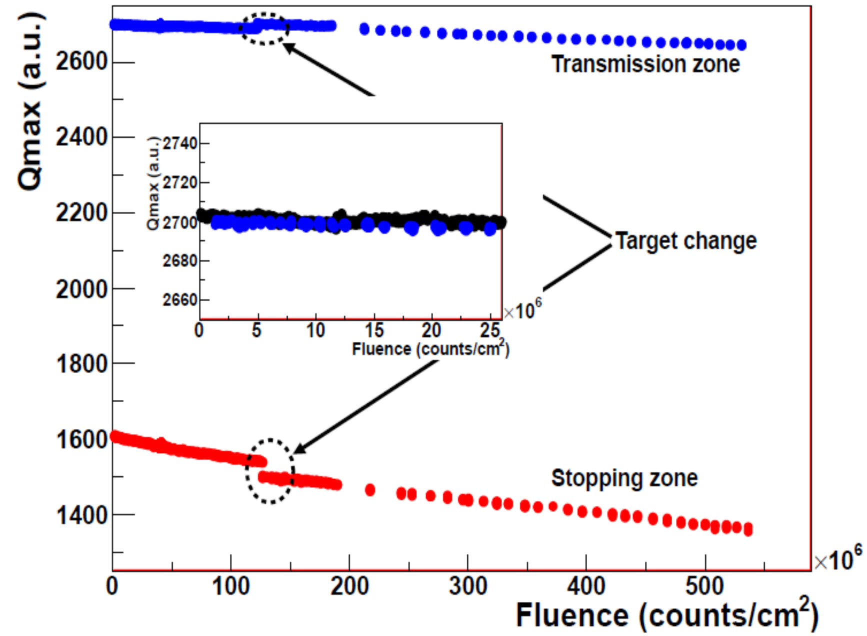


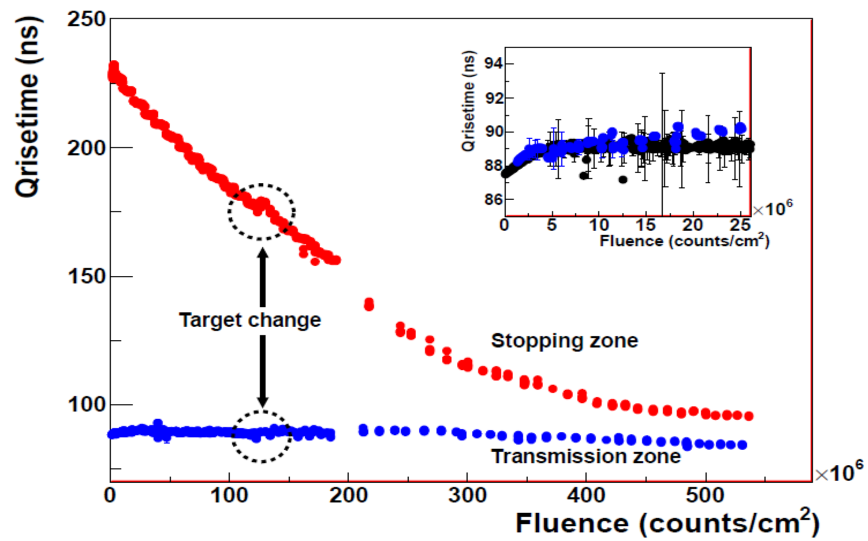
Recoil atoms, in turn, produce defects and "defect clusters"

Sensor: Effects of RD

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







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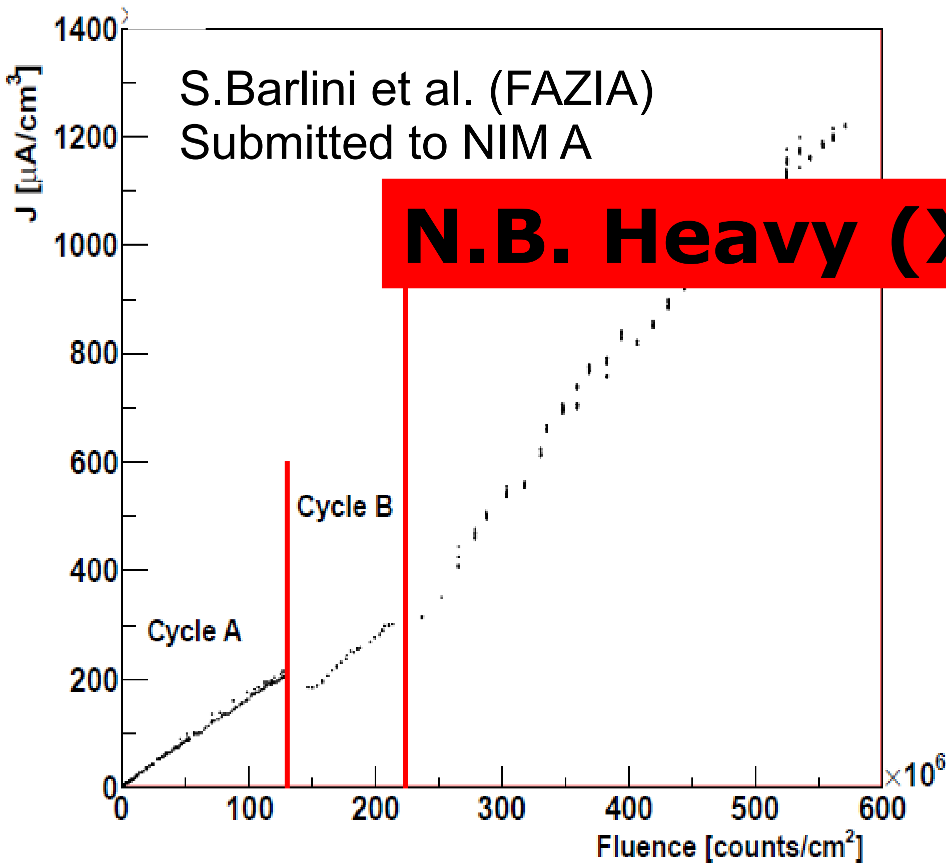
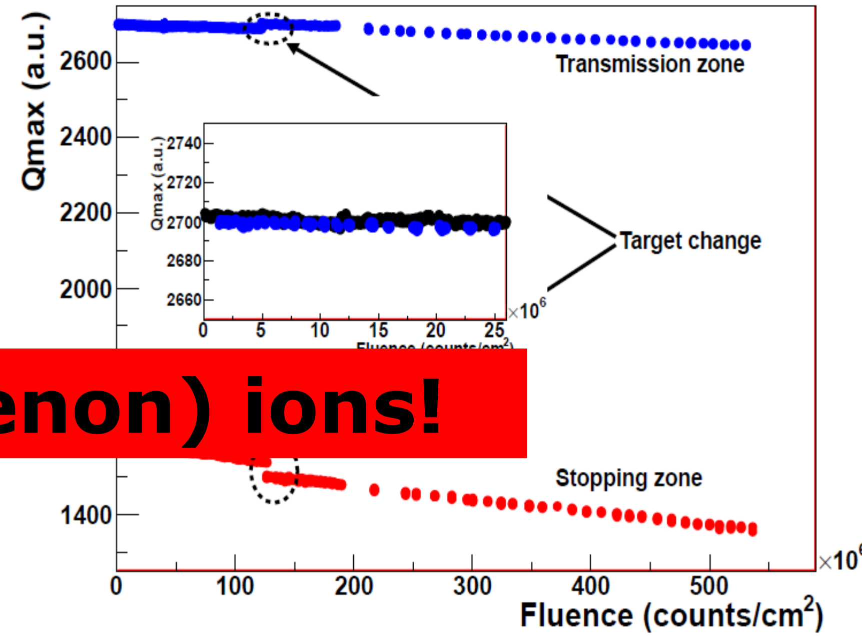
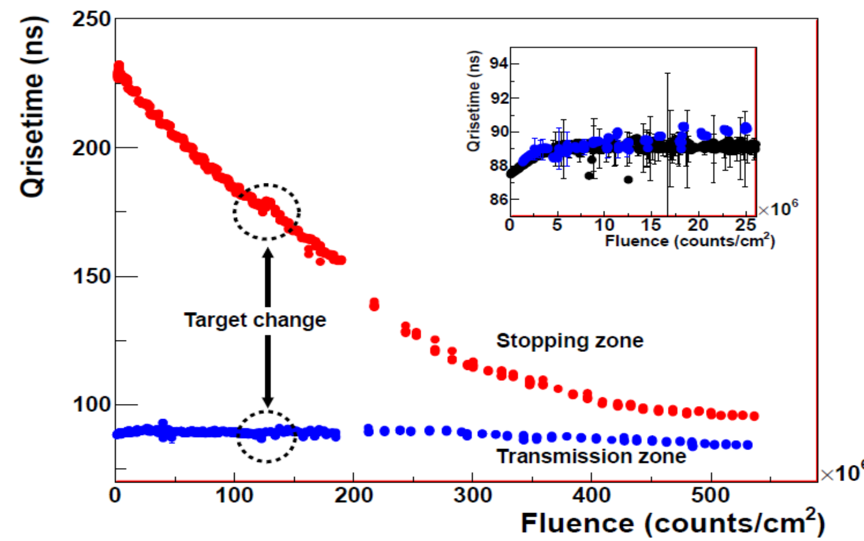


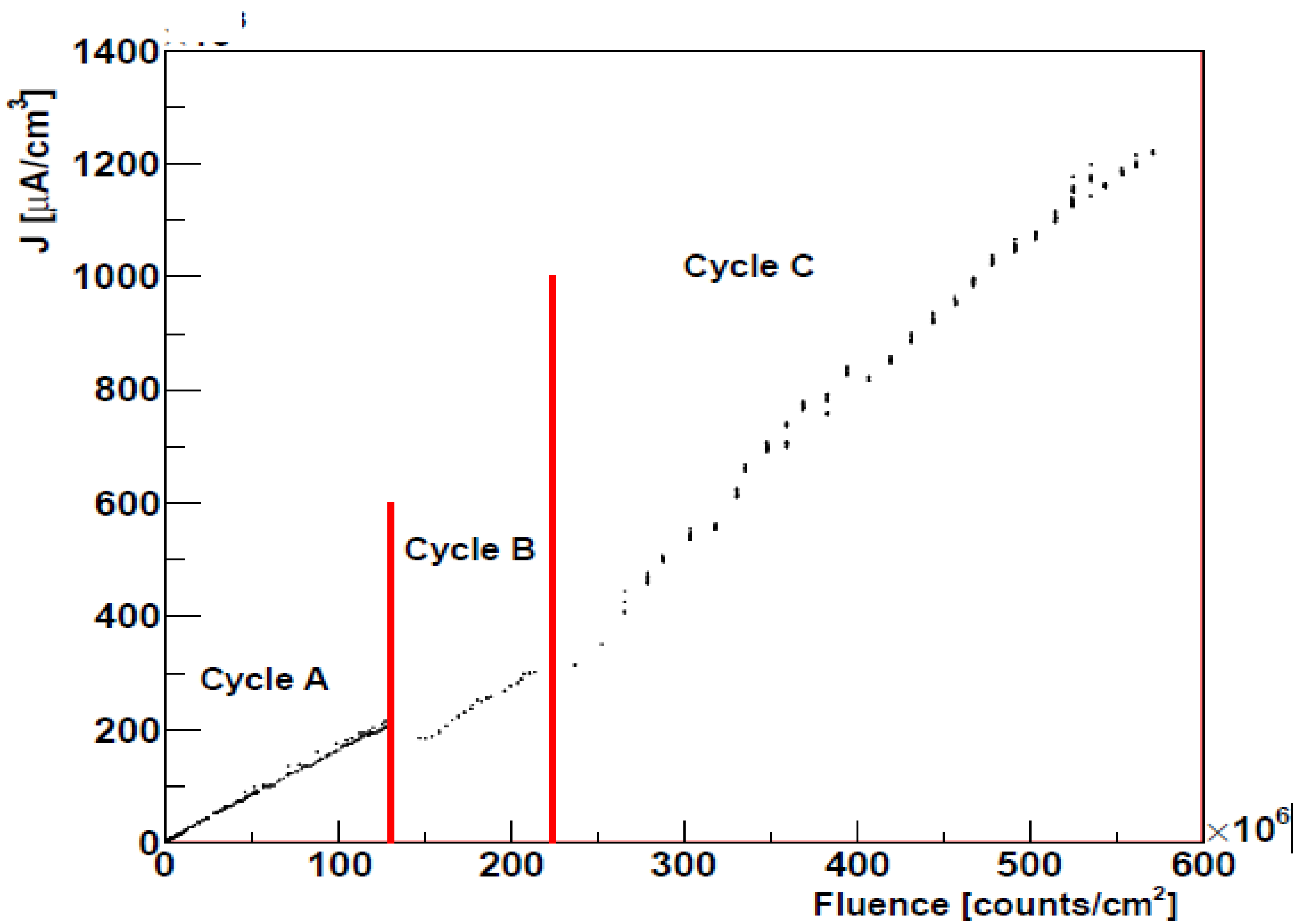


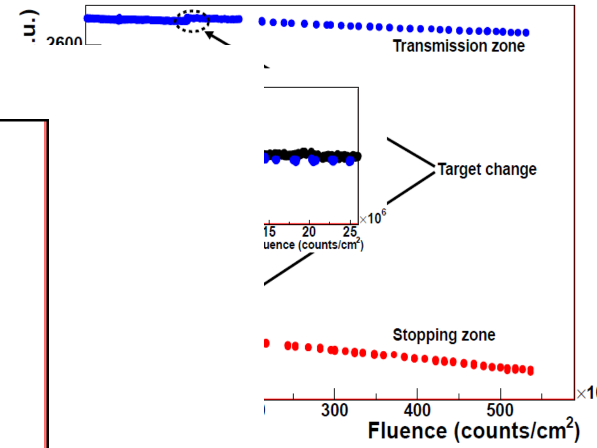
N.B. Heavy (Xenon) ions!

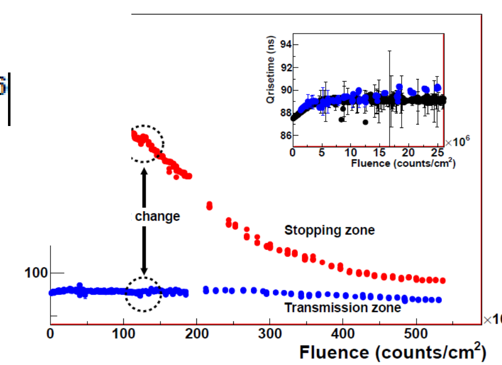


Sensor RD: leakage current

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

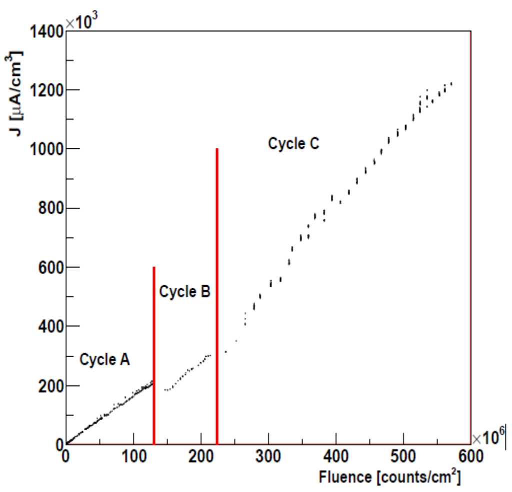






Sensor RD: collection efficiency

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



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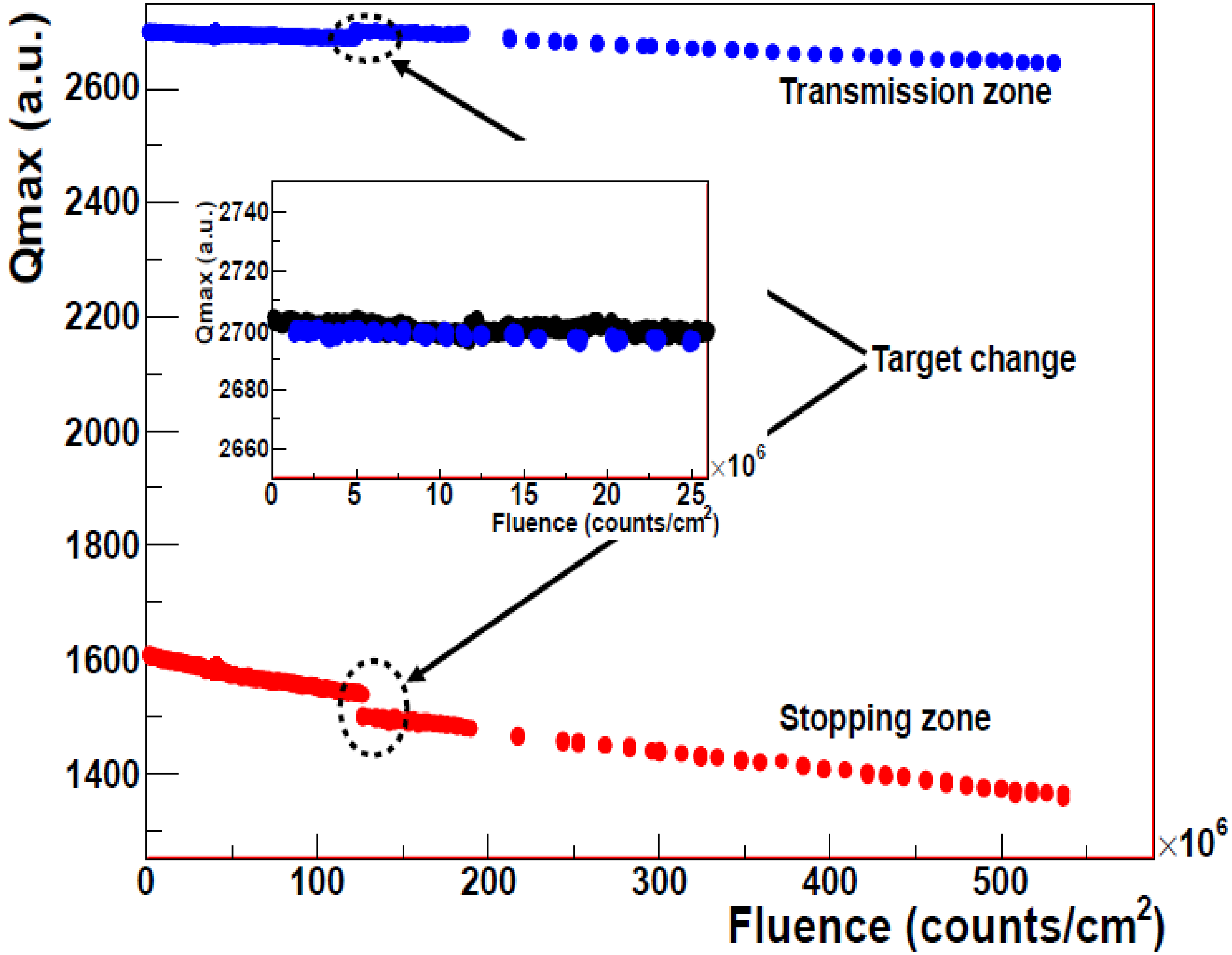
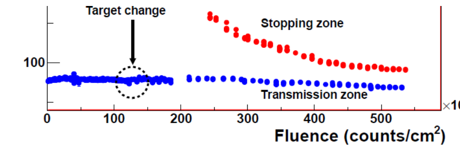
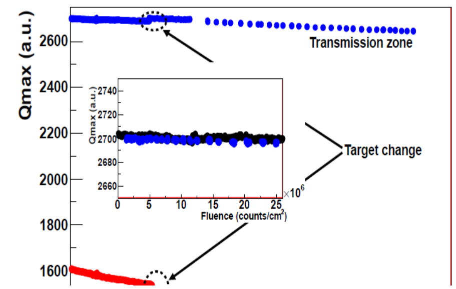
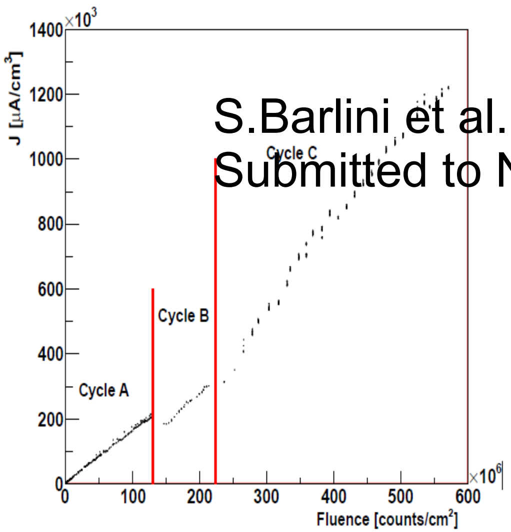




Sensor RD: collection time

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





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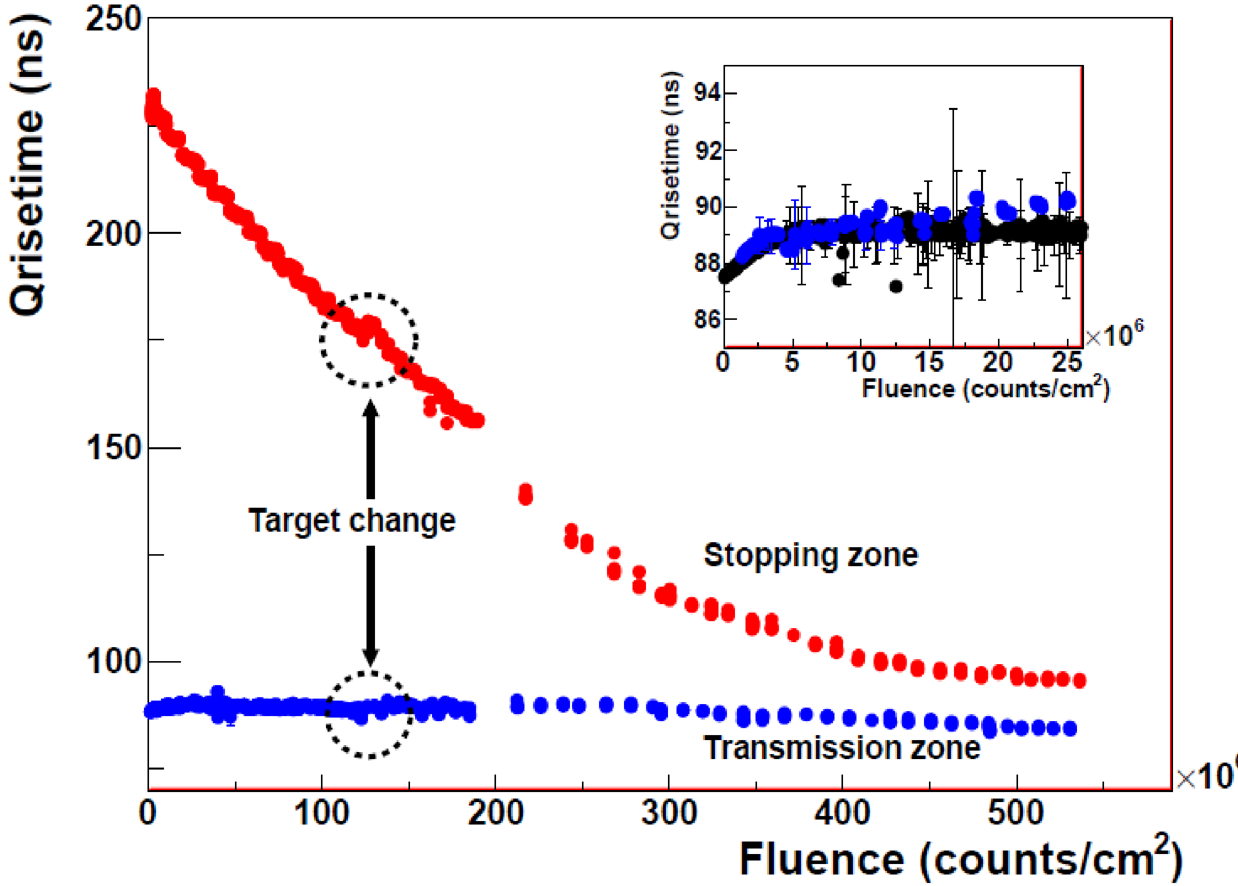
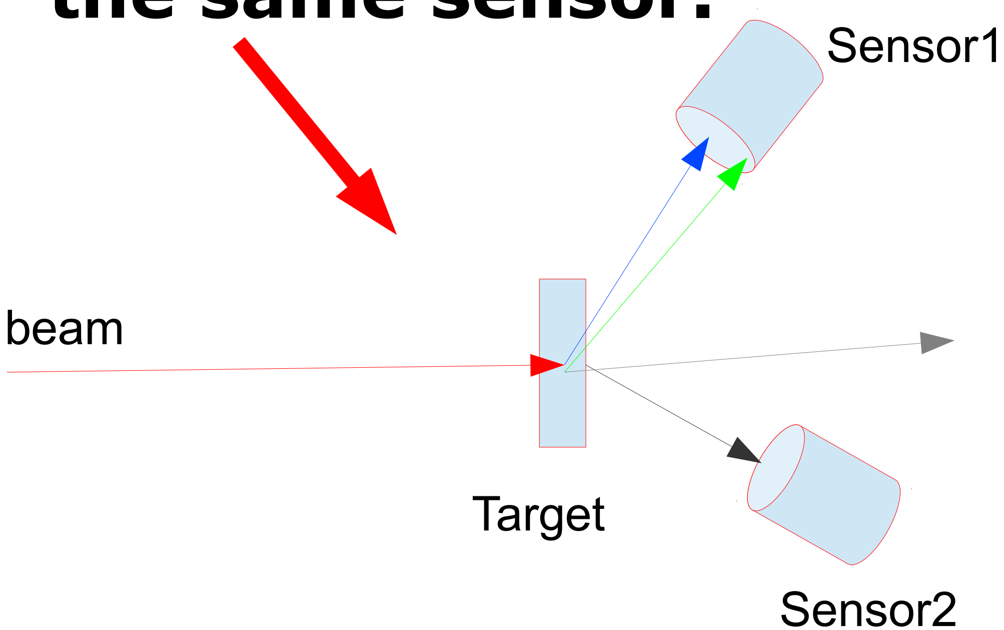


ECOS 2012 18-21 June 2012

Multiple hits and Pile-Up

Multiple Hit: **"true" coincidence. Two particles from the same projectile-target interaction hit the same sensor.**



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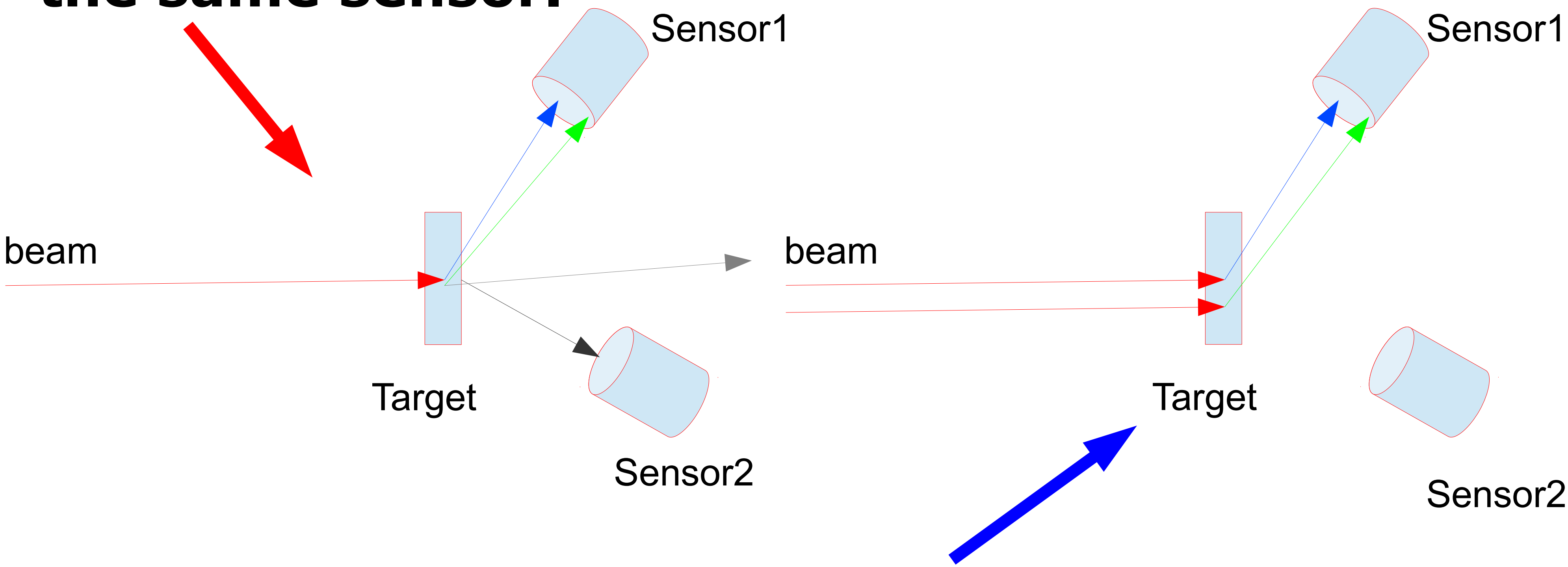
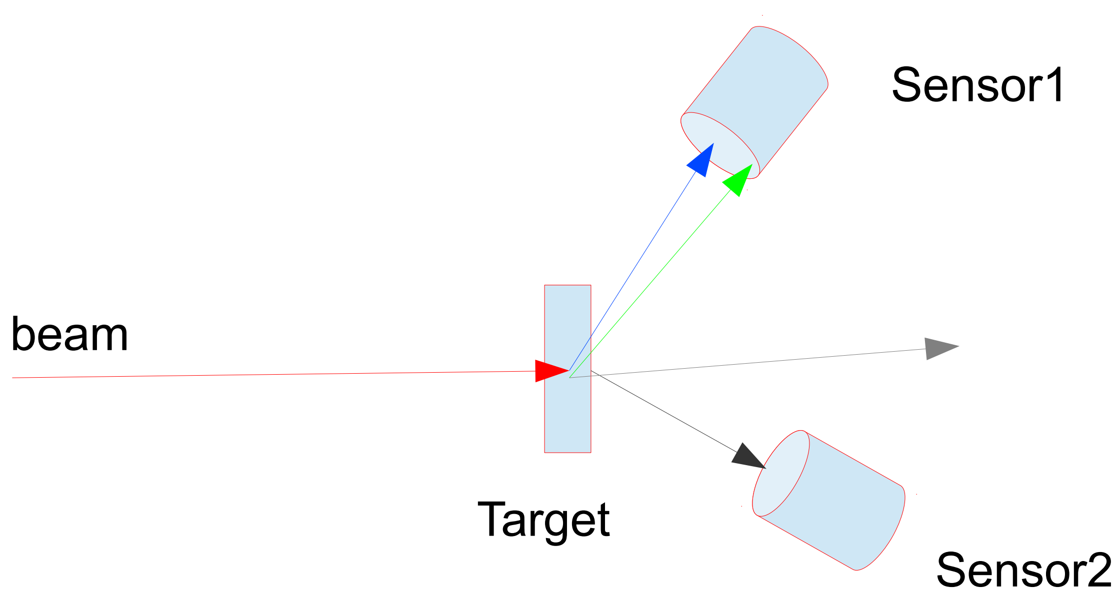


Pile-Up: a "chance" coincidence. Particles from two distinct projectile-target interactions hit the same sensor.

<u>Sensor: Multiple Hits</u>

Multiple Hit

Probability: depends on sensor detection efficiency (e.g. Solid angle), event multiplicity…<u>does not change with event rate (i.e. Beam intensity)</u>



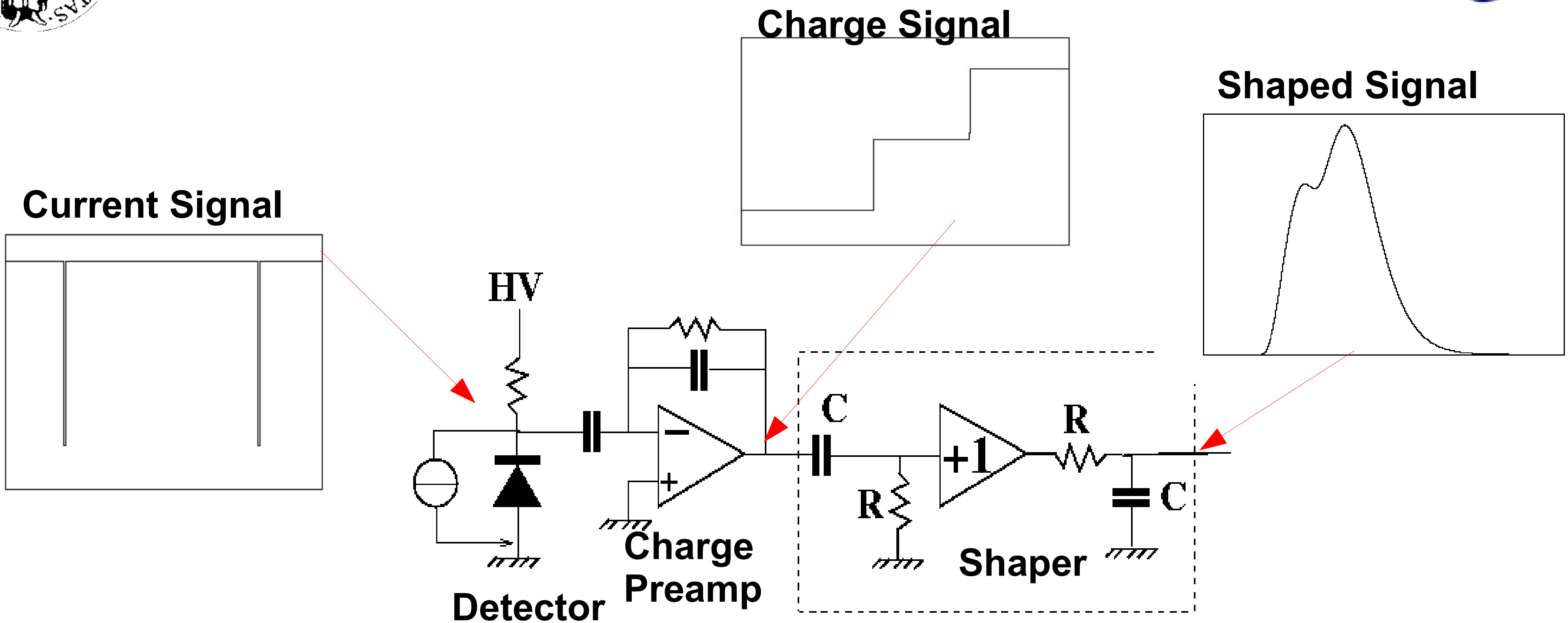
Time scales, mult.hits, pile-up

Times involved:

- **Time of Flight difference among particles (from one to tens ns depending on velocity and distance)**
- **Charge collection time (e.g. 10-100ns in Si)**
- **FEE resolving time (e.g. Shaping time constant, integration gate duration,…)**

optimise SNR => BW limit in FEE => FEE time usually dominates the resolving time

FEE: Pile-Up and high rate



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$$P_{pu} = (1 - e^{-RT})$$

FEE: How-to deal w/Pile-Up

$$P_{pu} = (1 - e^{-RT}) \approx RT \quad \text{if} \quad RT << 1$$

$$\text{Pile-Up events/s} = R \times (RT) \propto R^2$$

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Once pile-up has occurred we can:
1) ignore it (if we know they are few)
2) recognize and discard
3) recognize and disentagle (DSP methods)

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3) reduce sensor area

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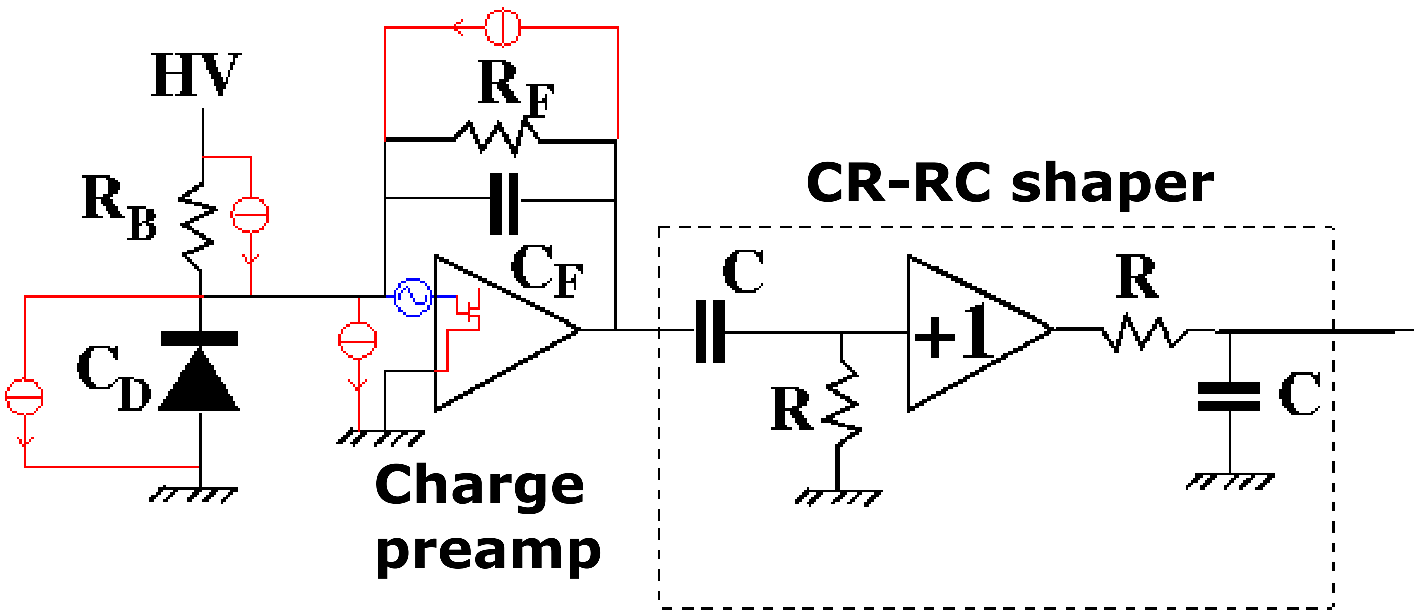
Smaller solid angle Ω

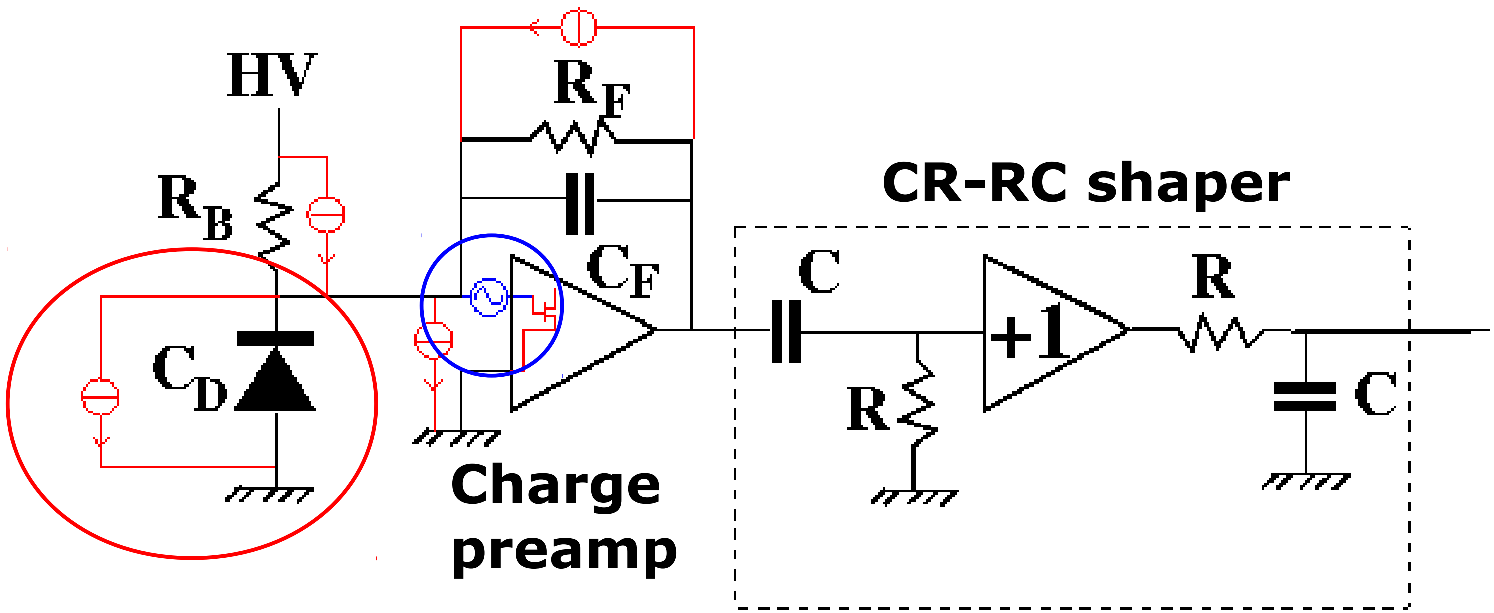
FEE: Electronic noise



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

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

FEE: Electronic noise



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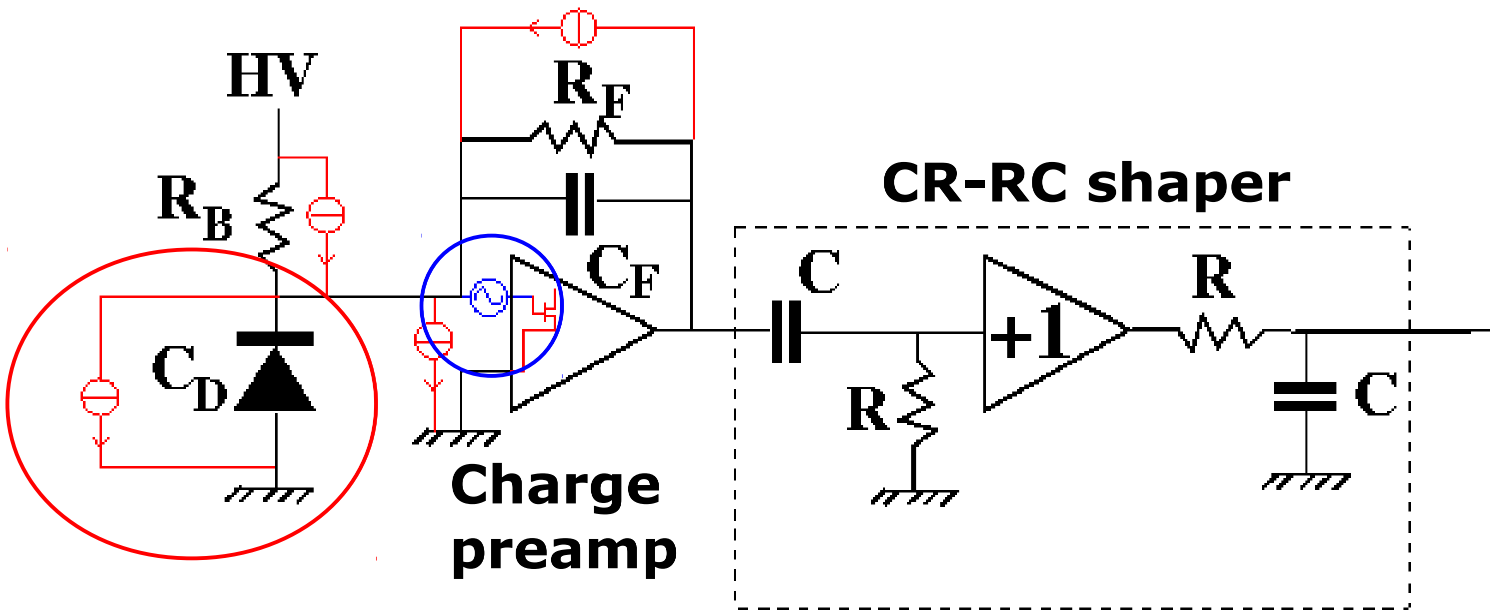


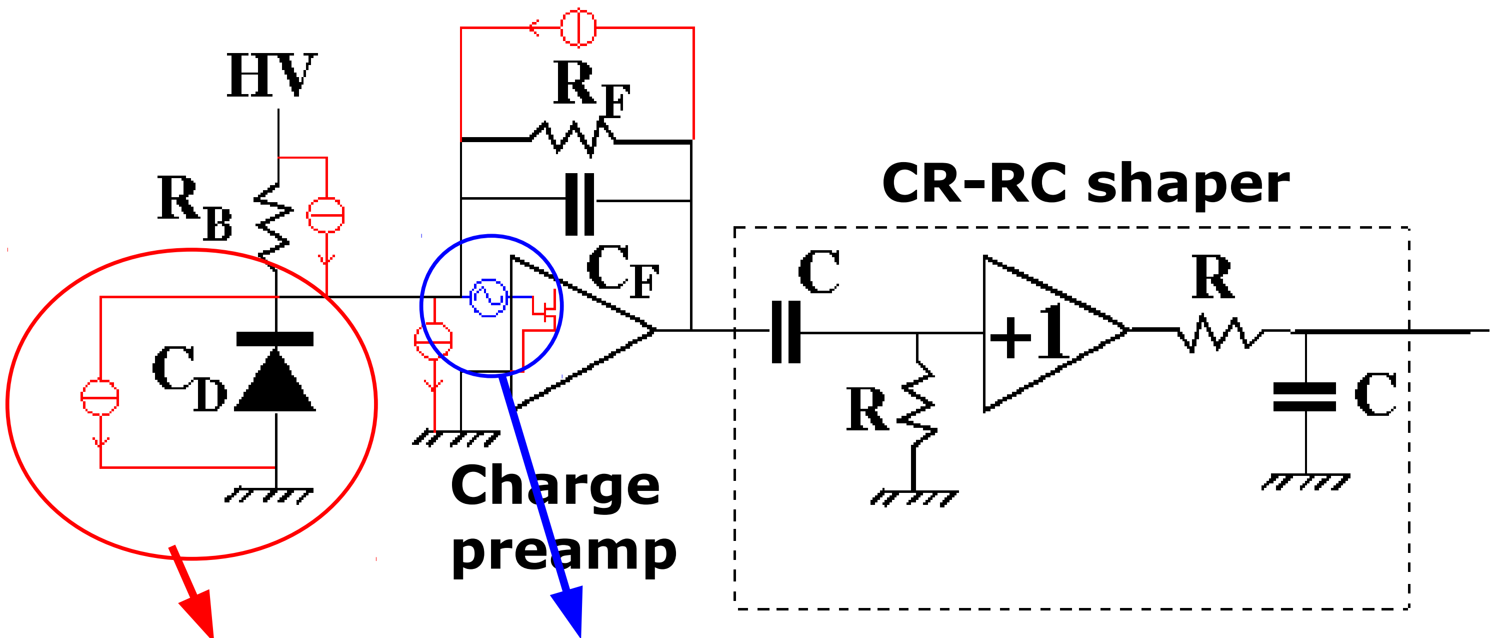
$$Q_n^2 = i_n^2\,\mathcal{F}_i\,T_s + e_n^2\,\mathcal{F}_v\,\frac{C_{in}^2}{T_s}$$

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



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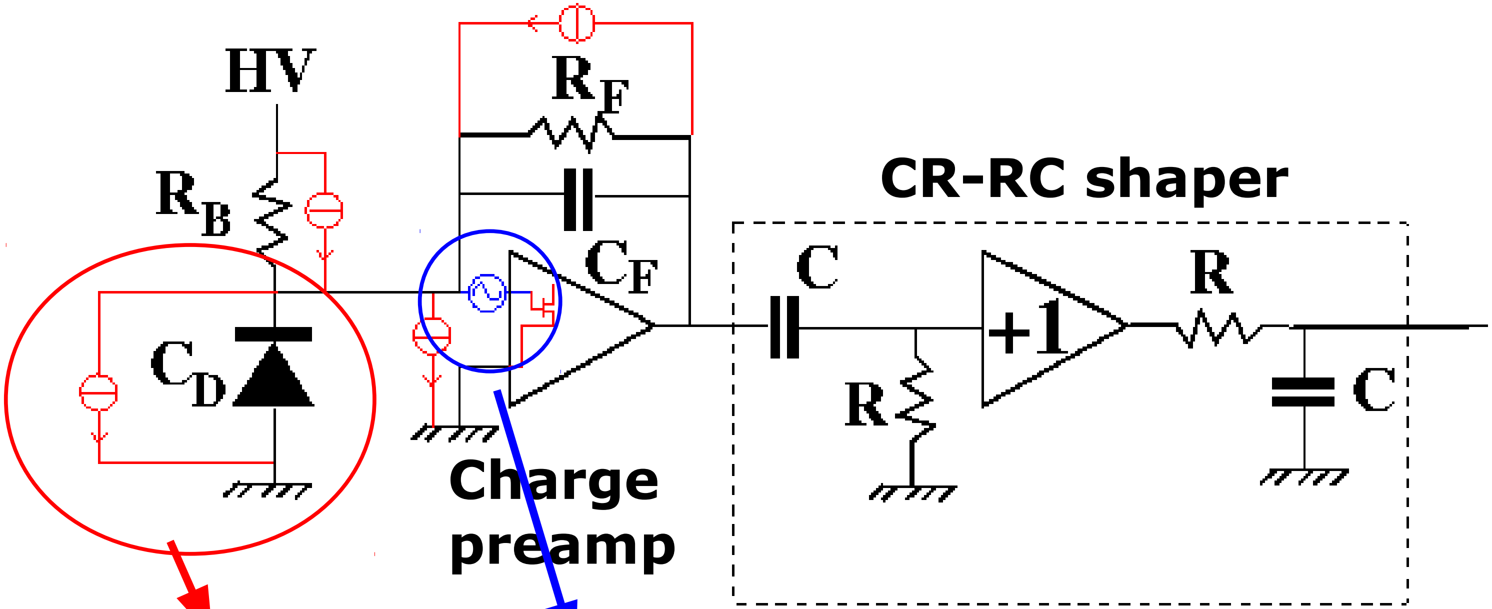

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$$i_n^2$$

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

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

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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**

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

FEE: Electronic noise

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

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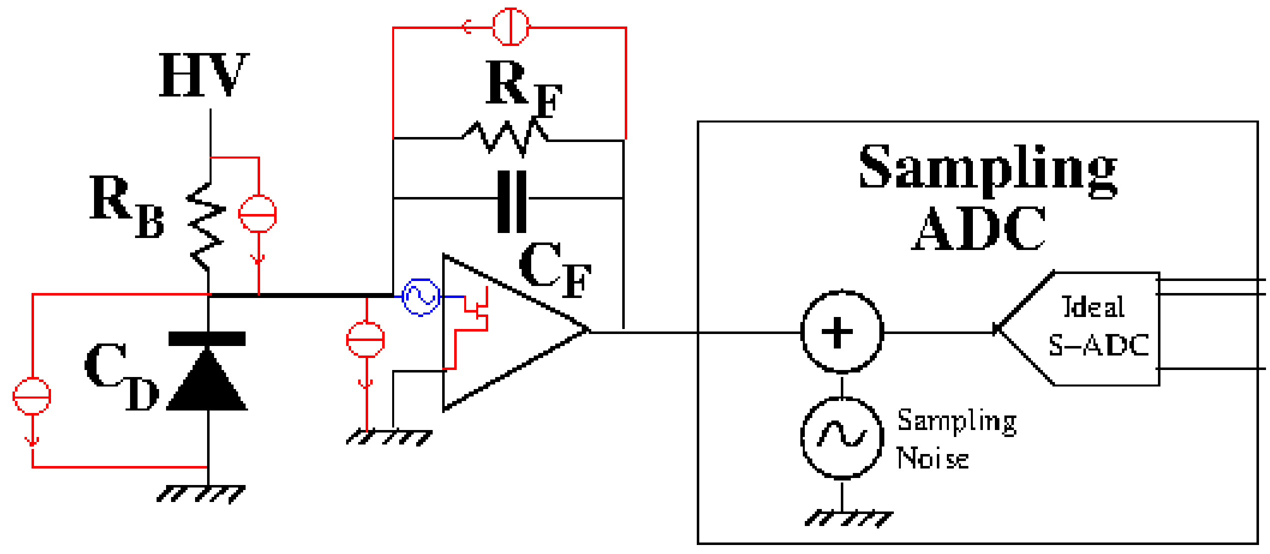
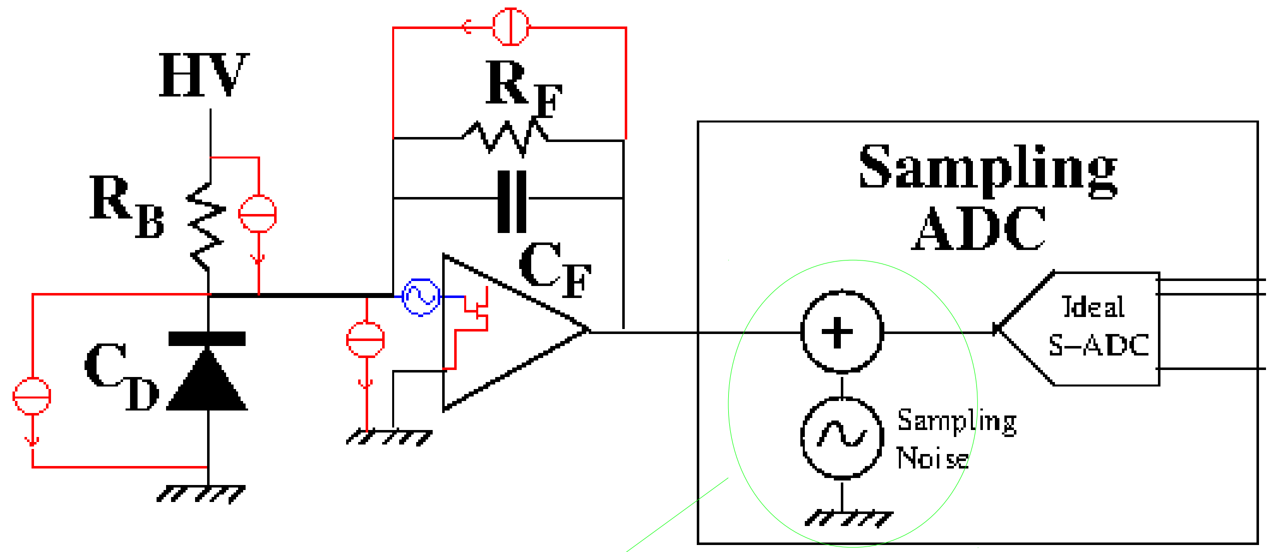
- **increases w/ decreasing input transistor transconductance => decreasing power**
- **"amplified" by input capacitance squared**

Both increase with temperature!

FEE: Noise with S-ADC



FEE: Noise with S-ADC

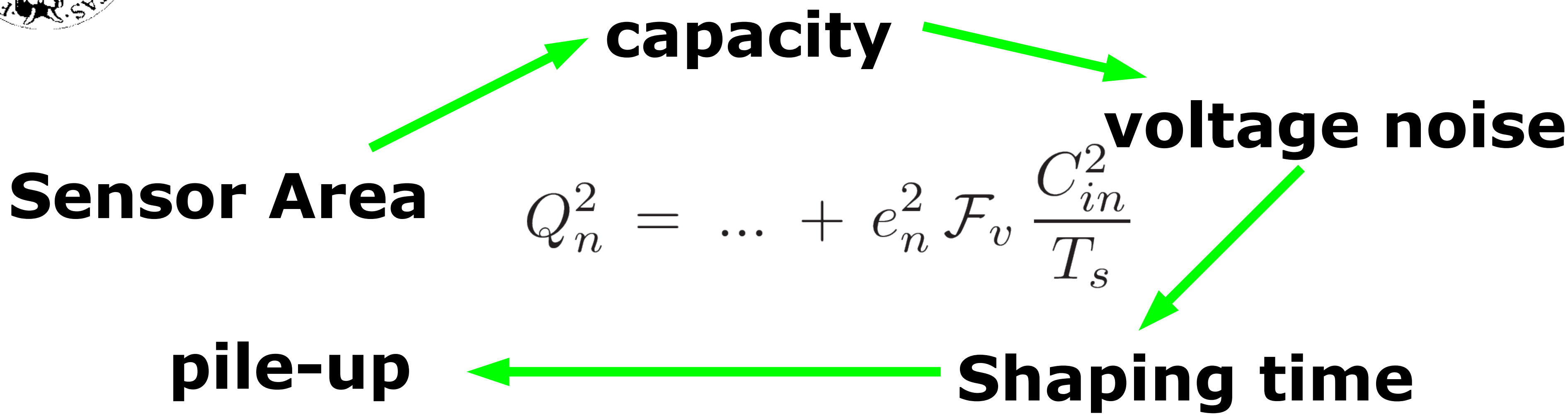


$$\sigma_n = \frac{2^{N_{bit}-ENOB}}{\sqrt{12}}$$

ENOB=effective number of bits

Interplay

Interplay: noise, RD, etc.



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

Interplay: noise, RD, etc.

capacity

voltage noise

Sensor Area

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

pile-up

Shaping time

Leakage current

$$i_n^2 \approx 2\, e\, I_D$$

current noise

Rad. Damage

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

Sensor Area

Reduce shaping time, keep SNR (if voltage noise allows)

Interplay: pile-up

A: Move sensor away =>reduces pile-up prob.

B: Reduce sensor area => also reduces pile-up

However for constant SNR:

$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s} \qquad e_n^2 \approx \frac{2.7 k_B T}{g_m} \propto \frac{2.7 k_B T}{I_{FET}}$$

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Option A=> solid angle Ω divided by n=> channel# times n (@same power per channel) => increase power n times

Interplay: pile-up

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Option A=> solid angle Ω divided by n=> channel# times n (@same power per channel) => increase power n times

Option B=> Ω divided by n => channel# times n… however:

Interplay: pile-up

A: Move sensor away =>reduces pile-up prob.

B: Reduce sensor area => also reduces pile-up

However for constant SNR:

$$Q_n^2 = i_n^2 \mathcal{F}_i T_s + e_n^2 \mathcal{F}_v \frac{C_{in}^2}{T_s} \qquad e_n^2 \approx \frac{2.7\, k_B T}{g_m} \propto \frac{2.7\, k_B T}{I_{FET}}$$

Option A=> solid angle Ω divided by n=> channel# times n (@same power per channel) => increase power n times

Option B=> Ω divided by n => channel# times n... however:

capacity divided by n => can scale down FET current (or shaping time Ts) by n^2

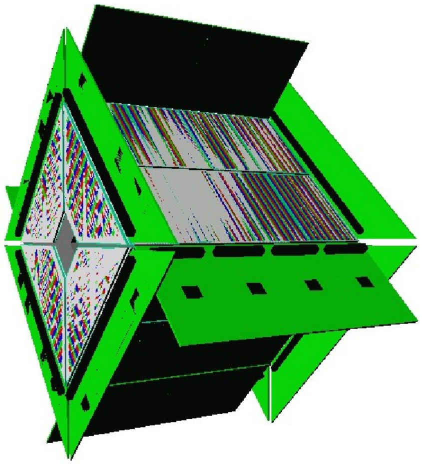
e.g. Current down by n^2=>total power scaled down by n

(...well, not exactly so...there is a fixed amount of digital power per channel...)

A study case

A study case: LCP ancillary detector

Inspired by D.Mengoni work for TRACE (TRacking Array for light Charged Particle Ejectiles)



Basic requirements:

1) particle identification
2) detection efficiency
3) granularity
4) transparency to gamma's
5) Energy resolution about 50keV FWHM for ^{241}Am
6) Timing resolution 500ps FWHM
7) dynamic range (energy) 0.2-300MeV
8) high rates

A study case: LCP ancillary detector ...a few possible choices

Basic requirements:

1) particle identification
2) detection efficiency
3) granularity
4) transparency to gamma's
5) Energy resolution about 50keV FWHM for ^{241}Am
6) Timing resolution 500ps FWHM
7) dynamic range (energy) 0.2-300MeV
8) high rates!

3)+4)+5)=>Silicon pad or strip detector

1)=>Two Si layers for ΔE-E, reverse mount for PSA

2)=>Many wafers (and FEE channels) needed

5)+8)=>cooling to reduce noise => short T_s

A study case: LCP ancillary detector ...some numbers

Expected rate per sensor (4 mm x 4 mm) 20kHz if
- **100pnA beam**
- **LCP multiplicity 6**
- **Target A=100, 1 mg/cm^2**

Pile-Up probability: 2% for 20kHz with T_s=1μs

Radiation Damage:
- **Fluence per day at 20kHz 1.1×10^{10} cm^{-2}...PSA tests mandatory (distinguish drift from resolution worsening)**

Conclusions

- Si detectors with small strip or pixels (mm) good candidates for large solid angle arrays

- Segmentation advantages:
  - PSA needs uniform doping. Easier to obtain on smaller areas (lower cost=>more spares, cfr. RD)
  - Better angular resolution
  - Lower pile-up probability (short shaping time)
  - Better noise and radiation hardness

- Huge amount of RD studies from HEP, though our constraints can differ (dedicated studies)

- Many open questions, we will need: experimental R&D work, detector simulations and...ingenuity!

Some open problems

- Spurious coincidences (particles from distinct P+T within resolving time) hard to avoid or reduce (e.g. pulsed beams with many particles/bunch!). What's the resolving time? Rate in target ~4 MHz, one every 250ns. Make decisions fast!

- Reliable measurement of total Z of the event could be of great help (ancillary+spectrometer).
However: PSA needed for low PID thresholds...

- Rad. Damage robustness of PSA and ΔE-E identification for LCP must be tested

- Rare events => high background...how to select? Trigger issues similar to HEP? Rate in target ~4 MHz, one every 250ns. Make decisions fast!

- ASIC electronics preferred (many channels in small space)...but performance of ASIC electronics in terms of PSA identification must be checked!

- limit of the present digitizing ACQ on market is anyway few 10kHz. At 100pnA we're there already.

Thanks!

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

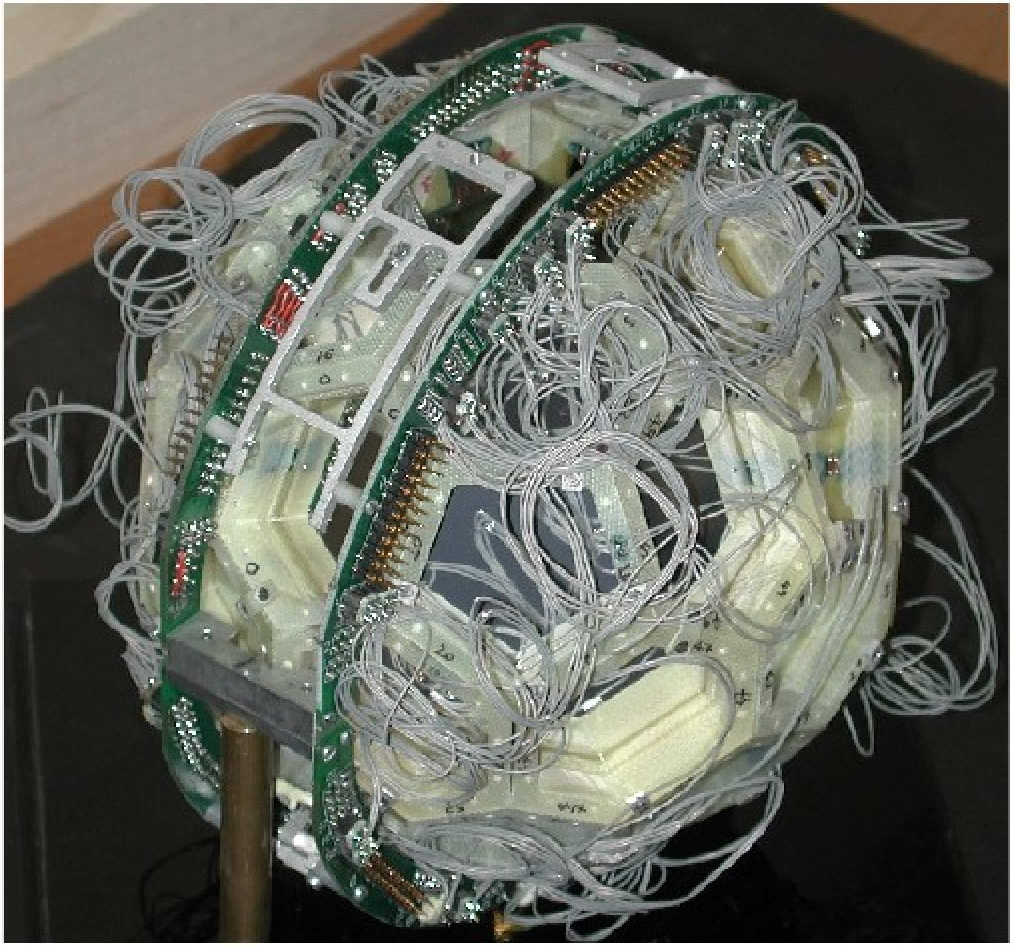
- taking out preamp signal for digitizers problematic

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

CPD: Arrays of Cells

Large solid angle coverage => Efficiency for complete events (multiplicity measurement, etc)

e.g. Ancillary light charged particles (LCP) detector for gamma detection arrays



EUCLIDES (LNL) ~ year 2000

Performances

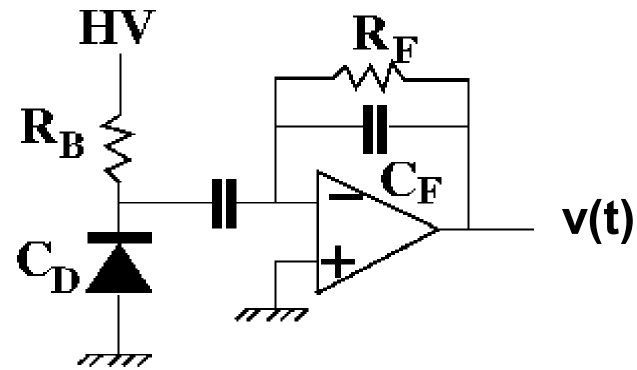
Deposited energy => collected charge

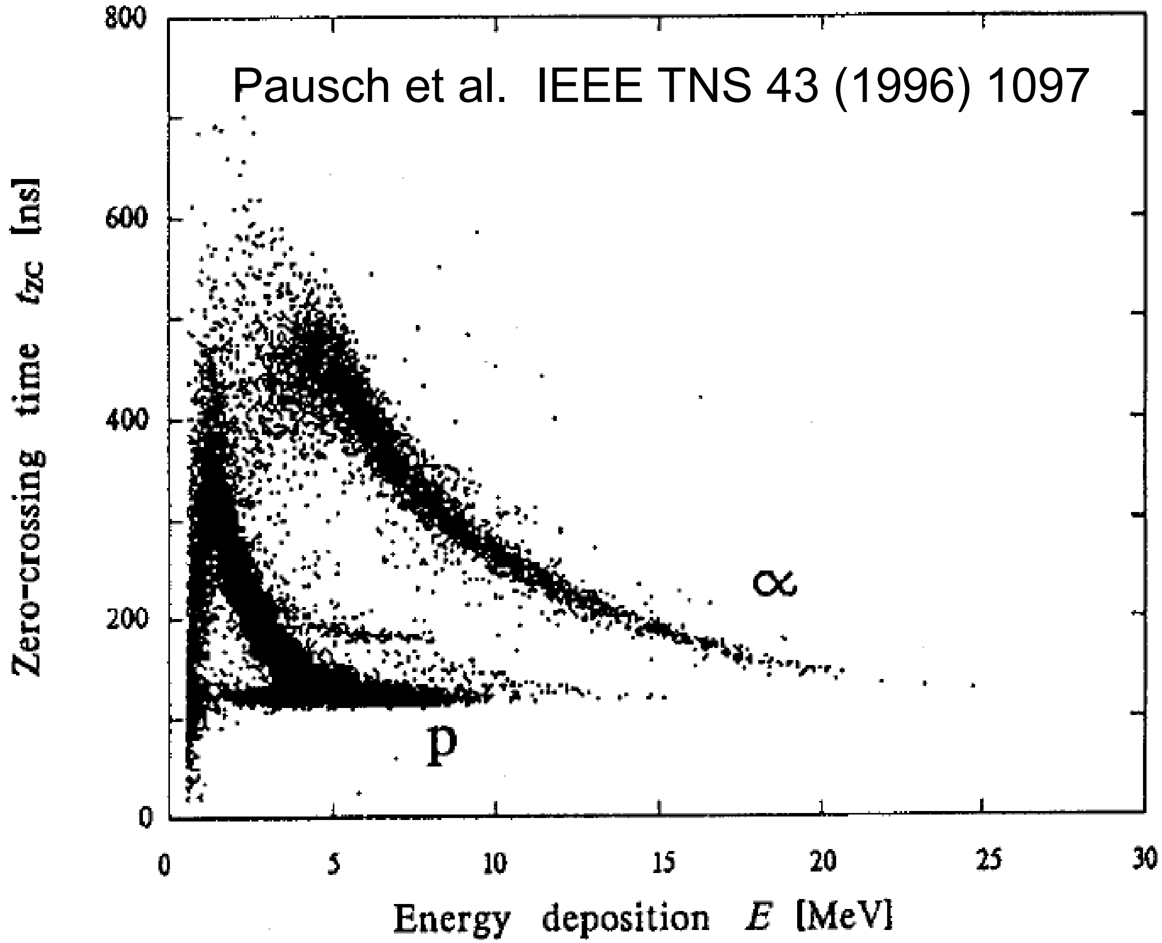
Fluctuations in carrier number, electronic noise etc => finite resolution in determining charge (energy).

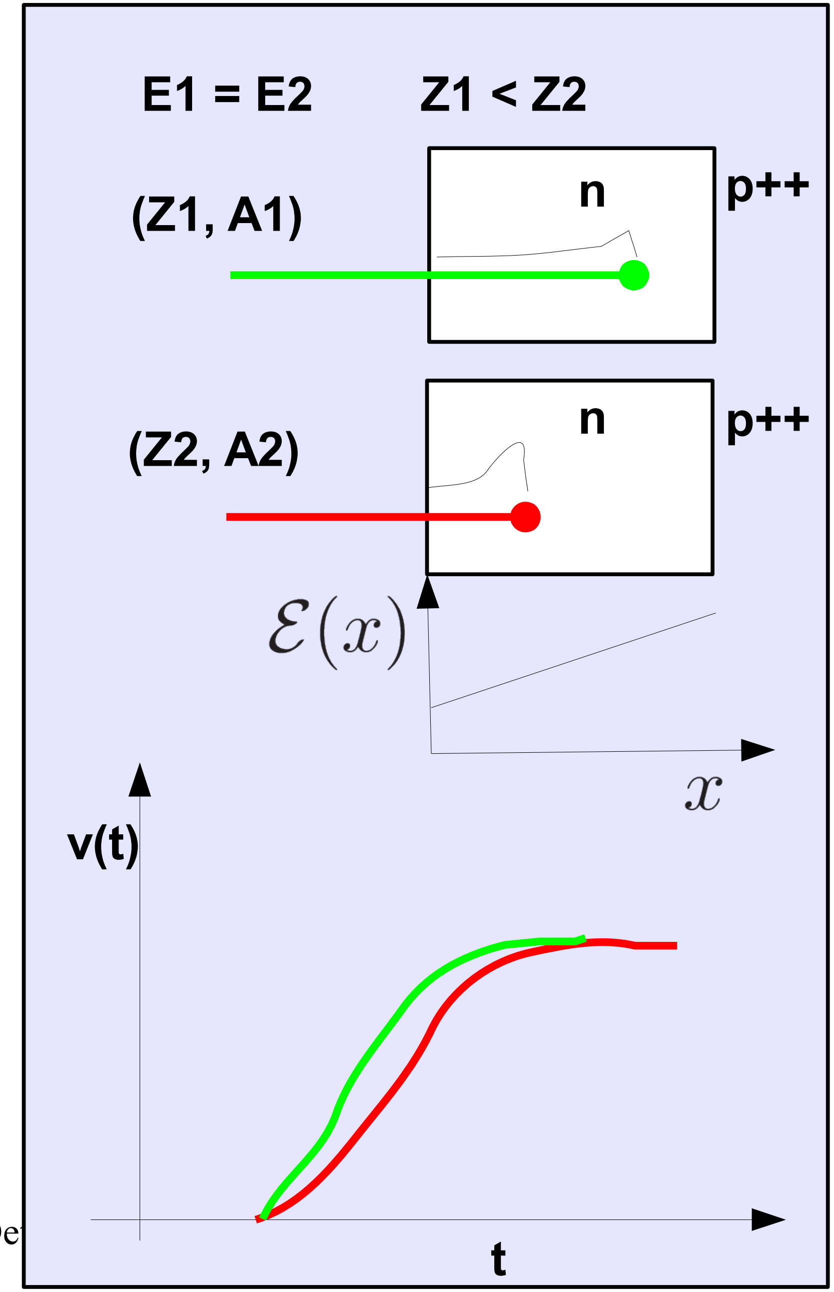
Collection time=>timing and resolving time.

	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

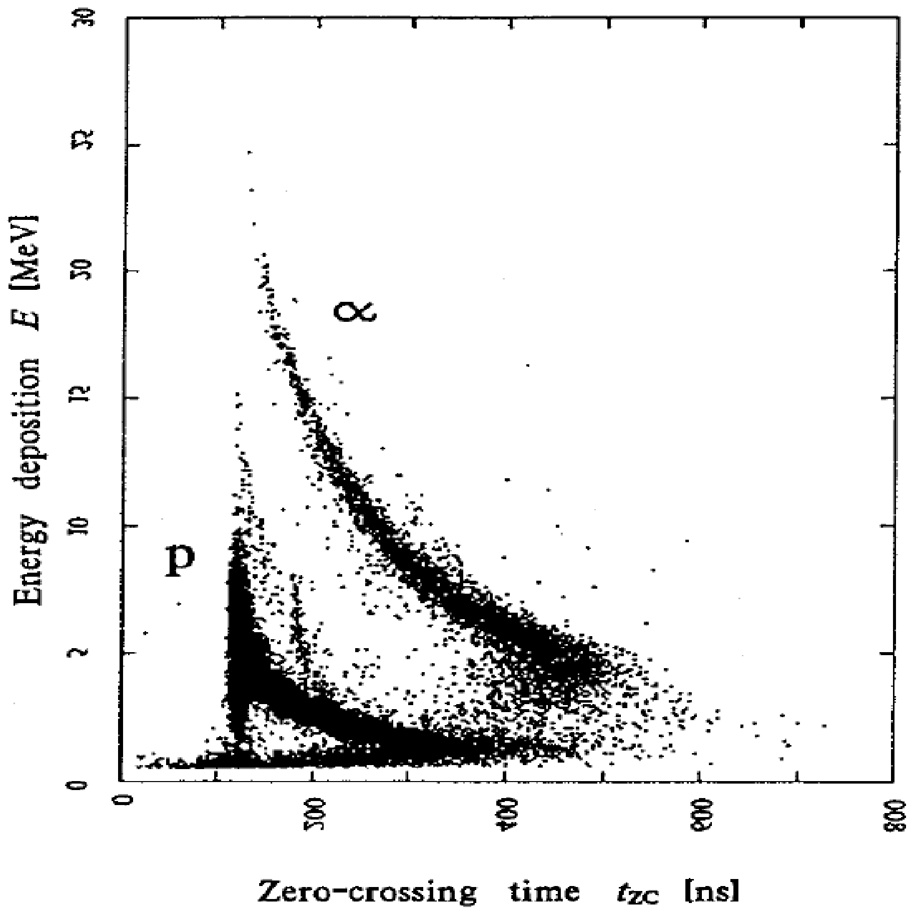




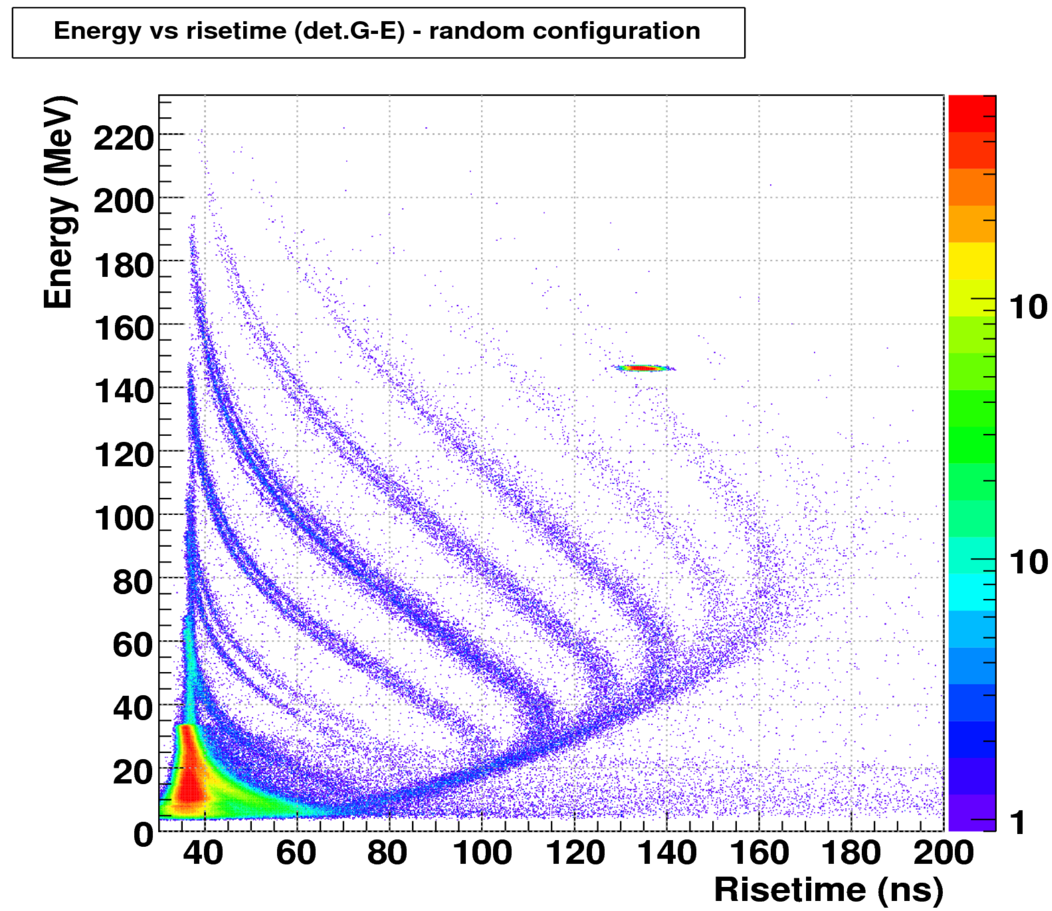


Particle ID: Pulse Shape Ident. in Silicon

Pausch image rotated and flipped for easier comparison.

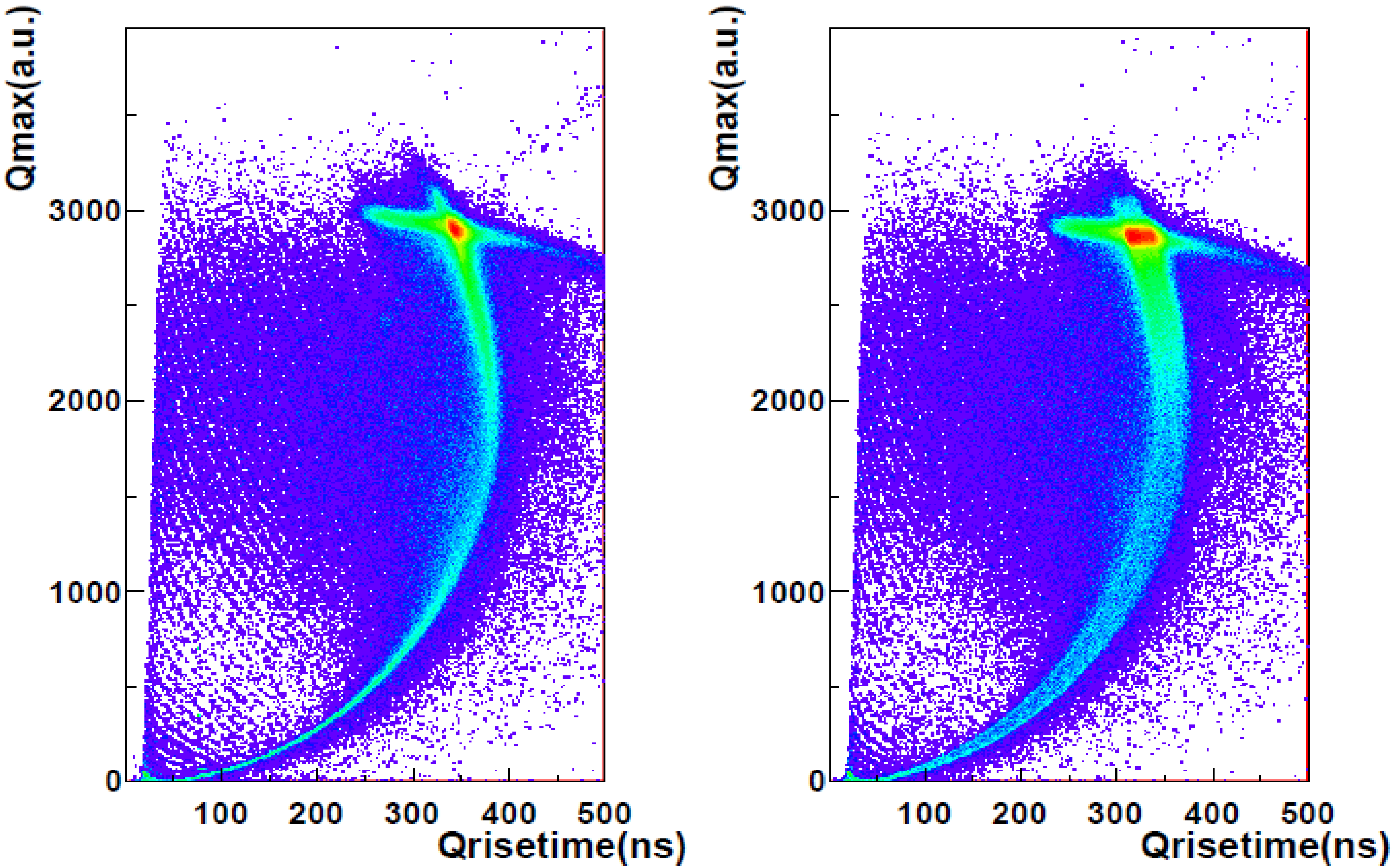


Pausch et al. IEEE TNS 43 (1996) 1097

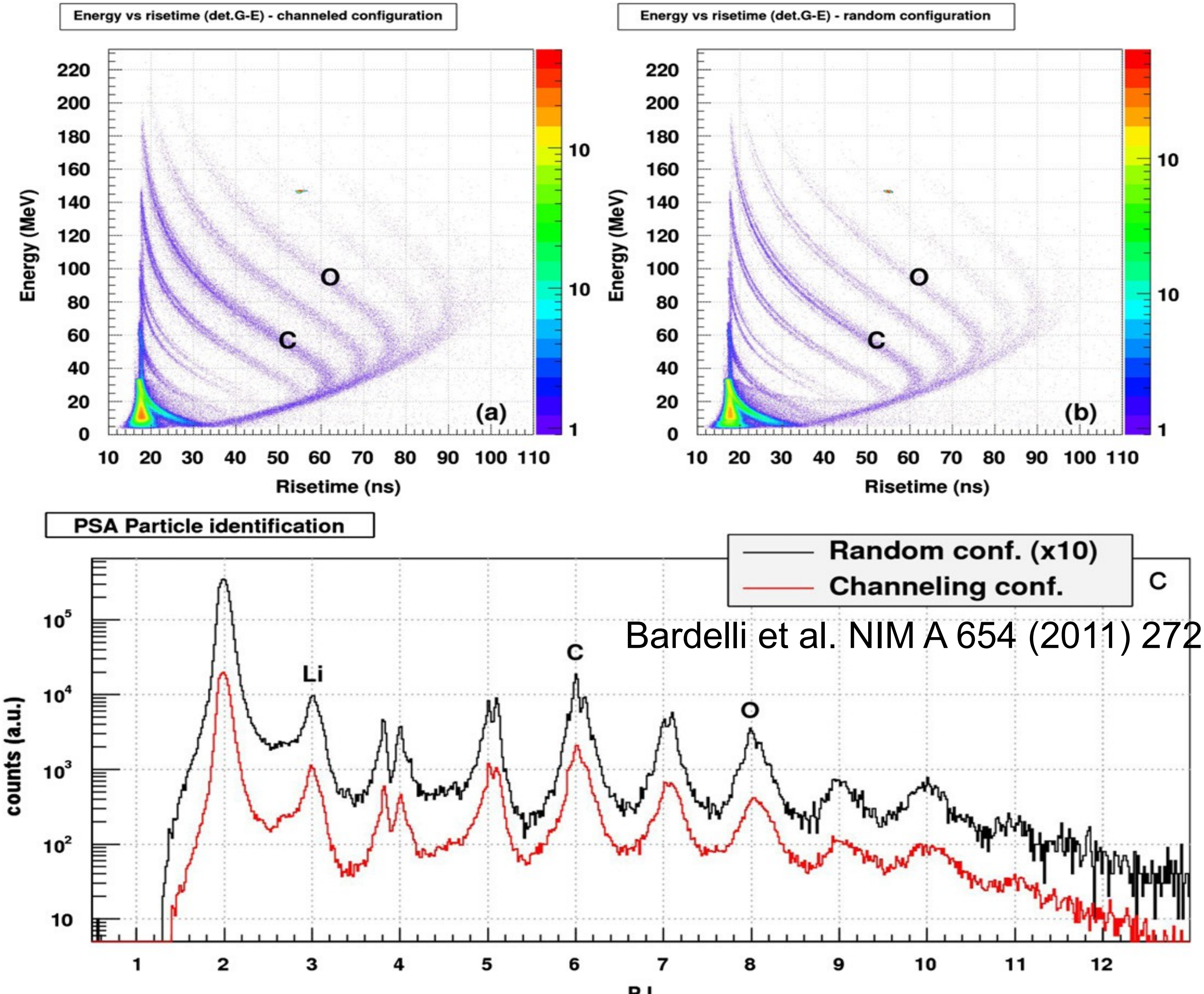


Bardelli et al. NIM A 654 (2011) 272

Particle ID: PSA and Rad. Damage



Particle ID: PSA and Channeling



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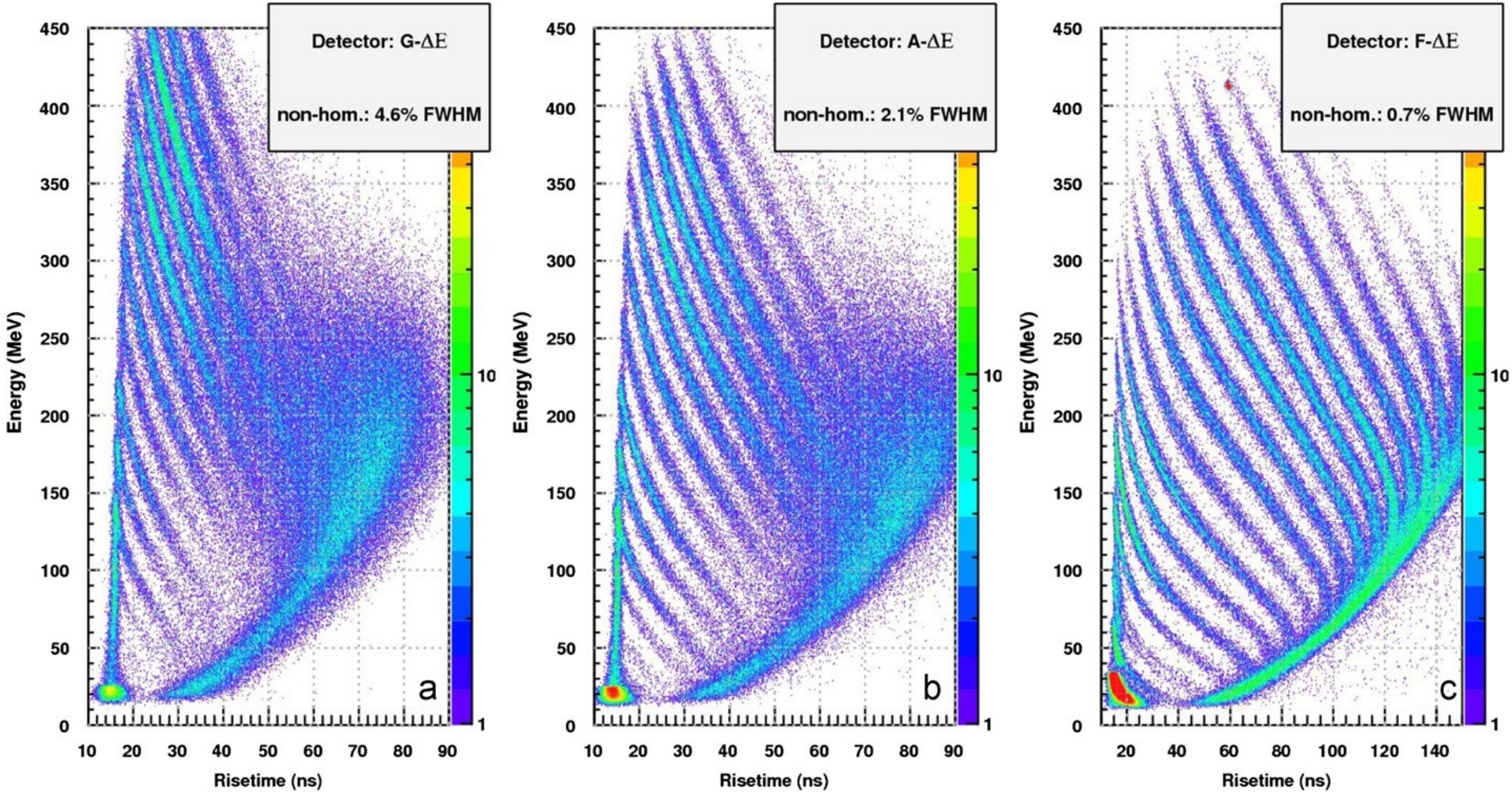
Particle ID: PSA and Doping Uniformity



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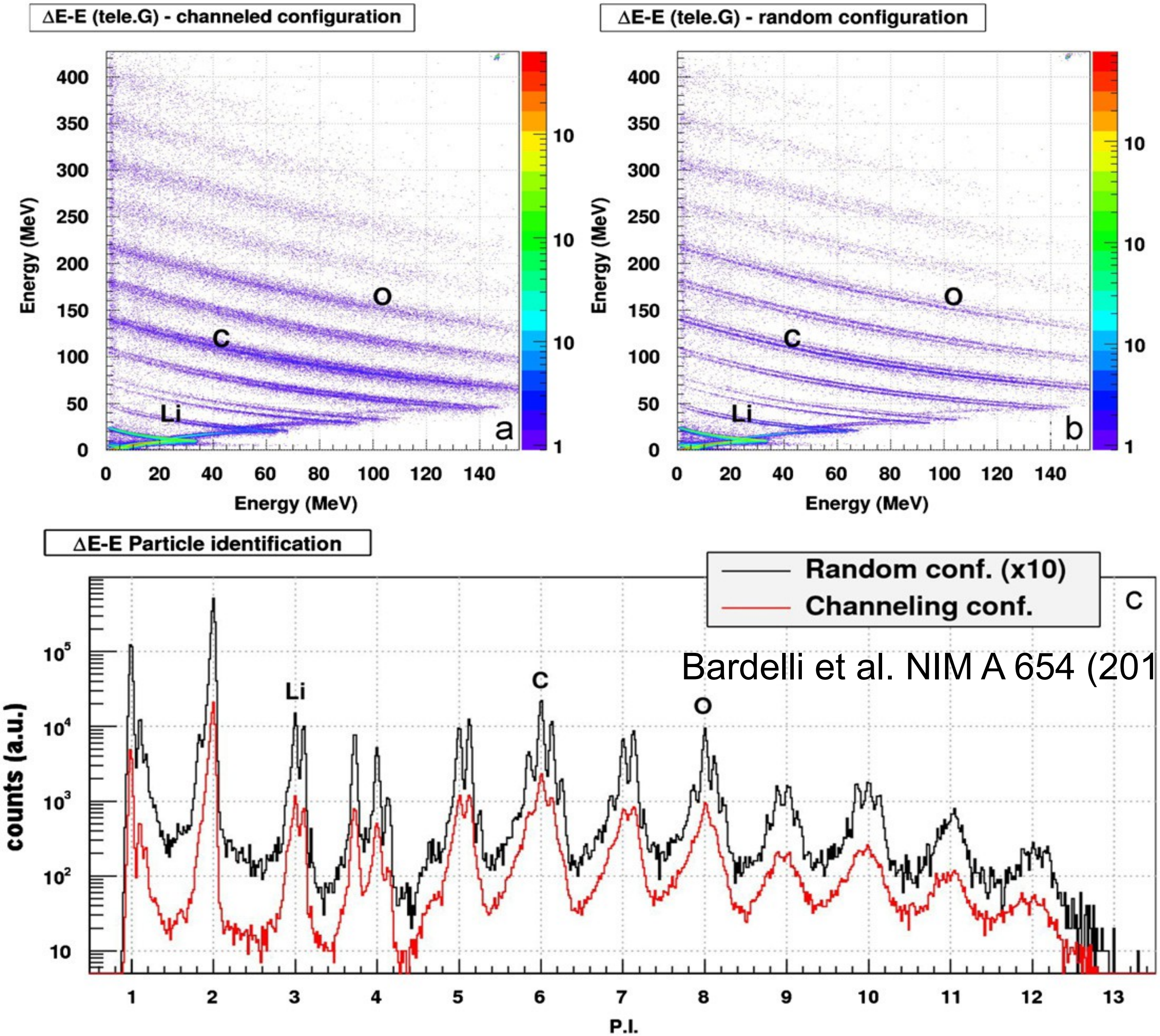
Particle ID: ΔE-E and Channeling



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Open questions

- ASIC or discrete electronics?

- charge or current preamps?

- how to recognize event mixing due to finite ToF? (slowest particles of n-th interaction detected at the same time as fastest particles of (n+1)-st interaction.