12th Workshop on European Collaboration for Higher Education an Research in Nuclear Engineering and Radiological Protection

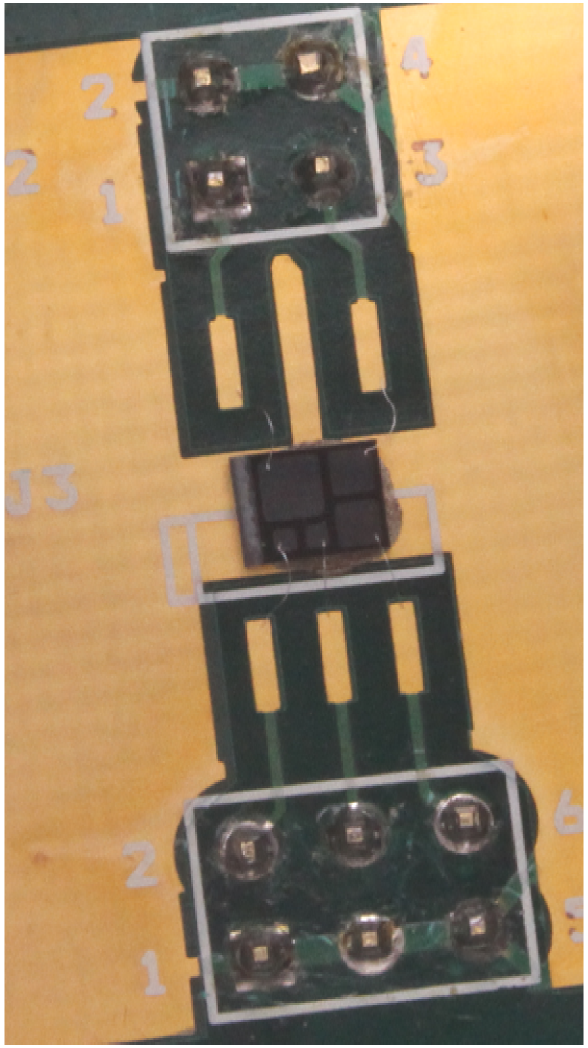
30 may - 1 June 2016 Cervia

SiC DETECTORS TO MONITOR IONIZING RADIATIONS EMITTED FROM NUCLEAR EVENTS AND PLASMAS

L. Torrisi and **A. Cannavò**

Dipartimento di Scienze Fisica – MIFT, Università di Messina,
Viale F.S. D'Alcontres 31, 98166, S. Agata (Me), Italy

Outline



- Properties of Silicon Carbide

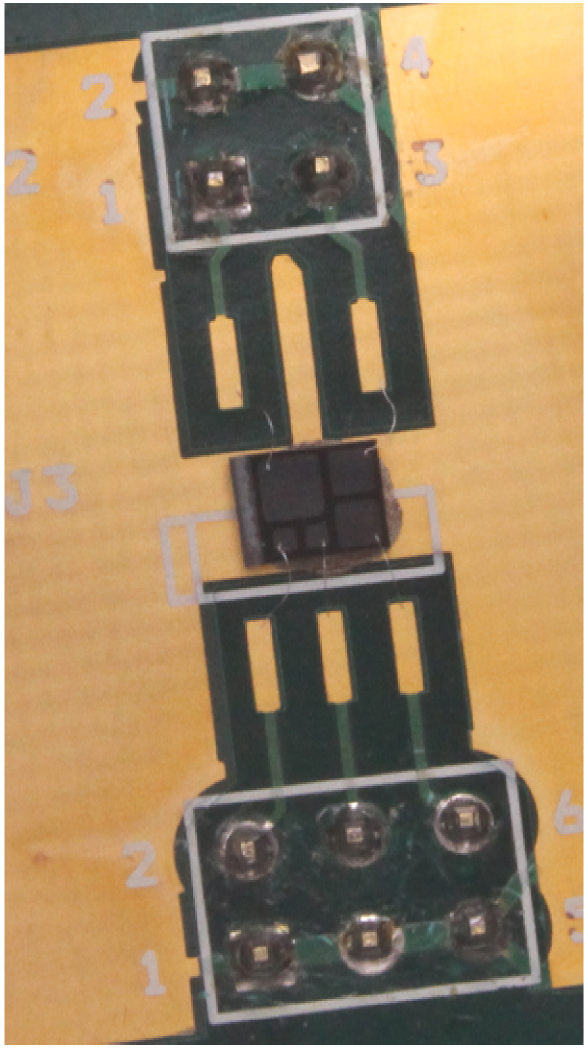
- Characterization of a SiC diode at low fluence for:
  - α-particles
  - electrons
  - X-rays

- Time of Flight (TOF) technique in plasmas generated by laser producing high radiation fluence

- First study for SiC applications in radiation dosimetry

- Conclusions

OUTLINE



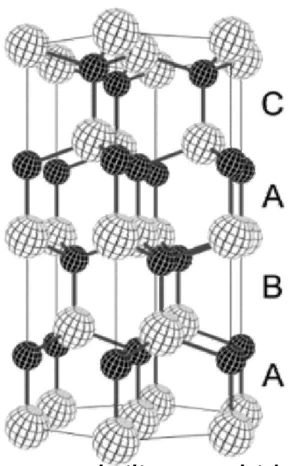
- ❑ Properties of Silicon Carbide
- ❑ Characterization of a SiC diode at low fluence for:
  - α-particles
  - electrons
  - X-rays
- ❑ Time of Flight (TOF) technique in plasmas generated by laser producing high radiation fluence
- ❑ First study for SiC applications in radiation dosimetry

  Preliminary
- ❑ Conclusions

Introduction: Why Silicon Carbide?

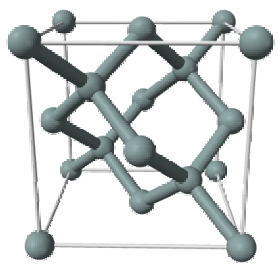
Physical property	4H-SiC	Silicon	GaAs	Diamond
Crystal structure	**Hexagonal**	Diamond	Zinc-blende	Diamond
Band gap [eV]	**3.26**	1.12	1.43	5.45
Density [g/cm^3]	**3.21**	2.33	5.32	3.52
Electron mobility [cm^2/Vs]	**800-1000**	1450-1500	8500	1800-2200
Holes mobility [cm^2/Vs]	**100-115**	450-600	400	1200-1600
Breakdown electric field [MV/cm]	**2.2-4.0**	0.2-0.3	0.3-0.6	10
Mean e-h pair energy [eV]	**7.78**	3.63	4.21	13
Thermal conductivity [W/cm °C]	**3.0-5.0**	1.5	0.5	20
Max working temperature [°C]	**1240**	300	460	1100
Effective atomic number	**12.54**	14	32.06	6
Displacement energy [eV]	**25**	13-20	15.5	43

Interatomic distances



4H-SiC

Si-C 1.89 Å
Si-Si & C-C 3.08 Å



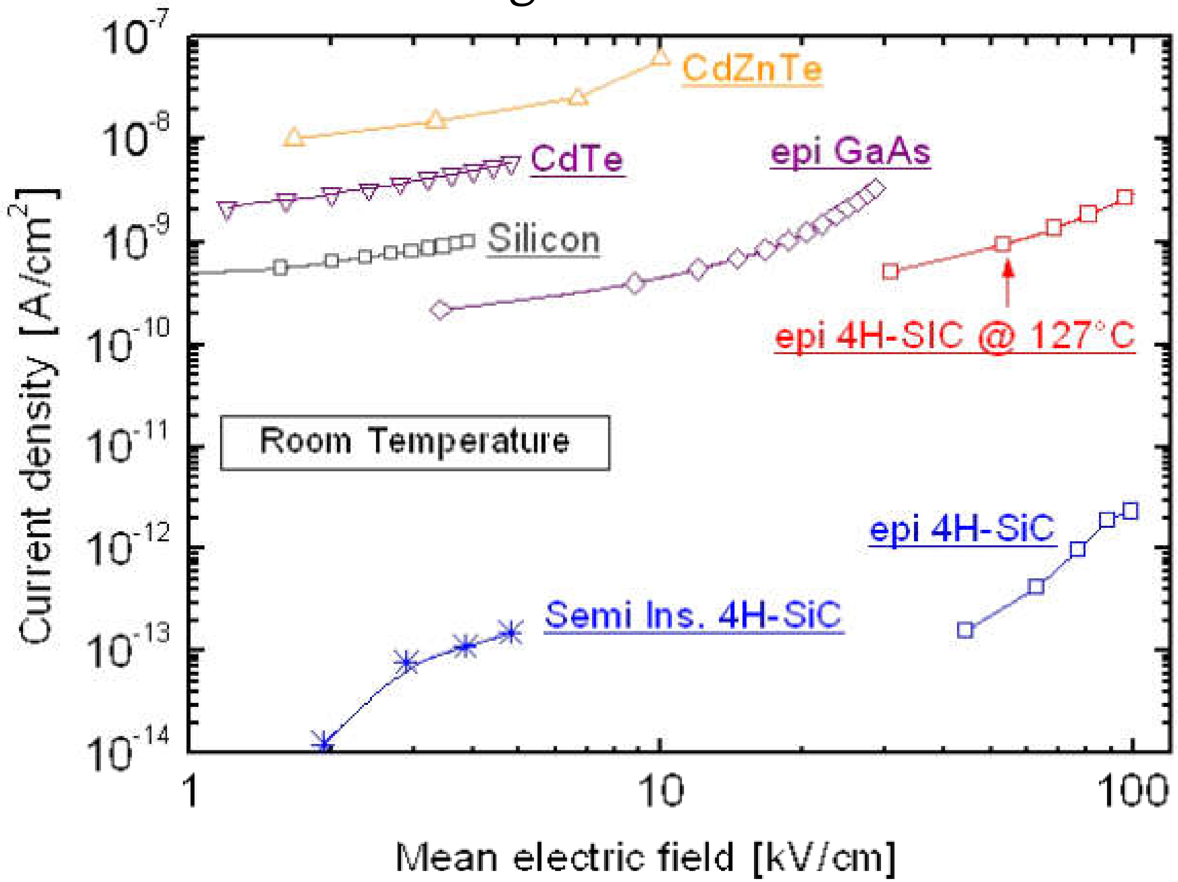
Silicon

Si-Si 2.35 Å

Torrisi et al., Single crystal silicon carbide detector of emitted ions and soft x rays from power laser-generated plasmas J. Appl. Phys. 105, 123304 (2009)

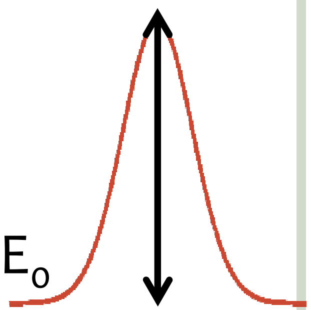
ADVANTAGES OF SIC RESPECT TO TRADITIONAL SI DETECTOR

Low leakage current → low noise



1. SiC reverse current is a factor 10 - 100 lower than Silicon at room temperature → increase sensibility
2. The high energy gap makes this detector blind to visible radiation → remove the shielding systems
3. The higher thermal conductivity → increase the maximum working temperature up to 1200 °C vs. 300 °C for Si
4. Higher displacement energy threshold → a better radiation hardness
5. Effective atomic number is closer in SiC (12.5) than Silicon (14)
6. High linearity between the signal pulse and energy released in the active region of the device

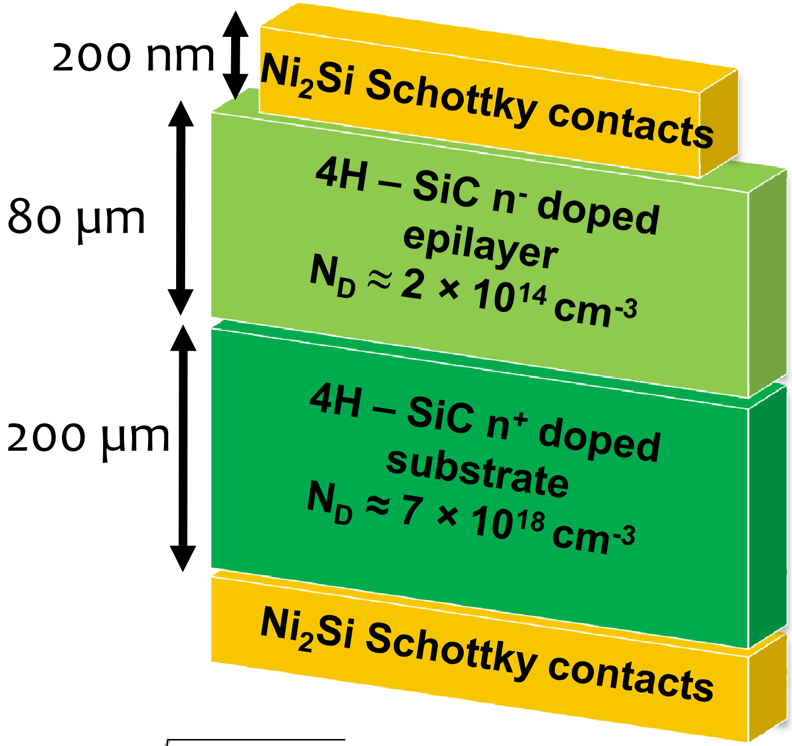
Signal ∝ E_0



F. Nava et al., Silicon carbide and its use as a radiation detector material, Meas. Sci. Technol.19 (2008) 102001 (25)

Detector structure

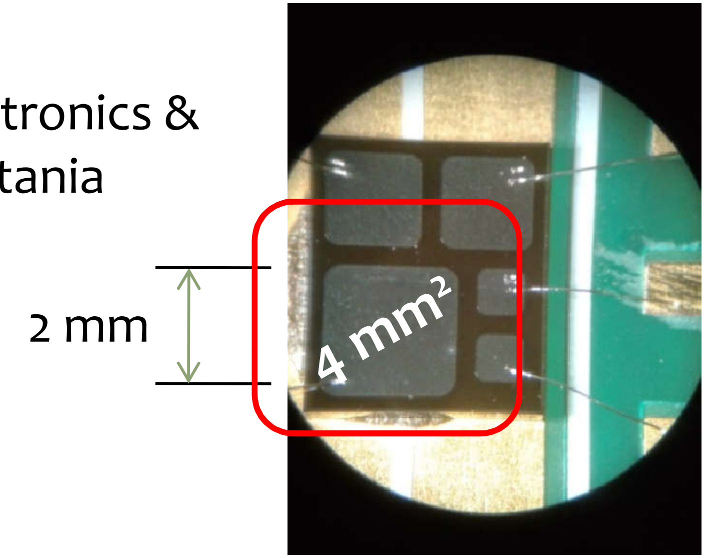
Single crystal 4H-SiC Schottky diode



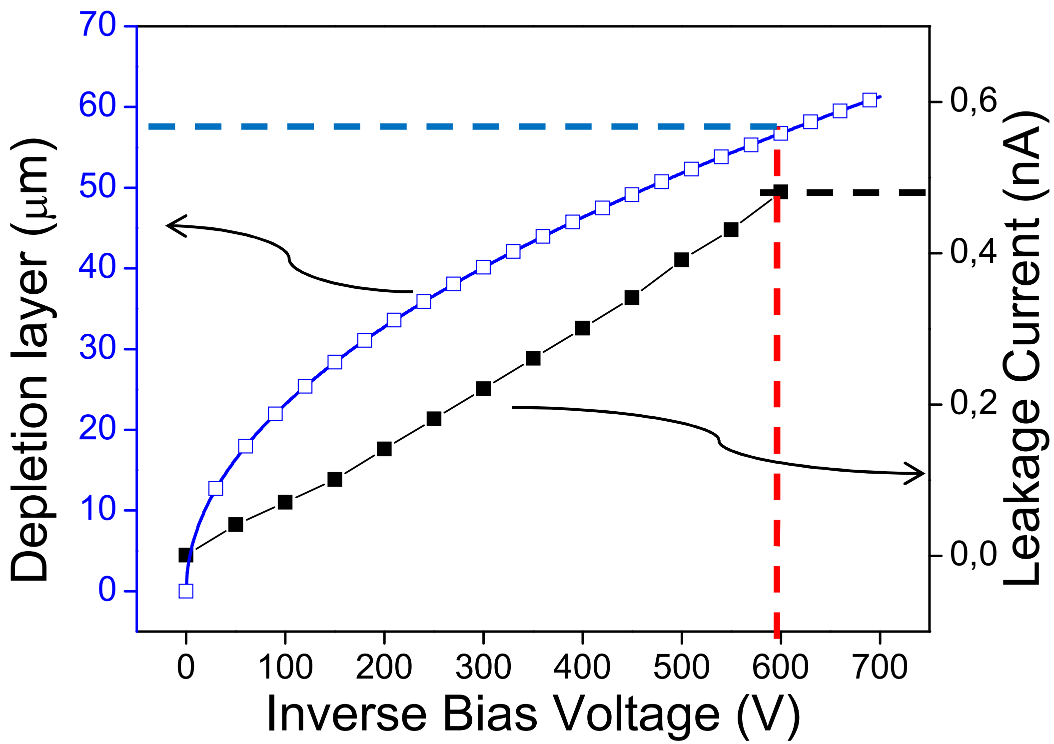
$$W = \sqrt{\frac{2\varepsilon_0\varepsilon_r}{qN_D}V}$$

ε_r = relative permittivity = 9.66
N_D = doping concentration = 2 $\times 10^{14}$ cm^{-3}
q = elementary charge
V = inverse bias voltage

ST-Microelectronics & CNR-IMM Catania



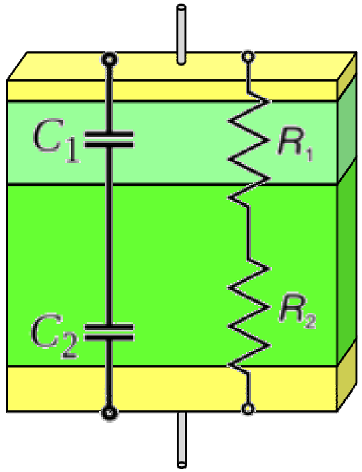
Optical microscope image



Resistance and Capacitance

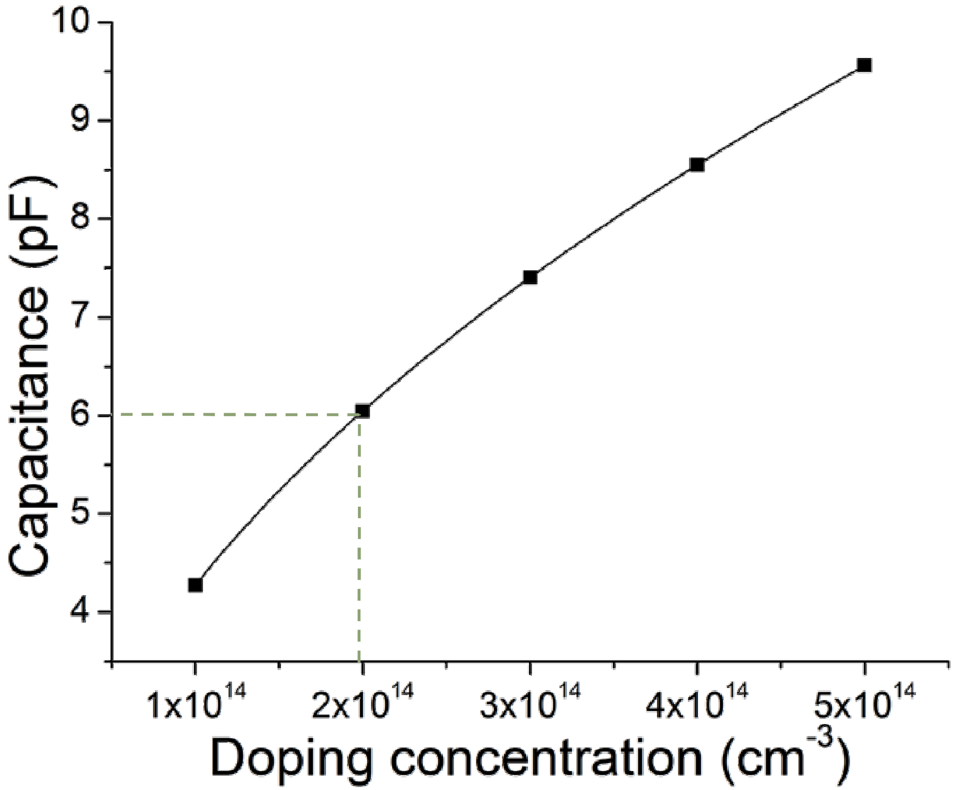
$$C = \varepsilon_0 \varepsilon_r \frac{A}{W} = A\sqrt{\frac{q\varepsilon_r\varepsilon_0 N_D}{2V}}$$

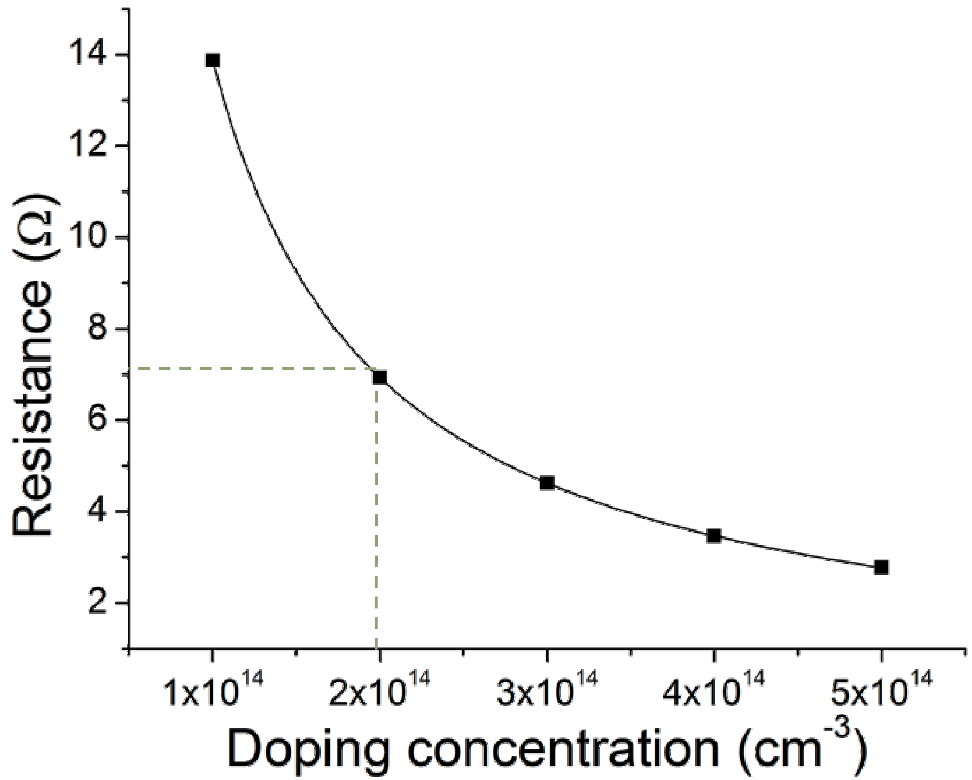
A = diode surface = 4 mm2
N_D = 2 ×10[14] cm[-3]



$$R = \rho\frac{W}{A} = \frac{1}{q\mu_e N_D}\frac{W}{A}$$

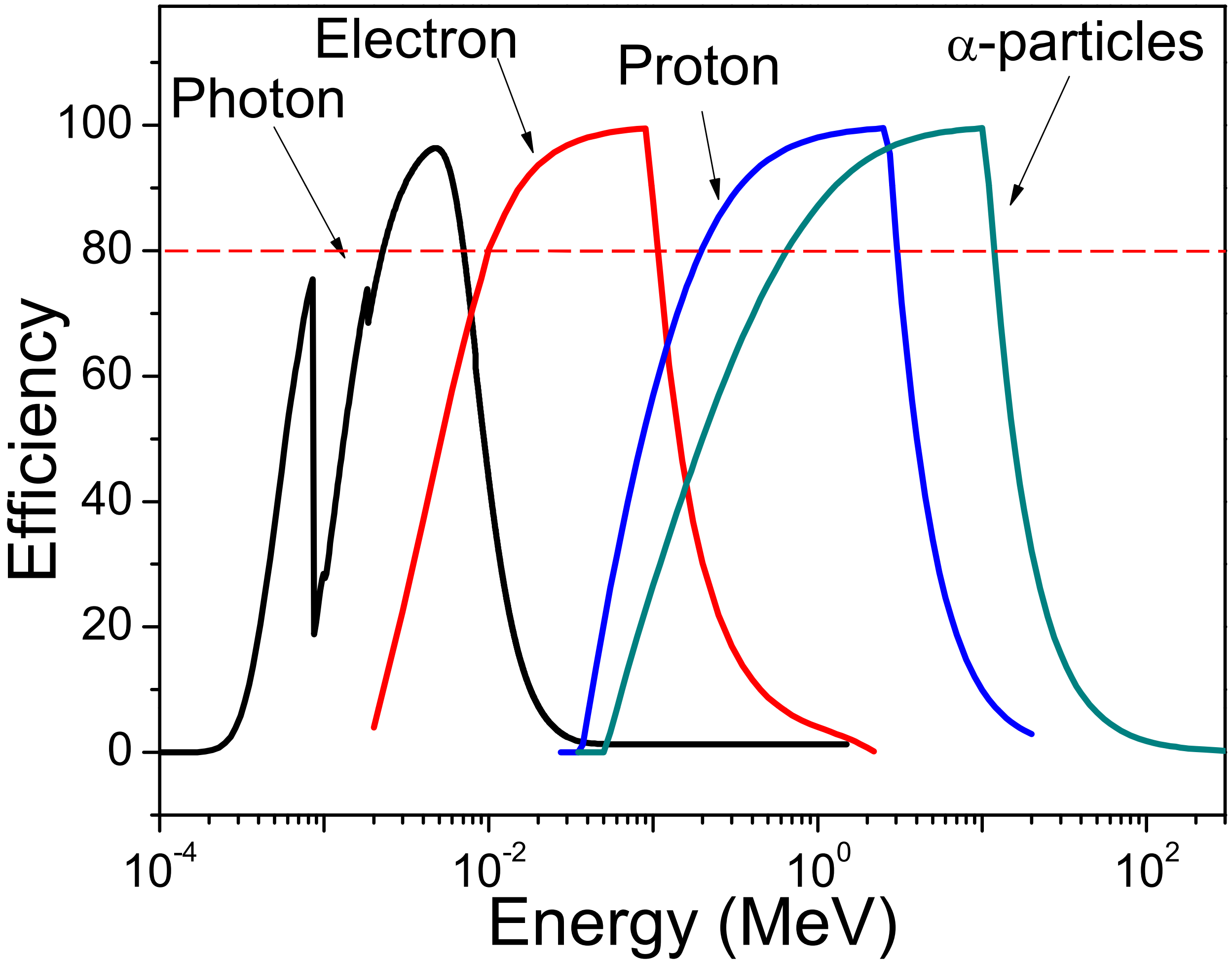
μ_e = 900 cm2 $V^{-1}s^{-1}$
electron mobility
ρ = resistivity

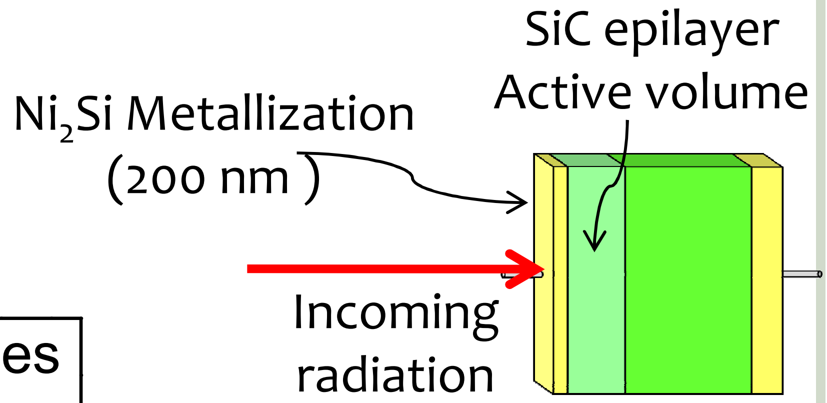


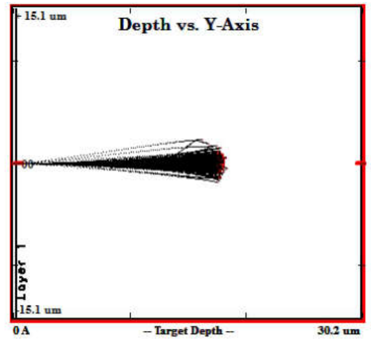


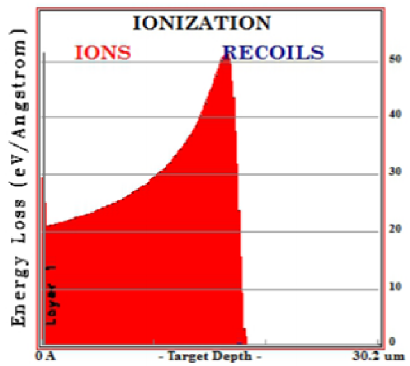
Simulated efficiency

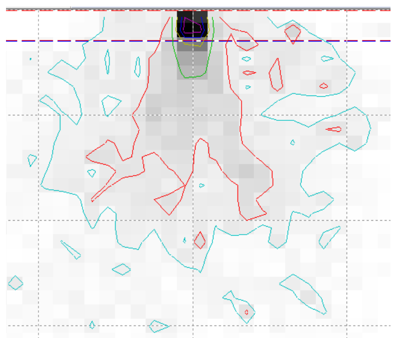
Active region = 80 μm





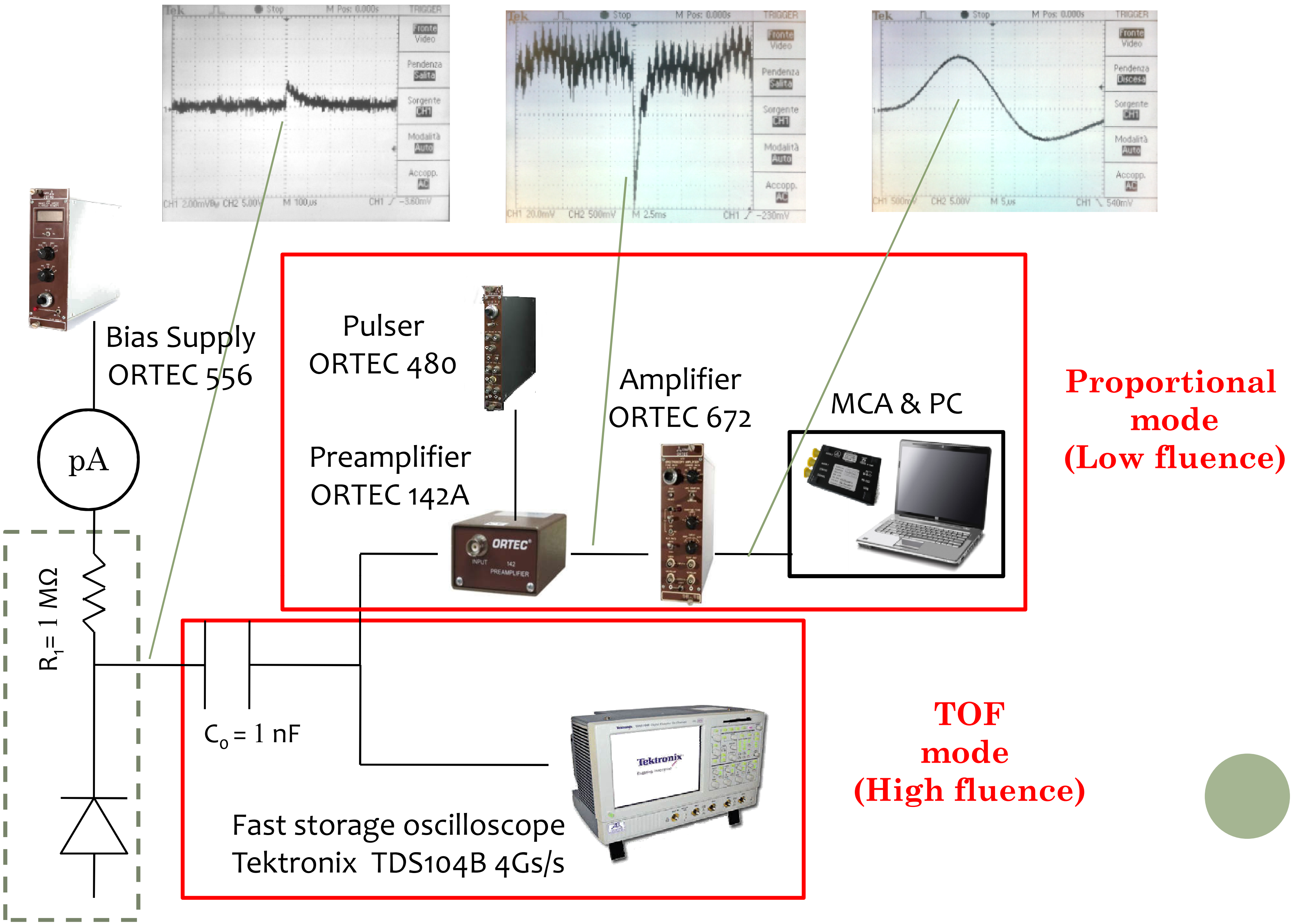




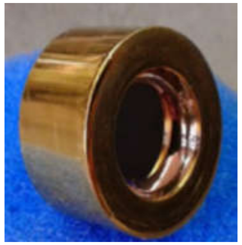


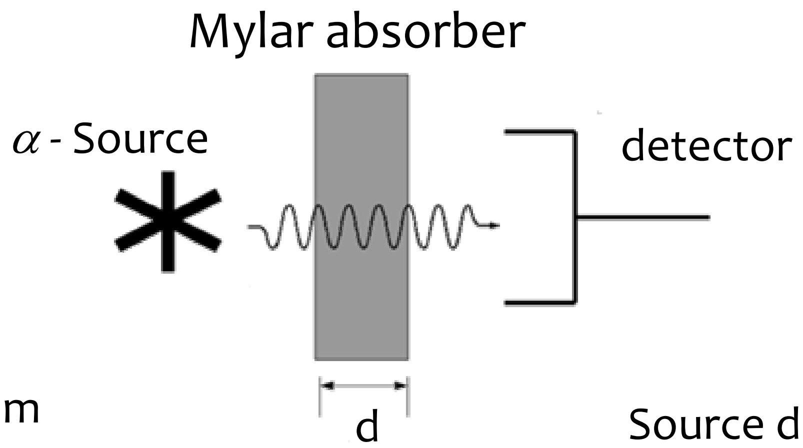
CXRO for photon: http://henke.lbl.gov/optical_constants/filter2.html
eSTAR for electron: http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
SRIM2008 for proton and heavier positive ions: http://www.srim.org/

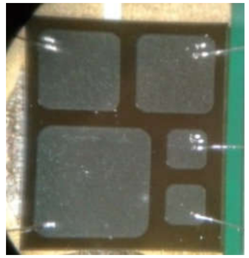
EXPERIMENTAL SET-UP



α–PARTICLES SPECTROSCOPY

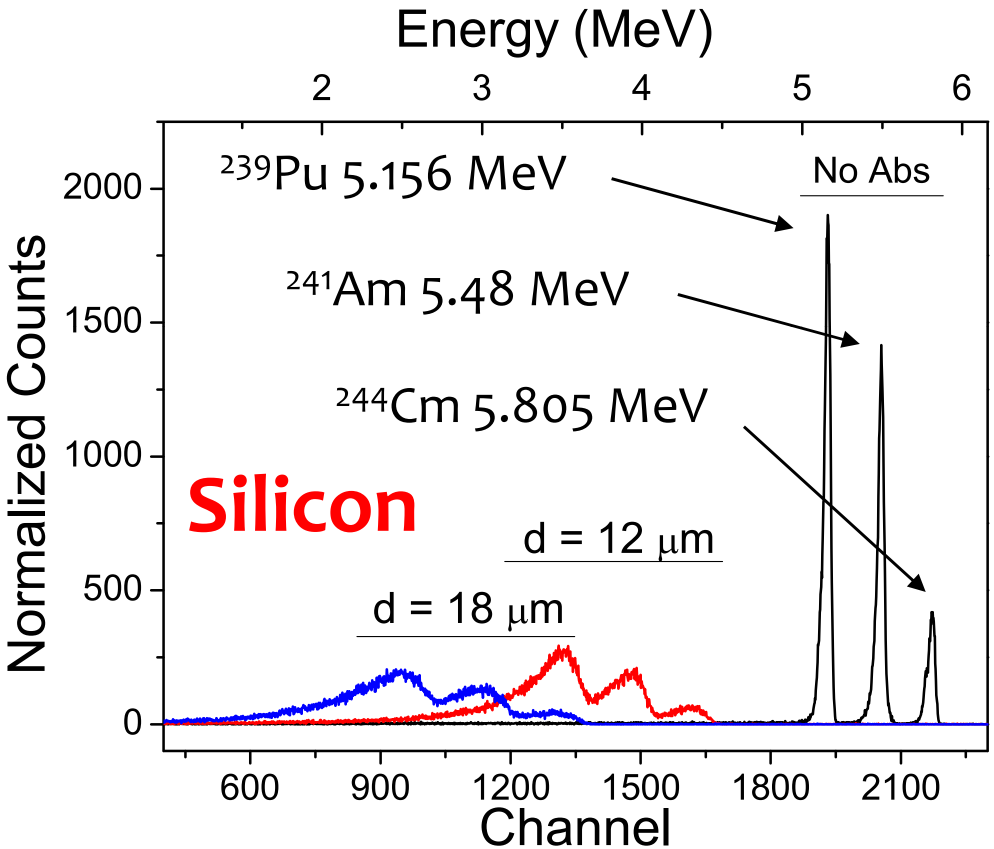


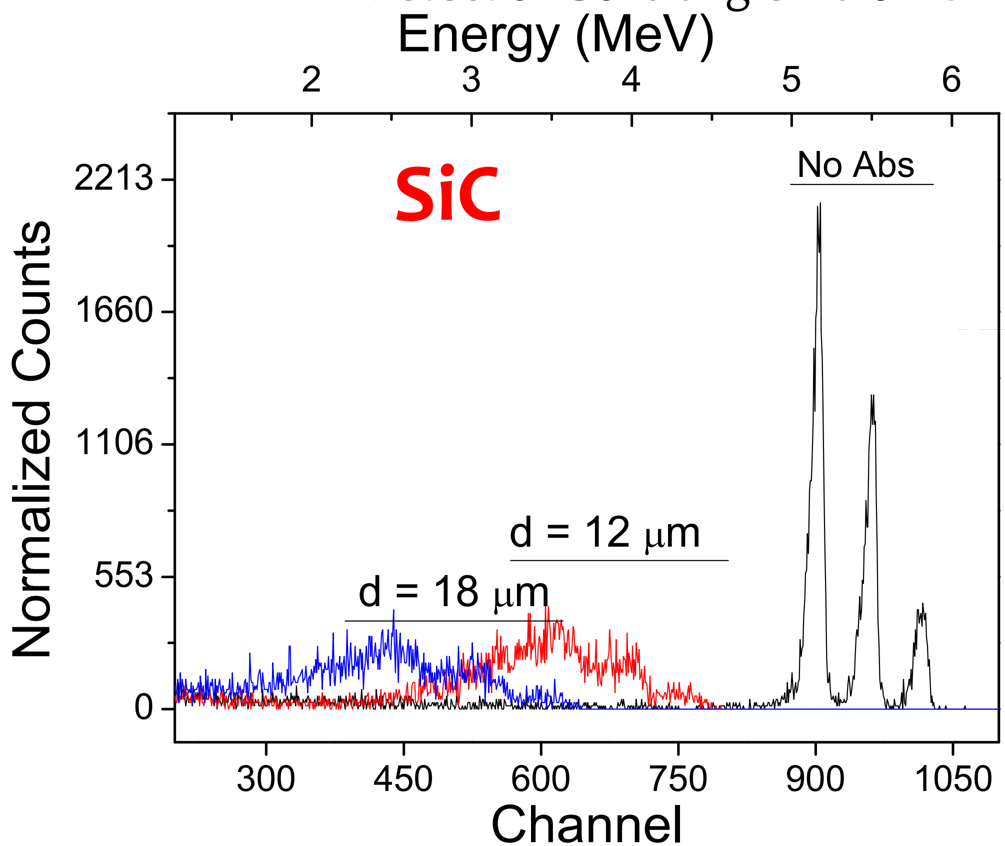




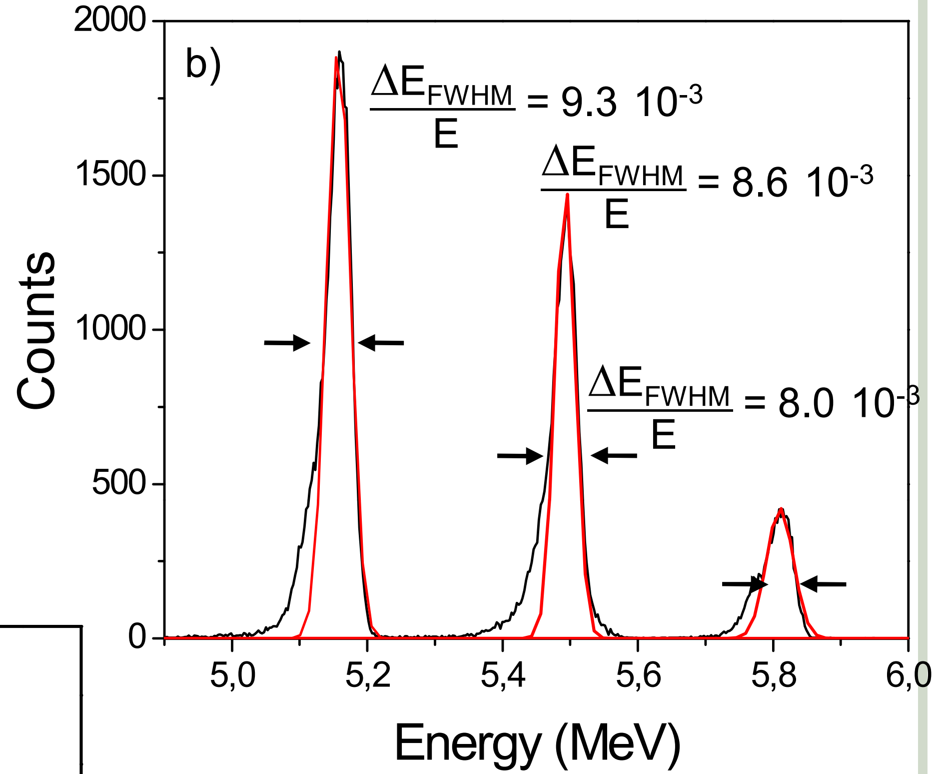
Detector Bias = + 50 V
Time = 300s
Source detector distance = 6mm
Surface of diode = 0.5 cm^2
Detection Solid angle = 8.3 msr

Detector Bias = -200V
Time = 300s
Source detector distance = 6mm
Surface of diode = 0.04 cm^2
Detection Solid angle = 0.6 msr

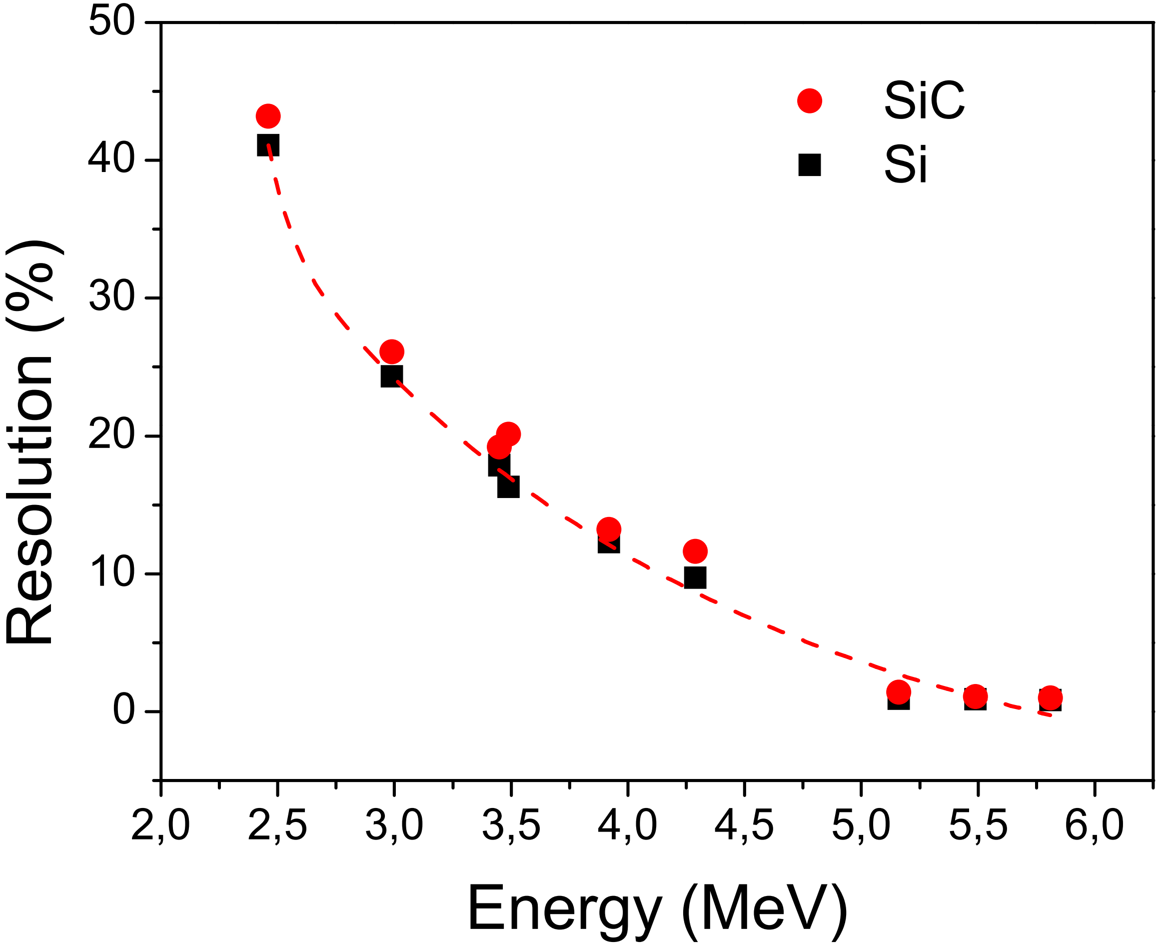




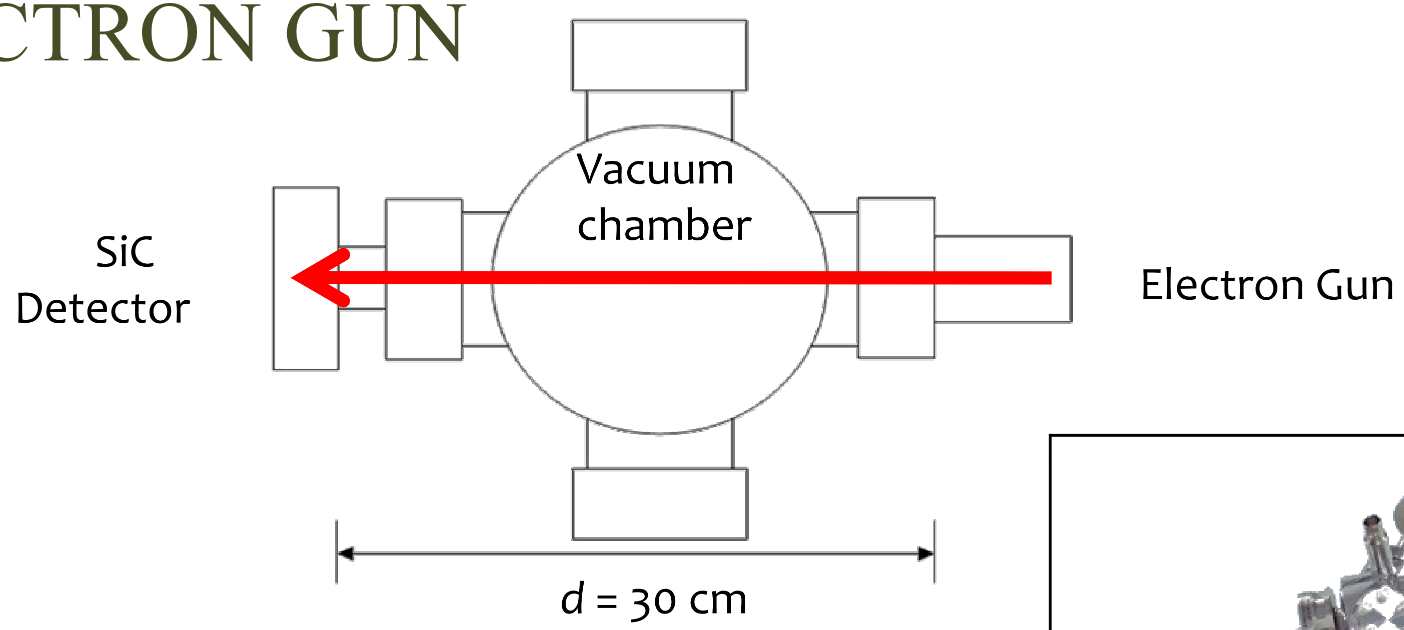
ENERGY RESOLUTION

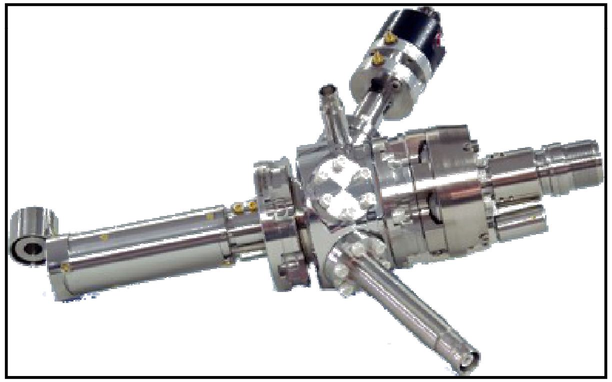


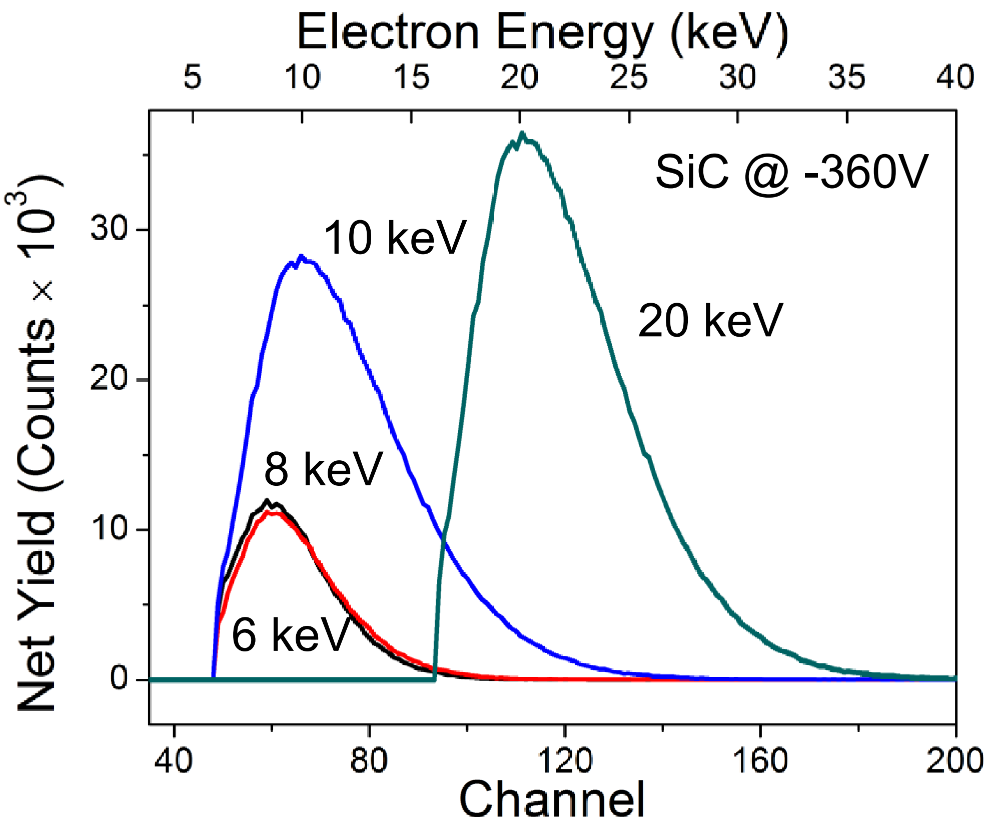
- Centroid
- Full Width Half Maximum (FWHM)



ELECTRON GUN







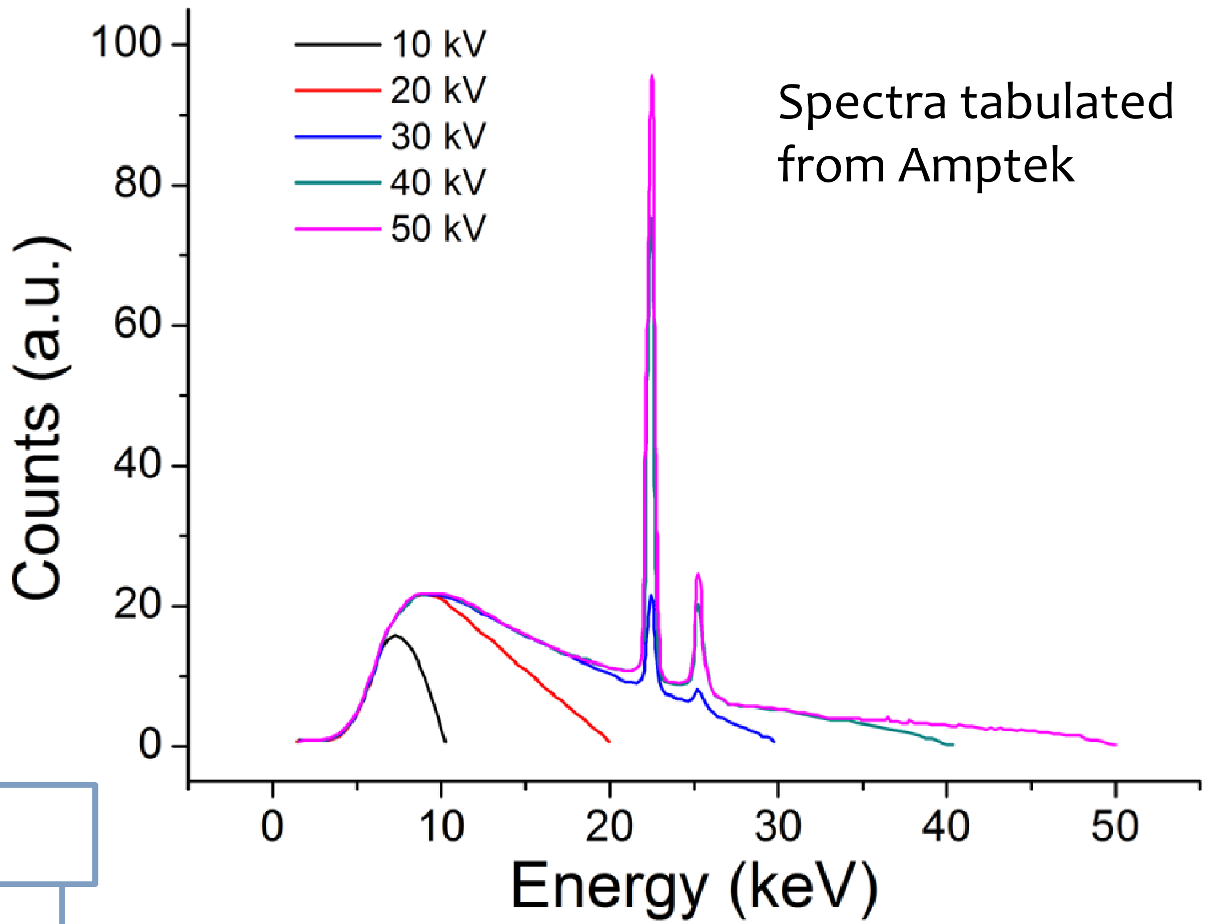
Kimball Physics
Electron Gun Systems
EGG-3101 Model

Energy: 100 eV - 20 keV
Beam current: 10 nA - 100μA

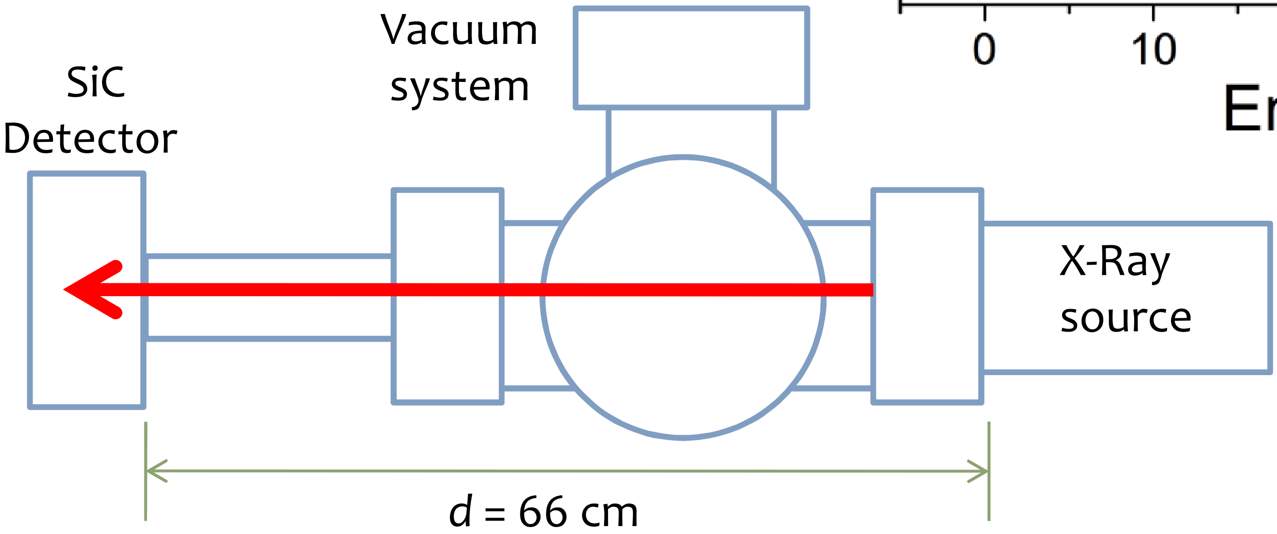
Acquisition time 300 s

X-RAY MEASUREMENTS (AMPTEK)

Mini X-Ray Tube
Tube voltage 1-50 kV
Tube current 5-80 μA
Silver Target

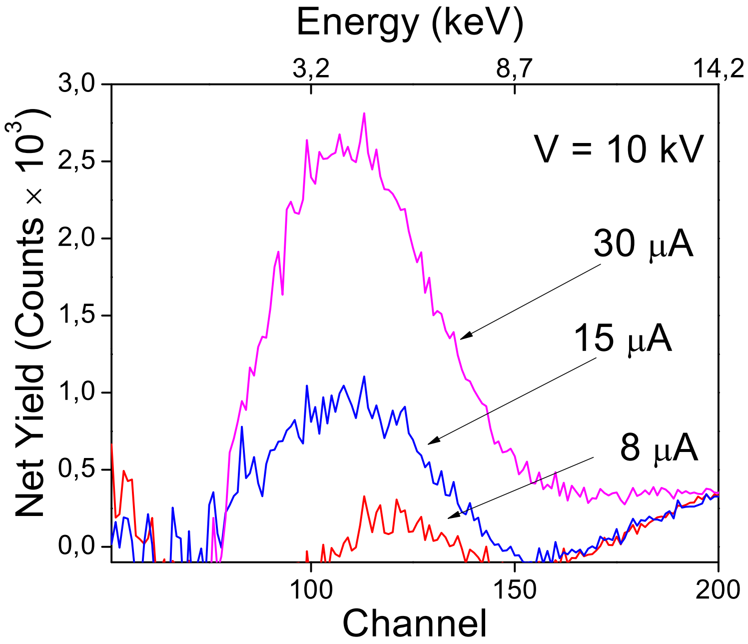


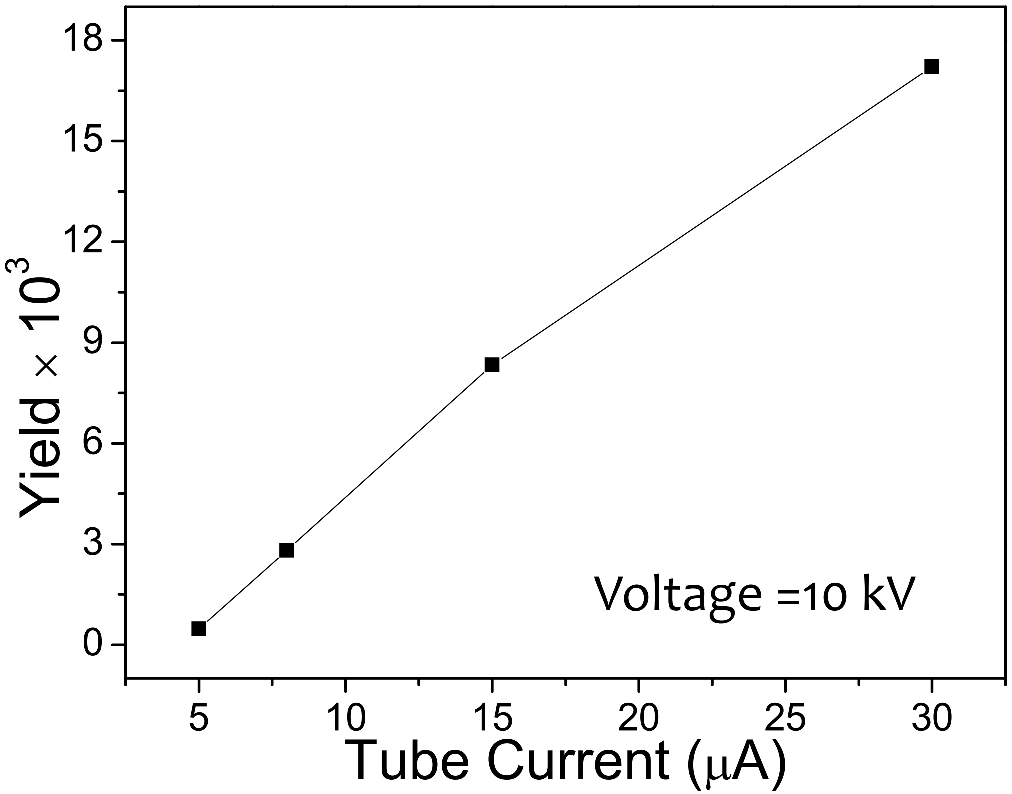
Spectra tabulated from Amptek

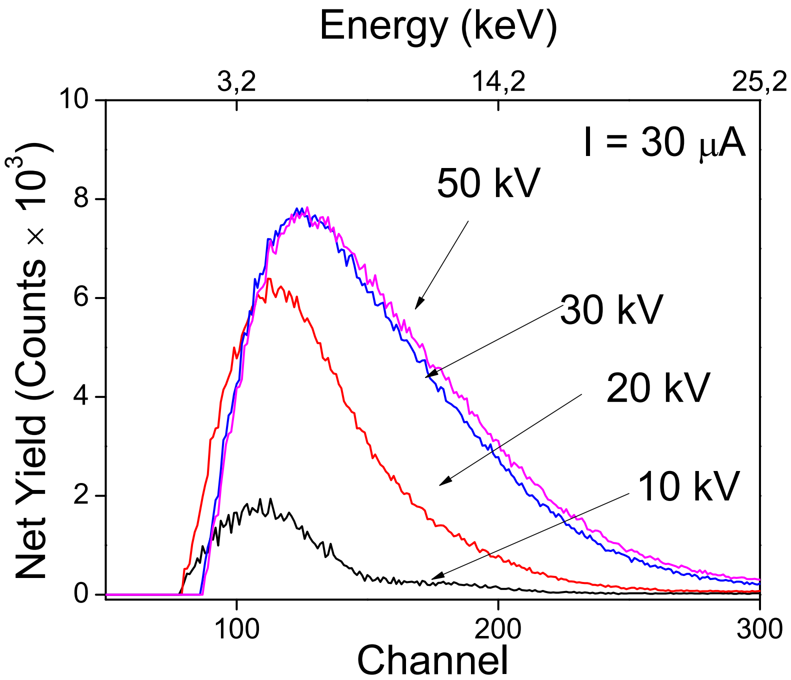


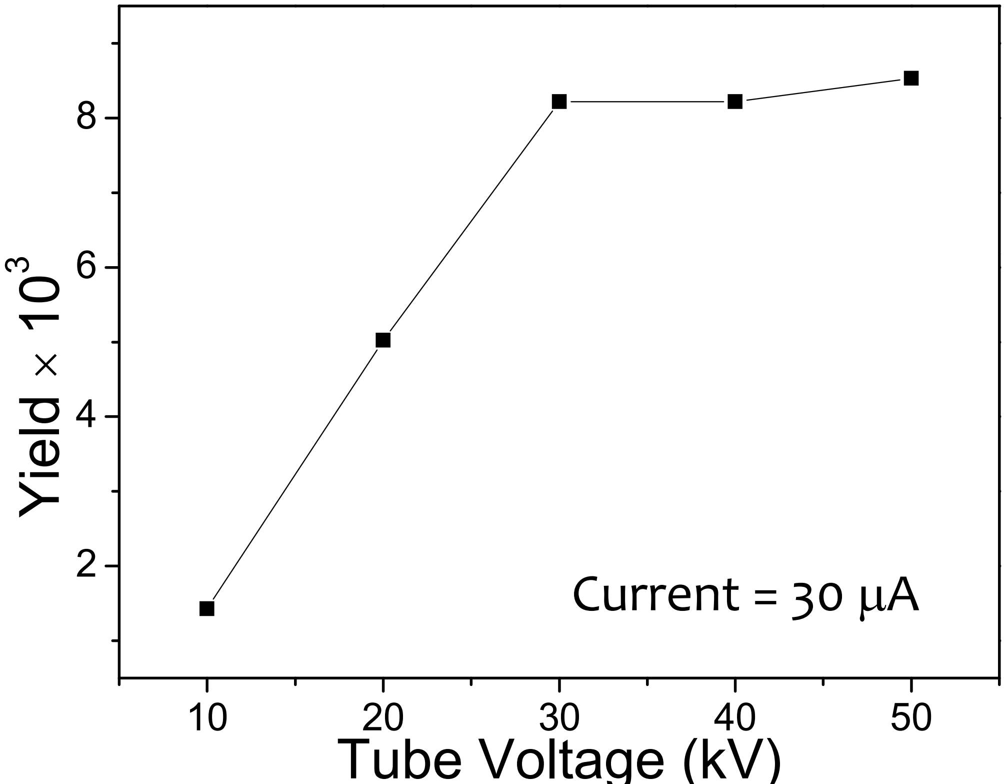
http://www.amptek.com/products/mini-x-ray-tube/

RESULTS

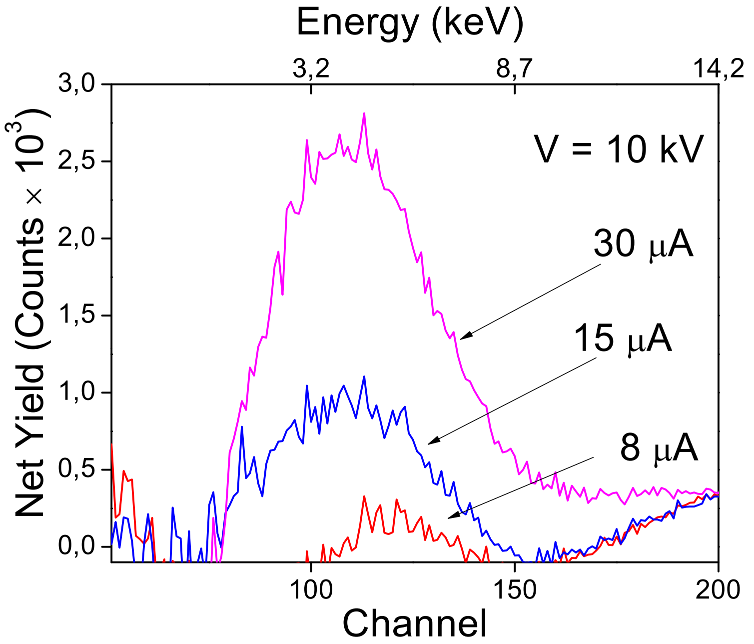

Energy (keV)
3,2
8,7
14,2
V = 10 kV
30 μA
15 μA
8 μA
Net Yield (Counts × 10³)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
100
150
200
Channel


18
15
12
9
6
3
0
Yield × 10³
Voltage =10 kV
5
10
15
20
25
30
Tube Current (μA)

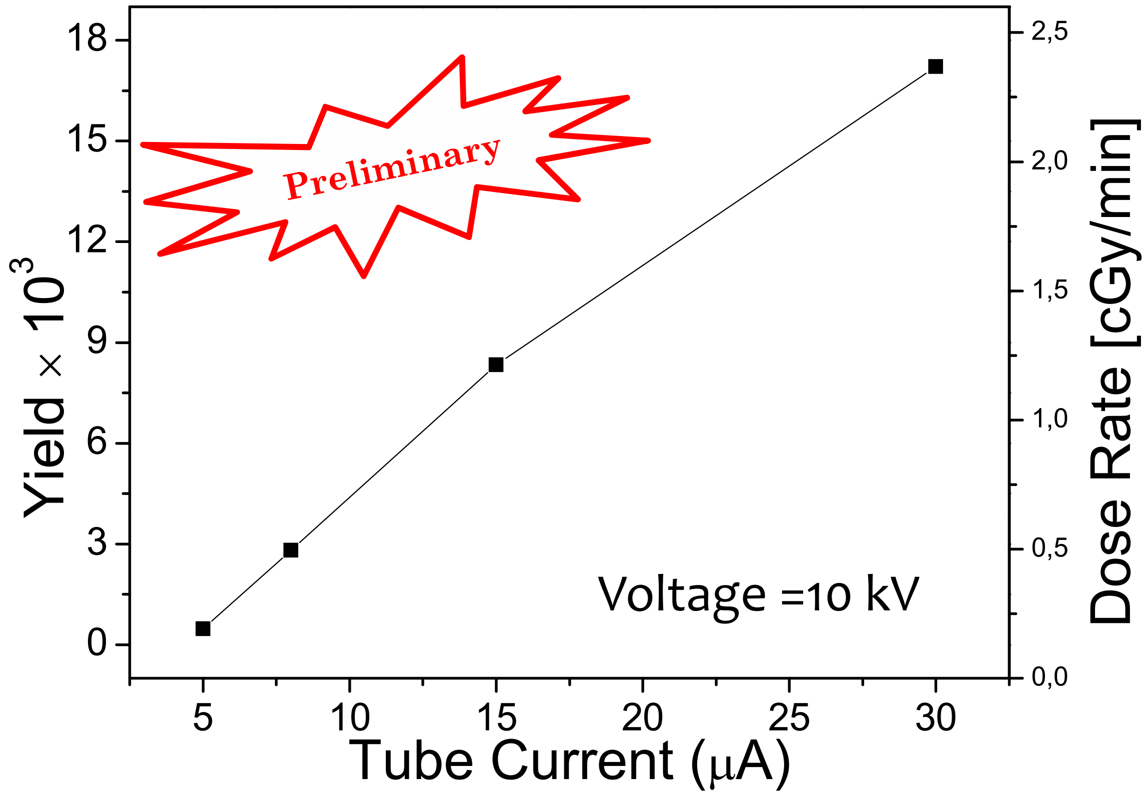

Energy (keV)
3,2
14,2
25,2
I = 30 μA
50 kV
30 kV
20 kV
10 kV
Net Yield (Counts × 10³)
10
8
6
4
2
0
100
200
300
Channel


8
6
4
2
Yield × 10³
Current = 30 μA
10
20
30
40
50
Tube Voltage (kV)

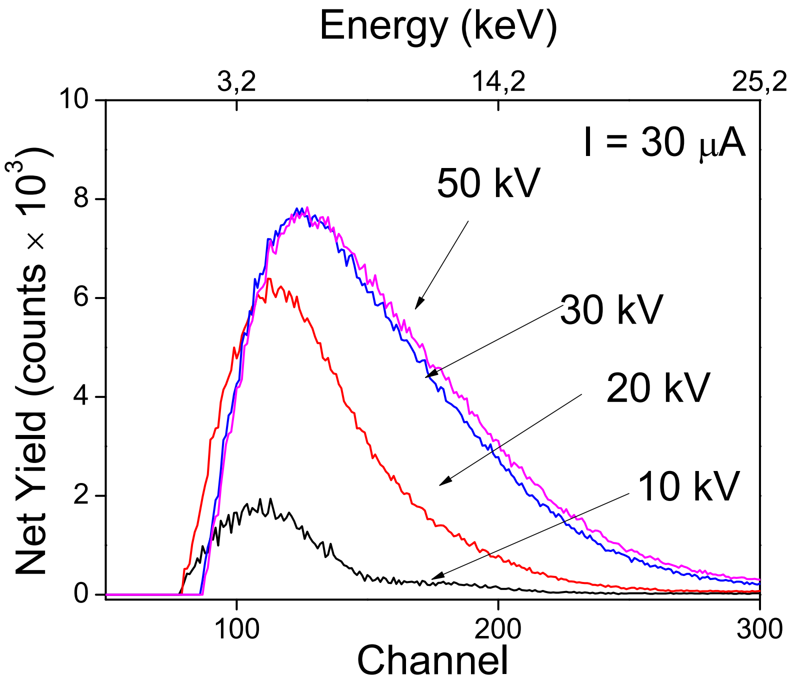
RESULTS



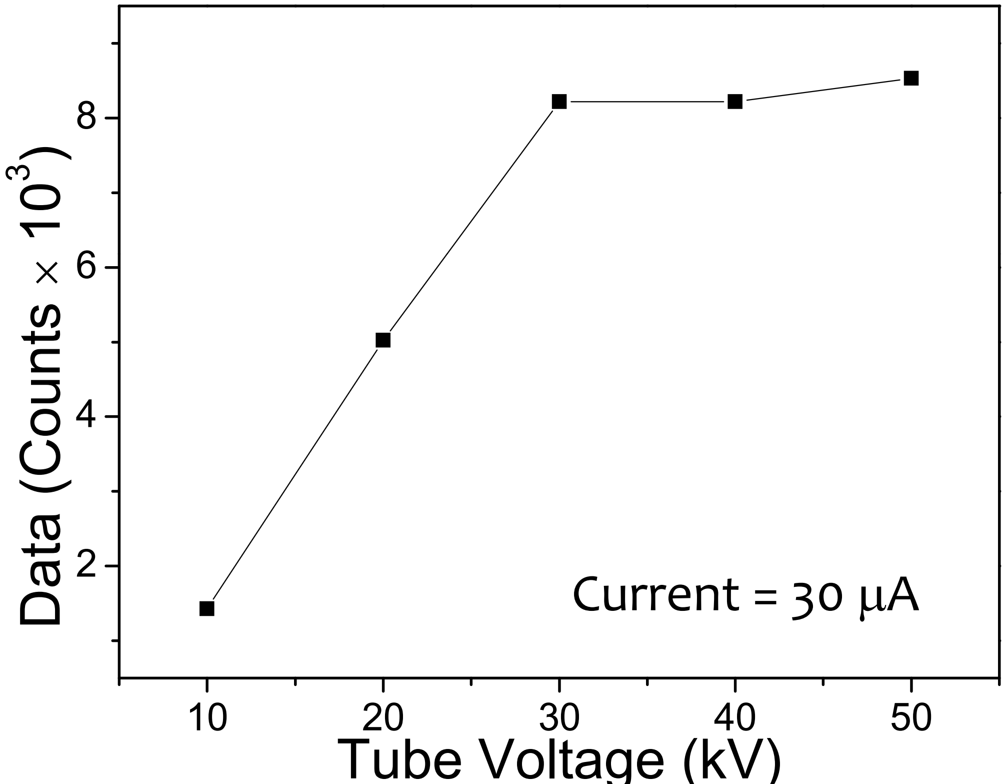
Energy (keV)
3,2
8,7
14,2
V = 10 kV
30 μA
15 μA
8 μA
Net Yield (Counts × 10^3)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
100
150
200
Channel



Preliminary
Yield × 10^3
18
15
12
9
6
3
0
Dose Rate [cGy/min]
2,5
2,0
1,5
1,0
0,5
0,0
Voltage =10 kV
5
10
15
20
25
30
Tube Current (μA)



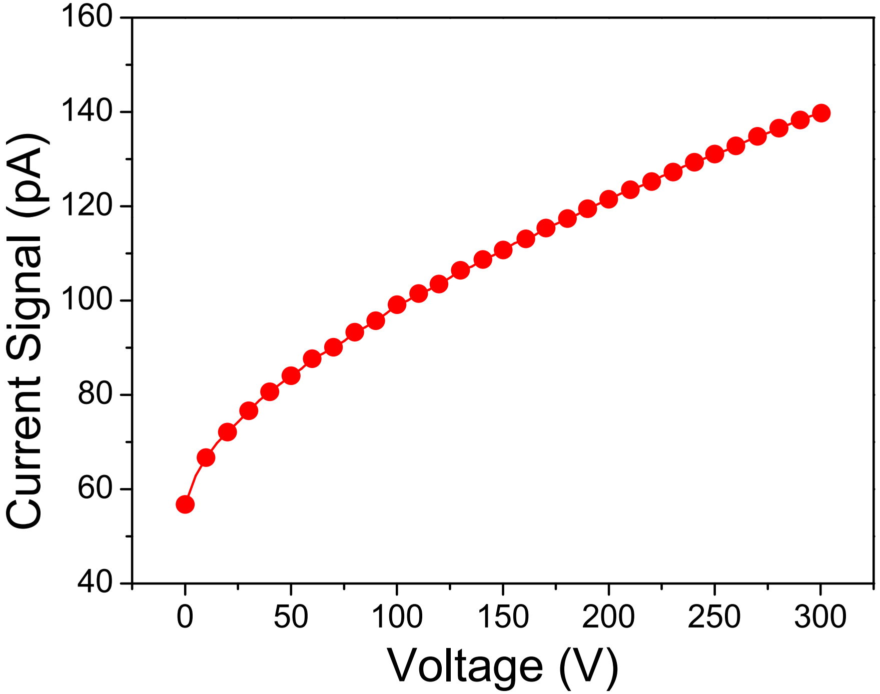
Energy (keV)
3,2
14,2
25,2
I = 30 μA
50 kV
30 kV
20 kV
10 kV
Net Yield (counts × 10^3)
10
8
6
4
2
0
100
200
300
Channel



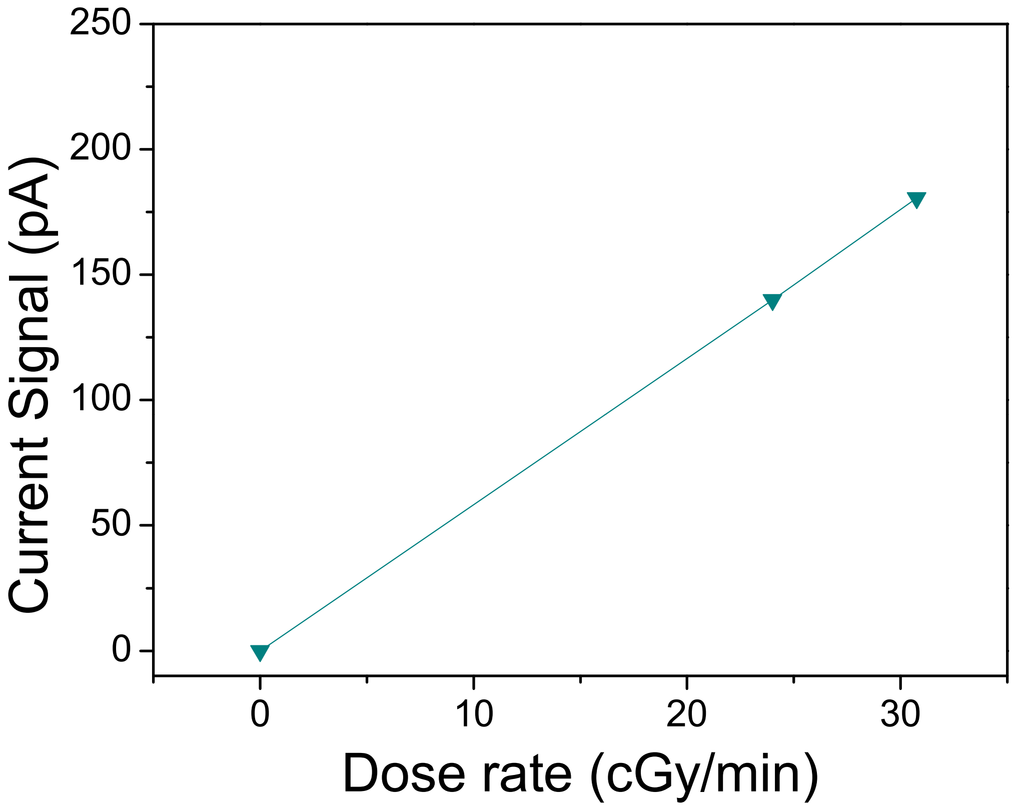
Data (Counts × 10^3)
8
6
4
2
Current = 30 μA
10
20
30
40
50
Tube Voltage (kV)

Application in radiation dosimetry

Preliminary



Source ^{60}Co (1.3 + 1.1 MeV)
SiC @ - 300 V
Dose Rate 0.24 Gy/min

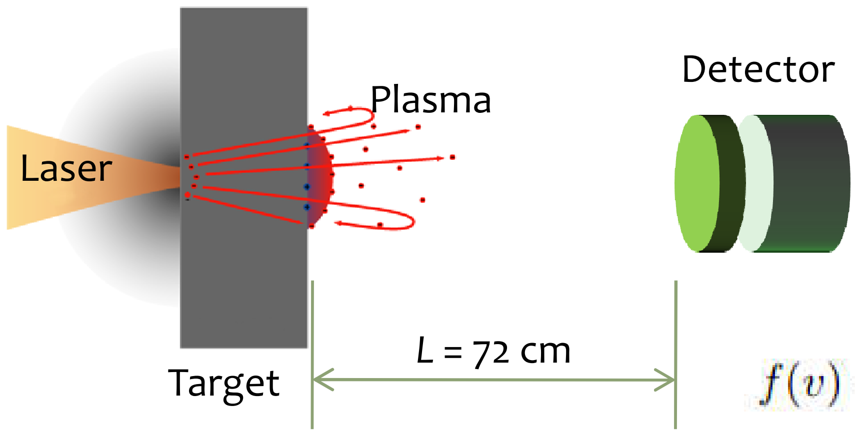


Source ^{60}Co
SiC @ - 300 V

M. Bruzzi et al., High quality SiC applications in radiation dosimetry, Applied Surface Science 184 (2001) 425-430

Radiation emitted by plasma-laser

TNSA configuration

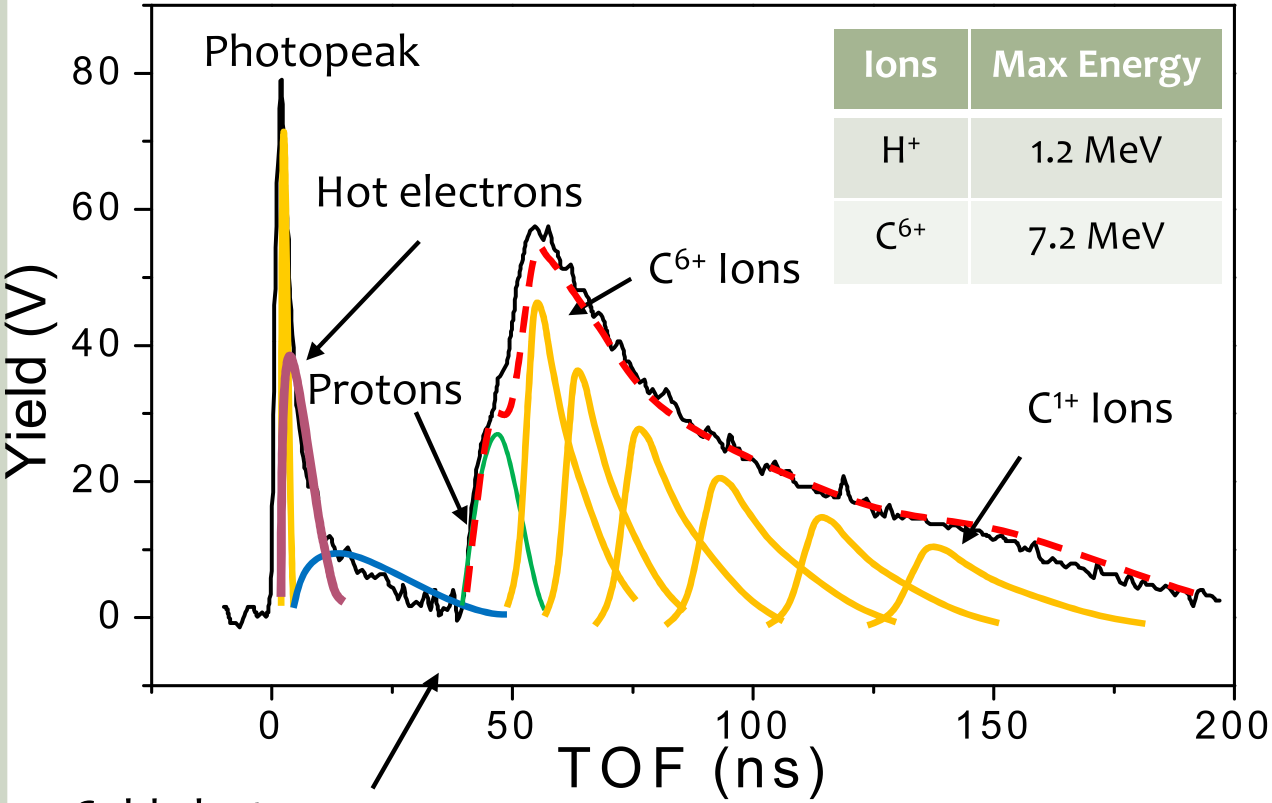


Coulomb

Boltzmann

Shifted

$$f(v) = A\sqrt{\left(\frac{m}{2\pi k_B T}\right)^3} v^3 \exp\left[-\left(\frac{m}{2k_B T}\right)(v - v_k - v_c)^2\right]$$



Ions	Max Energy
H^+	1.2 MeV
C^{6+}	7.2 MeV

PALS laboratory:
Iodine laser
Laser wavelength 1315 nm
Pulse energy 600 J
Pulse duration 300 ps
Intensity 10^{15} W cm^{-2}

Target–detector L = 72 cm
Targets Polyethylene PE
Target thickness 10 μm

http://www.pals.cas.cz/

Conclusions

SiC detector offers many advantages:

•The SiC detector with 80 μm depth active region allows to investigate hard X-rays, energetic electrons (~ 300 keV) and high ion energy (~ tens MeV);

•At low fluence a readout electronics in regime of proportionality to the energy radiation could be employed;

• Good linearity, efficiency, energy resolution comparable to Si (SSB) detector;

•In TOF regime SiC detector can be employed to detect high fluence radiation such those emitted from laser generated plasmas;

•More information can be extracted such as the ion energy distribution from plasma by using a Coulomb Boltzmann Shifted function distribution to deconvolve the TOF SiC spectra.

• The advantages to use SiC detectors instead than Si detector are due to the possibility to be employed in presence of high intensity visible light, to be employed at room temperature with a very low dark current of the order of 10 pA, the possibility to have higher sensitivity due to their linear response to the dose rate also using very low dose rates of the order of one cGy/min for photons

Reference

[1] L. Torrisi, M. Cutroneo, G. Ceccio, A. Cannavò et al., Near monochromatic 20 Me V proton acceleration using fs laser irradiating Au foils in target normal sheath acceleration regime, Phys. Plasmas 23, 043102 (2016)

[2] A. Cannavò, L. Torrisi, L. Calcagno, Energy resolution comparison between Si and SiC detectors, PhD Activity report 2014, ISSN 2038-5889

[3] A. Cannavò, L. Torrsi, Advanced SiC detectors for laser-generated plasma diagnostic, PhD Activity report 2015, ISSN 2038-5889

[4] L. Torrisi and A. Cannavò, SiC detector damage and characterization for high intensity laser-plasma diagnostics 2016 JINST 11 P05009

[5] L. Torrisi, A. Sciuto, L. Calcagno et al., Laser-plasma X-ray detection by using fast 4H-SiC interdigit and ion collector detectors 2015 JINST 10 P07009

[6] A. Cannavò, L. Torrisi, L. Calcagno, SiC detector characterization for radiation emitted by laser-generated plasmas, 2016 JINST 11 C05008

PARTICULAR THANKS TO

CNR IMM, Catania
ST Microelectronics, Catania
Dipartimento di Fisica, Catania
Dipartimento di Fisica, Messina
PALS laboratory, Prague

Thank you for the attention

Time-of-flight Regime