Research highlights in the CNA 3 MV tandem accelerator

Javier Garcia Lopez

Scientific Coordinator of CNA
3 MV TANDEM Laboratory

- All stable ions available: H – Au
- Energy range: 600 keV – few MeV
- Beam currents: μA – pA
- Continuous and pulsed beams

IBA Techniques (RBS, PIXE..)
Materials Modification
Irradiation Damage
Neutron Physics
Nuclear Instrumentation
Targets were prepared at the “Instituto de Ciencia de Materiales de Sevilla” (ICMS) by the NanoMatMicro group.

<table>
<thead>
<tr>
<th></th>
<th>GODINHO et al. (MS)</th>
<th>Vanderbist et al. (Ionic Implant.)</th>
<th>Raabe et al. (Ionic Implant.)</th>
<th>Ujic et al. (Ionic Implant.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal (10^{15} at/cm²)</td>
<td>9250 (Si)</td>
<td>1200 (Al)</td>
<td>4200 (Al)</td>
<td>1200 (Al)</td>
</tr>
<tr>
<td>He (10^{15} at/cm²)</td>
<td>4060</td>
<td>275</td>
<td>270</td>
<td>130</td>
</tr>
<tr>
<td>O (10^{15} at/cm²)</td>
<td>700</td>
<td>60</td>
<td>100</td>
<td>??</td>
</tr>
<tr>
<td>He/Si</td>
<td>0.44</td>
<td>0.22</td>
<td>0.06</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Self-supported solid target for inverse kinematics experiments with exotic nuclei

Development of He solid targets for nuclear reaction experiments

Si: $9250 \times 10^{15}$ at/cm$^2 = 430$ µg/cm$^2$
He: $4060 \times 10^{15}$ at/cm$^2 = 27$ µg/cm$^2$
O: $700 \times 10^{15}$ at/cm$^2 = 19$ µg/cm$^2$

$^4$He($^6$Li, $^6$Li)$^4$He Elastic scattering

Li$^{2+}$

$E = 6.0$ MeV
$\theta = 30^\circ$

Sample
detector

Counts

Energy (keV)

$^6$Li recoiled by Li
$^4$He recoiled by Li
Li scattered by $^4$He
Li scattered by Si
Characterization of $^{33}\text{S}$ samples for $^{33}\text{S}(n,\alpha)^{30}\text{Si}$ cross-section measurements at the n_TOF facility of CERN

J. Praena et al. NIM A 890 (2018) 142-147
3 MV TANDEM Laboratory

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IBA Techniques (RBS, PIXE..) Materials Modification Irradiation Damage Neutron Physics Nuclear Instrumentation
Epithermal neutrons (keV): astrophysics. $^7$Li(p,n) reaction

Monoenergetic protons → Al degrader

Stellar neutron spectrum at KT = 30 keV

J. Praena et al. NIM A, 727 1-6 (2013)

Fast neutrons: D(d,n) up to E(neutron) = 8 MeV

Bonner Spheres for neutron spectrometry
M. Romero-Expósito et al. Radiation Protection Dosimetry (2018), 180 80-84

Single Event Upset has been studied for the SRAMs developed in U. Islas Baleares.
### HiSPANoS TOF & n_TOF-CERN: comparison (from J. Praena)

<table>
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<tr>
<th>NEUTRON FLUX n/(cm²·s)</th>
<th>HiSPANoS TOF 7Li(p,n) Ep=2,5 MeV 0,5m</th>
<th>n_TOF EAR-1 (188m)</th>
<th>n_TOF EAR-2 (20m)</th>
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<td>Energy interval</td>
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<td>1 keV</td>
<td>4·10⁴</td>
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<tr>
<td>100 keV</td>
<td></td>
<td></td>
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<tr>
<td>100-300 keV (HiSPANoS)</td>
<td>3·10³</td>
<td>4,2·10⁵</td>
<td>7,3·10⁶</td>
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<td>1 MeV (n_TOF)</td>
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10 uA (after accelerator) * 40 ns (pulse width at chopper) * (500kHz) = 200 nA @ 500 kHz

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<tr>
<th>∆E/E</th>
<th>HiSPANoS (1ns - 0.5m)</th>
<th>HiSPANoS (1ns - 1m)</th>
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<td>1 keV</td>
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<td>5,4·10⁻⁴</td>
<td>8,5·10⁻³</td>
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Materials Modification
Irradiation Damage
Neutron Physics
Nuclear Instrumentation
Characterization of SC detectors

IAEA Coordinate Research Programme (CRP) F11016 (2011-2015)
“Utilization of ion accelerators for studying and modeling of radiation induced defects in semiconductors and insulators”

COOPERATION AND MUTUAL UNDERSTANDING LEAD TO GROWTH AND GLOBAL ENRICHMENT

NUS - Singapore
Turin - Italy
DU - India
CNA - Spain
Malaysia
IAEA
Surrey UK
SANDIA USA
Helsinki - Finland
Ruđer Bošković - Croatia
ANSTO - Australia
JAPAN
Ion Beam Induced Charge (IBIC)

Electrodes

Generation of e-h pairs
Ionization profile dE/dx (SRIM)

MeV ion beam

$E_{\text{initial}}$

Charge Collection Efficiency (CCE)

$$CCE = \frac{\text{Charge induced}}{\text{Charge generated}}$$

$$CCE_{\text{exp}} = \frac{E_{\text{measured}}}{E_{\text{deposited}}}$$

Counts

Energy (MeV)

$E_{\text{measured}}$

Fast oscilloscope

Charge sensitive preamplifier

Amplifier

ADC + MCA

Transient signal (TRIBIC)
IBIC analysis using a nuclear microprobe

- Ion beam current: nA to few pps (micrometric slits)

- Scanning system: few mm²

-Synchronous signal acquisition system with scanning: mappings

IBIC mappings 1x1 mm² of Si sample irradiated with 17 MeV protons to $1 \times 10^{13}$ p/cm²

100% CCE

90% CCE
CCE degradation induced by MeV ion beams in semiconductor devices

J. Garcia Lopez et al. NIMB 371 (2016) 294-297
E. Vittone et al. NIMB 372 (2016) 128-142

\[
CCE = \frac{1}{E_0} \int_0^w \frac{dE}{dx} dx \left[ \frac{1}{w} \int_x^w dy \left( e^{-\int_y^x \frac{dz}{L_{maj}(z)}} \right) + \frac{1}{w} \int_0^x dy \left( e^{-\int_y^x \frac{dz}{L_{min}(z)}} \right) \right]
\]

Drift lengths:
\[L_{maj, min}(x) = (\mu \tau(x))_{maj, min} E(x)\]

- Probability that majority carrier formed at \(x\) reaches electrode at \(x=w\)
- Probability that minority carrier formed at \(x\) reaches electrode at \(x=0\)

Inputs
- Electrostatics of the device (\(w\) vs \(V\); \(E(x)\))
- Ionization profile (from SRIM)

Free parameters: \(\tau_e\) and \(\tau_h\)
Shockley-Read-Hall model

\[
\tau(\phi, x) = \frac{\tau_0}{1 + k \cdot \sigma \cdot V(x) \cdot \phi \cdot v_{th} \cdot \tau_0}
\]

- \(\tau(x, \Phi)\): Carrier lifetime after irradiation
- \(\tau_0\): Carrier lifetime for pristine material (experimental)
- \(\Phi\): Particle fluence (experimental)
- \(V_{th}\): Thermal velocity of carriers (calculation)
- \(V(x)\): Vacancy-interstitials Frenkel pairs profile (calculation SRIM)
- \(k\): Average number of active traps per vacancy (unknown)
- \(\sigma\): Trap cross section (unknown)

\((k \cdot \sigma)\) is indicative of the relative radiation hardness of the semiconductor

Radiation hardness of Si and SiC detectors irradiated with 17 MeV energy protons

J. Garcia Lopez et al.
NIMB 372 (2016) 143-150
• Scan system ensures homogeneous irradiation

• Ion rates about 20 kHz can be easily achieved

• Typical irradiated area 100x100 μm²

• Several fluences can be irradiated in a single device with minimum increase of the leakage current

• Fluence is calculated from number of pulses in acquisition system divided by the irradiated area (~1% uncertainty)

• Time required to achieve $10^{12}$ ions/cm² about 80 minutes
IAEA Coordinate Research Programme (CRP) F11020 (2017-2020)
“Ion beam induced spatio-temporal structural evolution of materials: Accelerators for a new technology era”

Safe, secure and peaceful use of nuclear technology

IAEA

BAC-INDIA

ANSTO AUSTRALIA

LLNL USA

BINA-ISRAEL

Melbourne Univ AUSTRALIA

QST-JAPAN

Singapore Univ SINGAPORA

CNA-SPAIN

Helsinki Univ FINLAND

Peking Univ CHINA

RBI CROATIA
• Irradiation at NDCX-II in Berkeley

Full fluence delivered in a single pulse $\sim 10$ ns.

Flux $\sim 10^{19}$ ions/cm$^2$s

Increase of temperature $\rightarrow$ Lower damage
Accumulation of cascades $\rightarrow$ Higher damage

• Irradiation at CNA

Ion current $\sim 10^4$ ions/s. Irradiated area 100x100 $\mu$m$^2$

Flux $\sim 10^8$ ions/cm$^2$s

Damaging ion beam: He$^+$ 1 MeV

Probing ion beam: He$^+$ 2 MeV

Fluences: 0.25 to $4 \times 10^{11}$ ions/cm$^2$
IBIC analysis of Hamamatsu S5821 PIN diodes

IBIC map (1.5X1.5 mm²) for diode #5 irradiated at LBNL

IBIC map (1.3X1.3 mm²) for diode irradiated at CNA

<table>
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<tr>
<th>$k\sigma$ (cm²)</th>
<th>LBNL</th>
<th>CNA</th>
</tr>
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<tbody>
<tr>
<td>$k\sigma$ (holes)</td>
<td>$4\pm1\times10^{-15}$</td>
<td>$4.5\pm0.5\times10^{-15}$</td>
</tr>
<tr>
<td>$k\sigma$ (electrons)</td>
<td>$1.6\pm0.3\times10^{-15}$</td>
<td>$0.7\pm0.1\times10^{-15}$</td>
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Changing the dose rate by about 10 orders of magnitude affects damage accumulation by a factor of two.
Spectrometric properties of commercial (Canberra, Ortec) thick Si(Li) detectors for charged particles

**KEY FEATURES:**

- Thickness up to 5 mm (up to 30 MeV protons, 3 MeV betas)
- Working at Room Temperature
- Areas from 200 mm$^2$ up to 1600 mm$^2$

**DRAWBACKS:**

- Large leakage current (several µA)
- Need high bias voltage (hundred volts)
- Sensitive to gamma-rays (Compton background)

**Use at CNA:**

- Characterization of the 18 MeV proton beam of the Cyclotron external beam
- **Depth profiling of $^3$He implanted in nanostructured W films**
Tungsten is the best candidate for plasma facing materials (PFM) applications, in both magnetic and inertial confinement nuclear fusion reactors.

Major threats to PFM: the arrival of high fluxes of energetic particles (mainly D, T, He and C)

Diffusion and retention of $^3$He and $^{12}$C

Samples implanted at JANNUS facility (Orsay, France)

Implantation depth $\sim$ 3 $\mu$m

Nominal fluence: 50x10$^{15}$ at/cm$^2$

Depth profiling at CNA using NRA

$^{12}$C(d,p)$^{13}$C $\ Q = 2.72$ MeV

$^3$He(d,p)$^4$He $\ Q = 18.35$ MeV

https://www.euro-fusion.org
NRA spectrum of $^3\text{He}$ and $^{12}\text{C}$ implanted nanostructured W film

Si(Li) detector: 5 mm thick; 300 mm$^2$
NRA spectrum of $^3$He and $^{12}$C implanted nanostructured W film

$\text{Ed}=1.5 \text{ MeV}$
$\theta=86 \text{ degrees}$

Counts

Energy (keV)

1900 counts

1050 counts

Peak from implanted $^3$He

Diffused $^3$He?
Odd detector behavior?
Spectrum from triple alpha source

Si(Li) detector: 5 mm thick; 300 mm²
Spectrometric properties of 5 mm thick Si(Li) detectors vs Radial position

- IBIC spectra using 1 MeV and 4 MeV protons
- Collimated beam (200 μm)
- Low count rate (~ 100 Hz) to avoid detector damage
- Beam fixed: detector moves using stepping motors

Only 38% of detector presents 100% CCE
Time response: charge collection time
Center of detector

Lithium-drifted “intrinsic” region

\[ E = \frac{V}{D} \]

n\textsuperscript{+} layer

Ramo’s theory:
\[ dq = q_0 \frac{dx}{D} \]

Equation of motion:
\[ dx = v_e dt = \mu_e E dt \]

\[ \frac{Q_e(t)}{q_0} = \frac{\mu_e E t}{D} = \frac{\mu_e V t}{D^2} \]

Collection time \( t_c = \frac{D^2}{\mu_e V} \approx 400 \text{ ns} \)

TRIBIC signal measured at the center of the detector

\[ T_{\text{RIBIC}} = 388 \text{ ns} \]
Time response: charge collection time
Edge of detector

\[ E(x) = E_0 (1 - \frac{x^2}{D^2}) \]

\[ n^+ \text{ layer} \]

Ramo’s theory:
\[ dq = q_0 \frac{dx}{D} \]

Equation of motion:
\[ dx = v_e dt = \mu_e E dt \]

\[ \frac{Q_e(t)}{q_0} = tgh\left(\frac{\mu_e E_0 t}{D}\right) \]

Collection time \( t_c \approx 2 \frac{D^2}{\mu_e V} \approx 800 \text{ ns} \)

TRIBIC signal measured at the edge of the detector

Longer collection time +
Defects (short carrier lifetime)
Low CCE
CERN RD50 Collaboration

**RD50**-Radiation hard semiconductor devices for very high luminosity colliders.
2. The main objective is:
   - Development of radiation hard semiconductor detectors for the luminosity upgrade of the LHC to $7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$.
3. One of the most important challenges is to achieve **radiation hardness up to $10^{16}\text{cm}^{-2}$**
4. The current activities of RD50 include:
   a) Identifying the defects through dedicated measurement techniques (DLTS, TSC, TCT) or monitoring the macroscopic changes in HEP experiments.
   b) Work out how to get rid of damage (or avoid it) —new technologies, new structures (3D sensors, HV CMOS, LGAD, simulation (FLUKA, GEANT4, TCAD…).
   c) test the solution:
      - neutron exposition in nuclear reactor,
      - proton irradiation at cyclotrons and synchrotrons,
      - new dedicated irradiation center @ CERN.
   d) Incorporate the feedback from experiments.

Source: Agnieszka Obłąkowska
The LGAD structures are optimized as tracking or timing detectors for high energy physics experiments where time resolution lower than 30 ps is required.

IBIC studies

- Gain homogeneity
- Behavior of peripheral areas
- Cross-talk effects
- Time evolution of the induced signal
- Comparison with laser measurements
IBIC analysis using 3 MeV protons

Maps
2.5 x 2.5 mm²

2.5 x 2.5 mm²

V = 90 volts

Peripheral structures

Inhomogeneous lateral gain (~ 10%)

V = 38 volts

More homogeneous lateral gain

Electric defect
* Neutron imaging (CHANDA)

* 3D-Si microdosimeters (U. Santiago, CNRS)

* Diamond detectors (Eurofusion, CHANDA)

* Fast Ion Loss Detectors (Eurofusion, ITER)

Thank you for your attention!!!
Back-up slides
Effective trapping cross section $k\sigma$

### One dimension

**Shockley-Read-Hall model**

$$\tau(x, \Phi) = \frac{\tau_0}{1 + k \cdot V(x) \cdot \sigma \cdot v_{th} \cdot \Phi \cdot \tau_0}$$

#### n-Si

- $\Phi = 5 \times 10^{12} \text{ p/cm}^2$: $(k\sigma)_h = 3.9 \pm 1.2 \times 10^{-16} \text{ cm}^2$
- $\Phi = 1 \times 10^{13} \text{ p/cm}^2$: $(k\sigma)_h = 4.5 \pm 1.1 \times 10^{-16} \text{ cm}^2$
- $(k\sigma)_e = 0.9 \pm 0.6 \times 10^{-16} \text{ cm}^2$
- $(k\sigma)_e = 0.8 \pm 0.5 \times 10^{-16} \text{ cm}^2$

**From DLTS, the most prominent electrically active defect induced by swift-ion irradiation in low doped n-type Si is $V_2(-/0)$**

- $(APL \ 98 \ (2011))$

- $\sigma_h \ V_2(-/0) = 5 \times 10^{-14} \text{ cm}^2$

- $\sigma_e \ V_2(-/0) = 5 \times 10^{-15} \text{ cm}^2$

**From $(k\sigma)_h$ and $(k\sigma)_e$**

$k \approx 1-2 \times 10^{-2}$

**About 1-2 % of the vacancies created by 17 MeV protons form electrically active traps in low-doped n-type Si**
<table>
<thead>
<tr>
<th></th>
<th>n-SiC</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_h(0)$</td>
<td>$560 \times 10^{-9}$ s ; $\tau_h(1 \times 10^{12}$ p/cm$^2) = 2 \times 10^{-9}$ s</td>
<td>$\tau_h(0)$</td>
</tr>
<tr>
<td>$V(x)$</td>
<td>$200$ vacancies/cm/ion; $v_{th}$ (holes) = $1.2 \times 10^7$ cm/s</td>
<td>$V(x)$</td>
</tr>
</tbody>
</table>

\[
\frac{k\sigma_h(SiC)}{k\sigma_h(Si)} \approx 250
\]

SiC is less “proton hard” compared to Si
HiSPANoS: chopper and buncher upstream terminal.

- 8 MHz single-drift
- Repetition rate = 2 MHz, 1 MHz, 500 kHz
- Pulse width -> FWHM=1 ns after terminal (HE) y before the analyzing magnet.
- Downstream the analyzing magnet ---> FWHM=2-3 ns.
- System will be ready to bunch protons and deuterons.
- Other ions need a previous study of the voltages.
**Shockley–Ramo theory**: induced current in the external circuit is due to charge carriers moving under influence of electric field in the sensitive volume of SC device.

Large E field; Defect free SC → $Q_s$

Low E field; Presence of defects → $Q_s$

$V_{out} \propto Q_s$

Deposited energy

Transport of free carriers
Drift-diffusion model: no recombination into drift region

Only Drift term
(majority + minority carriers)

\[ CCE = \frac{1}{E_i} \int_0^w \frac{dE}{dx} \, dx = 1 \]

Measuring transport properties of SC:
Curves CCE vs Voltage

![Diagram showing drift and depletion region with 4 MeV protons and minority carriers.](image)

V = 30 V
w = 300 µm

![Graph showing CCE vs reverse bias and energy vs counts.](image)
Drift-diffusion model: no recombination into drift region

Only Drift term
(majority + minority carriers)

\[ CCE = \frac{1}{E_i} \int_0^w \frac{dE}{dx} \, dx = 1 \]

V=15 V
w=230 μm

4 MeV protons

Depletion region
Neutral region

Drift

Counts

Reverse Bias (V)

Energy (MeV)

4 MeV

\( w \)
Drift-diffusion model: no recombination into drift region

Only Drift term
(majority + minority carriers)

\[ CCE = \frac{1}{E_i} \int_0^w \frac{dE}{dx} dx = 1 \]

Depletion region
Neutral region

\( w = R_p \)

\( V = 7 \, \text{V} \)
\( w = 160 \, \mu\text{m} \)

\( 4 \, \text{MeV protons} \)

\[ \text{Energy (MeV)} \]

\[ \text{Counts} \]

\[ \text{Reverse Bias (V)} \]
Drift-diffusion model: no recombination into drift region

\[ CCE = \frac{1}{E_i} \left( \int_0^w \frac{dE}{dx} \, dx + \int_w^{R_p} \frac{dE}{dx} e^{-\frac{x-w}{L_{\text{diff}}}} \, dx \right) \leq 1 \]

- Drift term (majority + minority carriers)
- Diffusion term (only minority carriers)

- Depletion region
- Neutral region
- Diffusion
- Drift

4 MeV protons

V = 5 V
w = 130 \( \mu \)m

\[ L_{\text{Diff}} = \text{Diffusion length of minority carriers} \]

3.8 MeV

Energy (MeV) vs. Reverse Bias (V)
Drift-diffusion model: no recombination into drift region

\[ CCE = \frac{1}{E_i} \left( \int_0^w \frac{dE}{dx} \, dx - \int_w^{R_p} \frac{dE}{dx} e^{-\frac{x-w}{L_{\text{Diff}}}} \, dx \right) \leq 1 \]

Depletion region

Neutral region

4 MeV protons

\( V = 4 \, \text{V} \)

\( w = 110 \, \mu\text{m} \)

\( L_{\text{Diff}} = \text{Diffusion length of minority carriers} \)

\[ \text{Diffusion} \]

\[ \text{Drift} \]

\[ \text{Counts} \]

\[ \text{Energy (MeV)} \]
Drift-diffusion model: no recombination into drift region

\[
CCE = \frac{1}{E_i} \left( \int_0^w \frac{dE}{dx} \, dx - \int_w^{R_p} \frac{dE}{dx} e^{-\frac{x-w}{L_{\text{Diff}}}} \, dx \right) \leq 1
\]

Depletion region
Neutral region

\( L_{\text{Diff}} = \text{Diffusion length of minority carriers} \)

V = 3 V
w = 95 \, \mu m

4 MeV protons

Drift term
(majority + minority carriers)

Diffusion term
(only minority carriers)

\( dE/dx \) (keV/\mu m)

Depth (\mu m)

\( dE/dx \) (keV/\mu m)

Energy (MeV)

Counts
Drift-diffusion model: no recombination into drift region

\[ CCE = \frac{1}{E_i} \left( \int_0^w \frac{dE}{dx} \, dx \right) + \int_w^{R_p} \frac{dE}{dx} e^{-\frac{x-w}{L_{diff}}} \, dx \leq 1 \]

Drift term
(majority + minority carriers)

Diffusion term
(only minority carriers)

\[ L_{Diff} = \sqrt{D_{\min} \cdot \tau_{\min}} \]

Minority carriers lifetime

V=0 V
\( w=75 \mu m \)

Depletion region
Neutral region

4 MeV protons

Diffusion

Reverse Bias (V)

Counts

Energy (MeV)

2.0 MeV
Radiation hardness of Si and SiC detectors irradiated with high energy protons

FZ n-type Si diodes
(Helsinki Institute of Physics)
300 μm intrinsic layer
Doping ~ 5x10^{11} at/cm³

C-V characteristics:
HIP and Sandia labs

50 μm thick n-type 4H-SiC epilayer on 4H-SiC substrate
(Japan Atomic Energy Agency)
1 mm x 1 mm x 80 nm Ni Schottky contact
Doping ~ 5x10^{14} at/cm³
Irradiation with 17 MeV protons

Proton fluences

N-type Si: $5 \times 10^{12}$ p/cm$^2$ - $1 \times 10^{13}$ p/cm$^2$

N-type SiC: $1 \times 10^{12}$ p/cm$^2$ - $1 \times 10^{13}$ p/cm$^2$

Vacancy profile (SRIM)

$\tau(\chi, \Phi) = \tau(\Phi)$

Radiation damage can be described in terms of $\tau(\Phi)_{e,h}$
Results: n-type Si

\[ \frac{\tau_h(\phi = 0)}{\tau_h(\phi = \frac{10^{13} \text{p}}{\text{cm}^2})} \approx 30 \]
Results: n-type SiC

![Graph showing CCE behavior at high bias for n-type SiC with different concentrations and lifetimes.]

\[
\frac{\tau_h(\phi = 0)}{\tau_h(\phi = \frac{10^{13} p}{cm^2})} \approx 1000
\]

CCE behavior at high bias

- Si (100% → 93.6%)
- SiC (100% → 98.7%)
HiSPANoS TOF & n_TOF-CERN: comparison.

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<td>100-300 keV (HiSPANoS)</td>
<td>5·10³</td>
<td>4,2·10⁵</td>
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<th>n_TOF EAR-1 (6ns - 188m)</th>
<th>n_TOF EAR-2 (6ns - 20m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy interval</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 keV</td>
<td>8,8·10⁻⁴</td>
<td>4,4·10⁻⁴</td>
<td>5,4·10⁻⁴</td>
<td>8,5·10⁻³</td>
</tr>
<tr>
<td>1 MeV</td>
<td>2,8·10⁻²</td>
<td>1,4·10⁻²</td>
<td>3,6·10⁻³</td>
<td>4,1·10⁻²</td>
</tr>
</tbody>
</table>

20 uA * 0.25 (8 MHz) *0.075 (500kHz) *0,9 (Tank Transmission) = 330 nA @ 500 kHz.
Cyclotron 18 MeV H⁺/ 9 MeV D⁺

- Radioisotope production for PET (¹⁸F, ¹¹C…)
- Irradiation of materials, high energy PIXE

2 m thick concrete wall

Cyclotron vault

Experimental vault

Cyclotron CNA model