Non-Ionising Energy Loss (NIEL) Calculation Software and Verification

Key people involved:

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P.G. Rancoita, D. Rozza, M. Tacconi

Institutions/Company: Univ. and INFN Milano-Bicocca, IMEM-CNR, CESI

General Support Technology Programme (GSTP)
Contract No.: 4000116146/16/NL/HK
Total Amount of Contract: € 390,000

Project Manager: Massimo Gervasi
ESA Technical Officer: Petteri Nieminem
Contract Duration: 17-12-2015 - December 2017

P.G. Rancoita, ESTEC 7 March, 2017

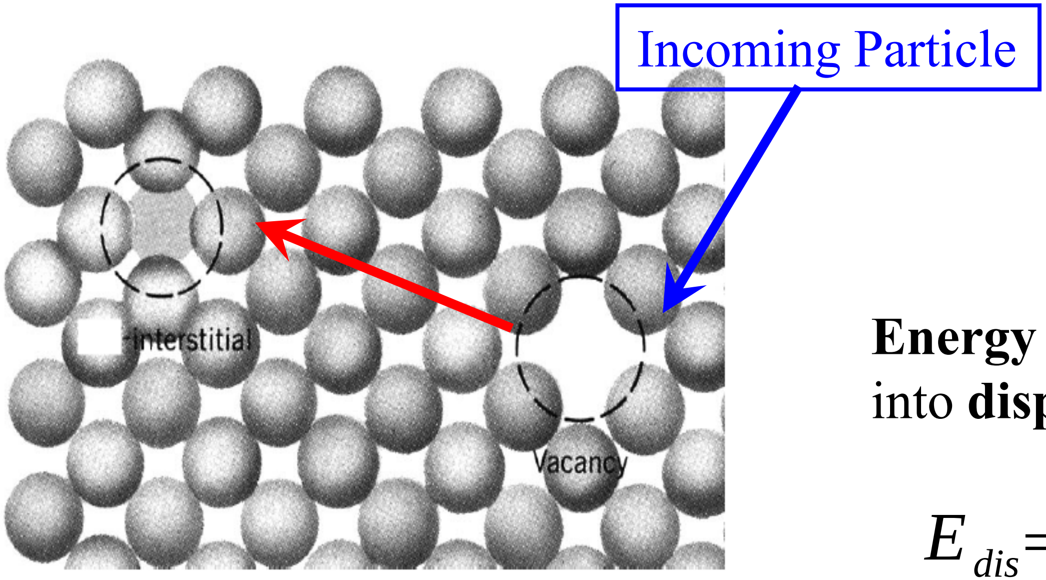
Second Year Tasks
(kick-off date Dec 16, 2015: from Dec 17. 2016 → 16 Dec. 2017)

Task 4: NIEL Data Analyses, Model and Software Framework Updates, Recommendations (2nd year)
Task 5: Maintenance (2nd year)
(Univ. and INFN Milano-Bicocca)

Task 3: DLTS measurements of Irradiated Test Samples (2nd year)
(Univ. and INFN Milano-Bicocca, IMEN-CNR, CESI)

SR-NIEL

Displacement Damage and NIEL



Frenkel-pairs:

$$FP \approx \frac{E_{dis}}{2.5T_d}$$

Displacement threshold energy

Energy density which goes into **displacement** [MeV/cm^3]:

$$E_{dis} = \int_{E_{\min}}^{E_{\max}} NIEL(E)\Phi(E)dE$$

Minimum incoming energy to generate displacement

Non-Ionizing Energy Loss:

$$NIEL(E) = N \int_{T_d}^{T_{\max}} TL(T)\frac{d\sigma(T,E)}{dT}dT$$

$\Phi(E)$: Spectral Fluence [cm^{-2}]
N: Number of Target Atoms [cm^{-3}]
T: Target kinetic Energy
$L(T)$: Lindhard’s partition function
$\frac{d\sigma(T,E)}{dT}$ differential cross section

Proton or nucleus Coulomb Cross Section on nuclei (>about 50 keV/nucl)

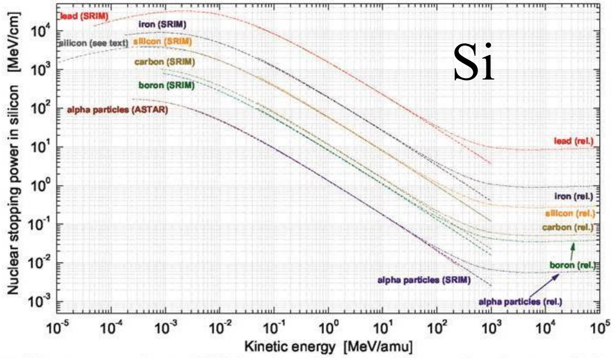


Fig. 2.23 Nuclear stopping powers (in units of MeV/cm) in a silicon medium for α-particles, boron-, carbon-, silicon-, iron- and lead-ions function of the kinetic energy of incoming ions in units of MeV/amu. The data for α-particles (ASTAR) are from [Berger, Coursey, Zucker a Chang (2010)]; those indicated as "silicon (see text)" are calculated using Eq. (2.79) for incoming ^{28}Si ions; the data for ^{208}Pb ("lead"), ("iron"), ^{28}Si ("silicon"), ^{12}C ("carbon"), ^{11}B ("boron") ions and α-particles - indicated as "SRIM"- are those available in [Ziegler, J.F. and M and Biersack (2008b)]. The data for ^{208}Pb ("lead"), ^{56}Fe ("iron"), ^{28}Si ("silicon"), ^{12}C ("carbon"), ^{11}B ("boron") ions and α-particles - indicat as "rel." - are obtained from Eq. (2.93) with a screening parameter modified using Eqs. (2.95 , 2.96).

It is based on the relativistic extension to ion-ion screened Coulomb scattering of the Wentzel-Moliere treatment - already used for electron and muon scattering in Geant4 –

$$\boxed{\frac{d\sigma(\theta)}{d\Omega}=\left(\frac{Z_1Z_2e^2}{pc\beta}\right)^2\frac{1}{(2A_s+1-\cos\theta)^2}}$$

with Moliere screening parameter

$$A_s=\frac{1}{4}\left(\frac{\hbar}{pa_{TF,un}}\right)^2\left[1.13+3.76\left(\frac{\alpha Z_1Z_2}{\beta}\right)^2\right]$$

m_1, m_2 are the rest masses of the two particles

$M_{1,2}$ is the invariant mass

$$\boxed{\begin{gathered}\frac{1}{\beta^2}=1+\left(\frac{\mu c^2}{pc}\right)^2\\ \mu=\frac{m_1m_2}{M_{1,2}}\end{gathered}}$$

and with screening lengths as in ICRU-49 (1993)

If Z_1 =1 **for incident particle** **If Z_1 >1**

$$\boxed{a_{TF}=\frac{0.88534a_0}{Z_2^{1/3}}}$$

$$\boxed{a_{un}=\frac{0.88534a_0}{\left(Z_1^{.23}+Z_2^{.23}\right)}}$$

References:

C. Leroy and P.G. Rancoita (2016), Principles of Radiation Interaction in Matter and Detection - 4th Edition -, World Scientific (Singapore), Sects. 2.2-2.2.2 (from 2nd edition)

M.J. Boschini et al. "Nuclear and Non-Ionizing Energy-Loss for Coulomb Scattered Particles from Low Energy up to Relativistic Regime in Space Radiation Environment." Proc. of the 12° ICATPP, Como 7-8/10/2010), World Scientific (Singapore) 2011, 9-23

Below 50 keV, use ZBL screened universal potential approach as from ICRU 1993 (protons and alphas)

ZBL Approximation
(lower than about 50 keV/nucl)

Approximation of the Ziegler, Biersack and Littmark (ZBL) screened potential

$$\boxed{d\sigma = \frac{-\pi \cdot a_U^2}{2}\,\frac{f(t^{\frac{1}{2}})}{t^{\frac{3}{2}}}}$$

The function *f(x)* comes from the fit (with 4 coefficients) of the nuclear stopping power as function of the universal reduced energy ε

$$t = \varepsilon^2 \frac{T}{T_{\max}}$$

Collision parameter

$$\varepsilon = \frac{a_U \cdot m_2}{e^2 Z_1 Z_2 (m_1 + m_2)} E$$

ZBL universal reduced energy

and with screening lengths as in ICRU-49 (1993)

If Z_1 =1 **for incident particle** **If Z_1 >1**

$$\boxed{a_{TF} = \frac{0.88534 a_0}{Z_2^{1/3}}}$$

$$\boxed{a_{un} = \frac{0.88534 a_0}{\left(Z_1^{.23} + Z_2^{.23}\right)}}$$

References:

S. R. Messenger et. al, “NIEL for Heavy Ions: An Analytical Approach”, IEEE Transaction on Nuclear Science, V 50, N 6 (2003)

S. R. Messenger et. al, “The Simulation of Damage Tracks in Silicon”, IEEE Transaction on Nuclear Science, V 51, N 5 (2004)

Electron Cross Section on nuclei

$$\left.\frac{d\sigma(\theta)}{d\Omega}\right|_{Mott+Scrr.+NFF} = \left.\frac{d\sigma(\theta)}{d\Omega}\right|_{Ruth(c.m.)} \boxed{R} \frac{(1-\cos\theta)^2}{(2A_s+1-\cos\theta)^2} F^2(q)$$

Rutherford in the center of mass:

$$\left.\frac{d\sigma(\theta)}{d\Omega}\right|_{Ruth(c.cm)} = \left(\frac{Ze^2}{\mu c^2\beta^2\gamma}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

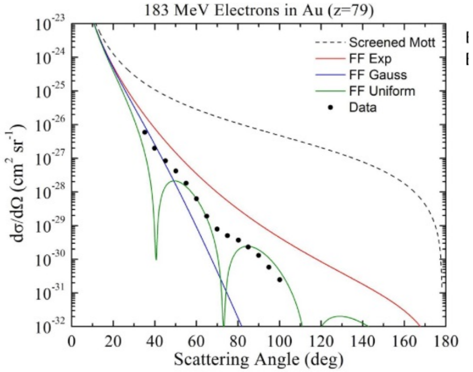
Molier's Screening Coefficient:

$$A_s = \frac{1}{4}\left(\frac{\hbar}{p a_{TF}}\right)^2 \left[1.13+3.76\left(\frac{\alpha Z}{\beta}\right)^2\right]$$

$$a_{TF} = \frac{0.88534 a_0}{Z^{1/3}}$$

Nuclear Form Factor

183 MeV Electrons



Ratio of Mott cross section over Rutherford

$$R \equiv \left.\frac{d\sigma(\theta)}{d\Omega}\right|_{Mott} \Bigg/ \left.\frac{d\sigma(\theta)}{d\Omega}\right|_{Ruth}$$

Mott Cross Section fit:

$$R = \sum_{j=0}^{4} a_j (1-\cos\theta)$$

$b_{j,k}$ are the fitting parameters

$$a_j = \sum_{k=1}^{6} b_{k,j} (\beta - \overline{\beta})^{k-1}$$

References:

C. Leroy and P.G. Rancoita (2016), Principles of Radiation Interaction in Matter and Detection - 4th Edition -, World Scientific (Singapore), Sects. 2.4-2.4.3

M.J. Boschini et al "An Expression for the Mott cross section of electrons and positrons on nuclei with Z up to 118" Radiat. Phys. Chem. (2013), http://dx.doi.org/10.1016/j.radphyschem.2013.04.020

M.J. Boschini et al."Nuclear and Non-Ionizing Energy-Loss of Electrons with low and Relativistic Energies in Materials and Space Environment" Proc. Of the 13th ICATPP (13th ICATPP, Como 3-7/10/2011).

SR (Screened Relativistic) –NIEL Treatment Summary

- sr-treatement (for nuclear stopping power and NIEL) regards the interactions on – screened nuclear potentials from protons, ions and electrons

  at low and relativistic energies,

for any ELEMENT or COMPOUND (by means of BRAGG's RULE up to 10 elements)

- It accounts for nuclear form factors (in case of electron scattering).
- It includes both Norgett-Robinson-Torrens (1975) and Akkerman and Barak (2006) partition functions
- It provives NID doses for spectral particle fluences (as suggested by users)

- the hadronic contributions (embedded from version 1.5) to overall NIEL are obtained from literature (when available):

  a) for incoming protons up to 1 GeV; Insoo Jun, Michael A. Xapsos, Scott R. Messenger, Edward A. Burke, Robert J. Walters, Geoff P. Summers, and Thomas Jordan, Proton Non-ionizing Energy Loss (NIEL) for Device Applications, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 50, NO. 6, DECEMBER 2003, 1924-1928; the hadronic contribution for energies from 1 up to 24 GeV in Si absorber was obtained from M. Huhtinen, Nucl. Instr. and Meth. A 491 (2002), 194-215.

  b) for incoming alpha-particles up to 1 GeV/nucl; Insoo Jun, Michael A. Xapsos, and Edward A. Burke, Alpha Particle Nonionizing Energy Loss (NIEL), IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 51, NO. 6, DECEMBER 2004, 3207-3210

Within *sr-niel framework*, damage functions (thus, NIEL values) for neutrons are also available:

- those derived from ASTM E-722 09 and 14 for Si and GaAs from version 2.1

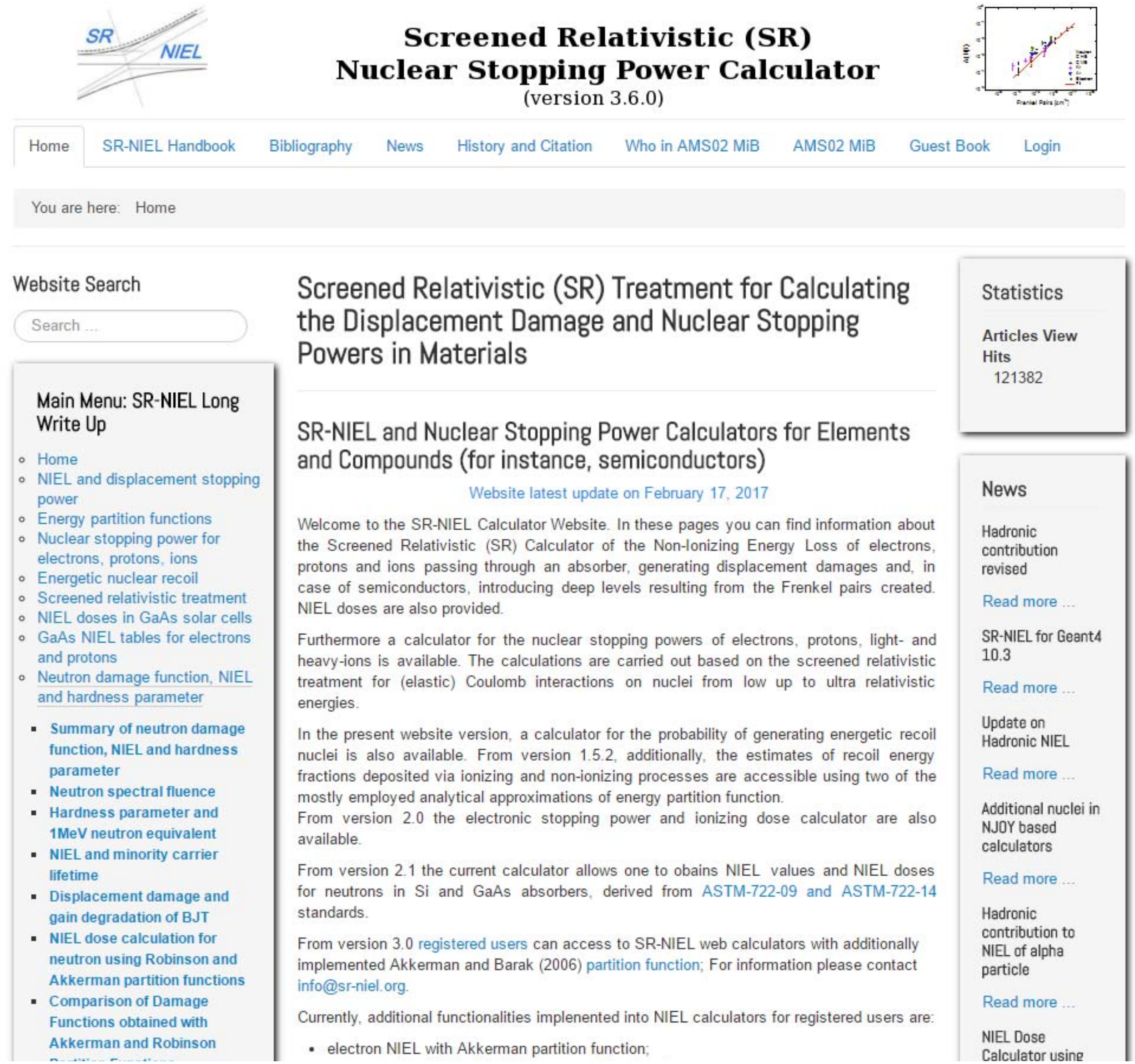
- Currently, available computations for many elements based on NJOY 2012 (from Los Alamos) as INFN-ENEA collaboration within ASIF framework; planned an updated based on NJOY 2012 (updated version) and NJOY 2016

In addition, in sr-niel website users can find the electronic stopping power (and, thus, estimated TID doses).

- From version 2.6, Protons and ions on single elemental absorbers and compounds (obtained both by means of Bragg’s rule and corresponding coumpond corrections, when available).
- Their values are obtatined using the "SRIM Module.exe" from SRIM 2013 code.
- From version 2.7, electrons on elemental absorbers and compounds obtained by polynomial (at 15th degree) fit capable to reproduce the NIST –ESTAR tables - based on ICRU Report 37 - with a maximum discrepancy < 1%.

Code for NIEL Calculation

SR-NIEL: Screened Relativistic (SR) Treatment of the Displacement Damage



Screened Relativistic (SR)
Nuclear Stopping Power Calculator
(version 3.6.0)

Main Menu: SR-NIEL Long Write Up

- Home
- NIEL and displacement stopping power
- Energy partition functions
- Nuclear stopping power for electrons, protons, ions
- Energetic nuclear recoil
- Screened relativistic treatment
- NIEL doses in GaAs solar cells
- GaAs NIEL tables for electrons and protons
- Neutron damage function, NIEL and hardness parameter
  - **Summary of neutron damage function, NIEL and hardness parameter**
  - **Neutron spectral fluence**
  - **Hardness parameter and 1MeV neutron equivalent**
  - **NIEL and minority carrier lifetime**
  - **Displacement damage and gain degradation of BJT**
  - **NIEL dose calculation for neutron using Robinson and Akkerman partition functions**
  - **Comparison of Damage Functions obtained with Akkerman and Robinson**

Screened Relativistic (SR) Treatment for Calculating the Displacement Damage and Nuclear Stopping Powers in Materials

SR-NIEL and Nuclear Stopping Power Calculators for Elements and Compounds (for instance, semiconductors)

Website latest update on February 17, 2017

Welcome to the SR-NIEL Calculator Website. In these pages you can find information about the Screened Relativistic (SR) Calculator of the Non-Ionizing Energy Loss of electrons, protons and ions passing through an absorber, generating displacement damages and, in case of semiconductors, introducing deep levels resulting from the Frenkel pairs created. NIEL doses are also provided.

Furthermore a calculator for the nuclear stopping powers of electrons, protons, light- and heavy-ions is available. The calculations are carried out based on the screened relativistic treatment for (elastic) Coulomb interactions on nuclei from low up to ultra relativistic energies.

In the present website version, a calculator for the probability of generating energetic recoil nuclei is also available. From version 1.5.2, additionally, the estimates of recoil energy fractions deposited via ionizing and non-ionizing processes are accessible using two of the mostly employed analytical approximations of energy partition function.
From version 2.0 the electronic stopping power and ionizing dose calculator are also available.

From version 2.1 the current calculator allows one to obains NIEL values and NIEL doses for neutrons in Si and GaAs absorbers, derived from ASTM-722-09 and ASTM-722-14 standards.

From version 3.0 registered users can access to SR-NIEL web calculators with additionally implemented Akkerman and Barak (2006) partition function; For information please contact info@sr-niel.org.

Currently, additional functionalities implenented into NIEL calculators for registered users are:

- electron NIEL with Akkerman partition function;

Statistics

Articles View Hits
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News

Hadronic contribution revised
Read more ...

SR-NIEL for Geant4 10.3
Read more ...

Update on Hadronic NIEL
Read more ...

Additional nuclei in NJOY based calculators
Read more ...

Hadronic contribution to NIEL of alpha particle
Read more ...

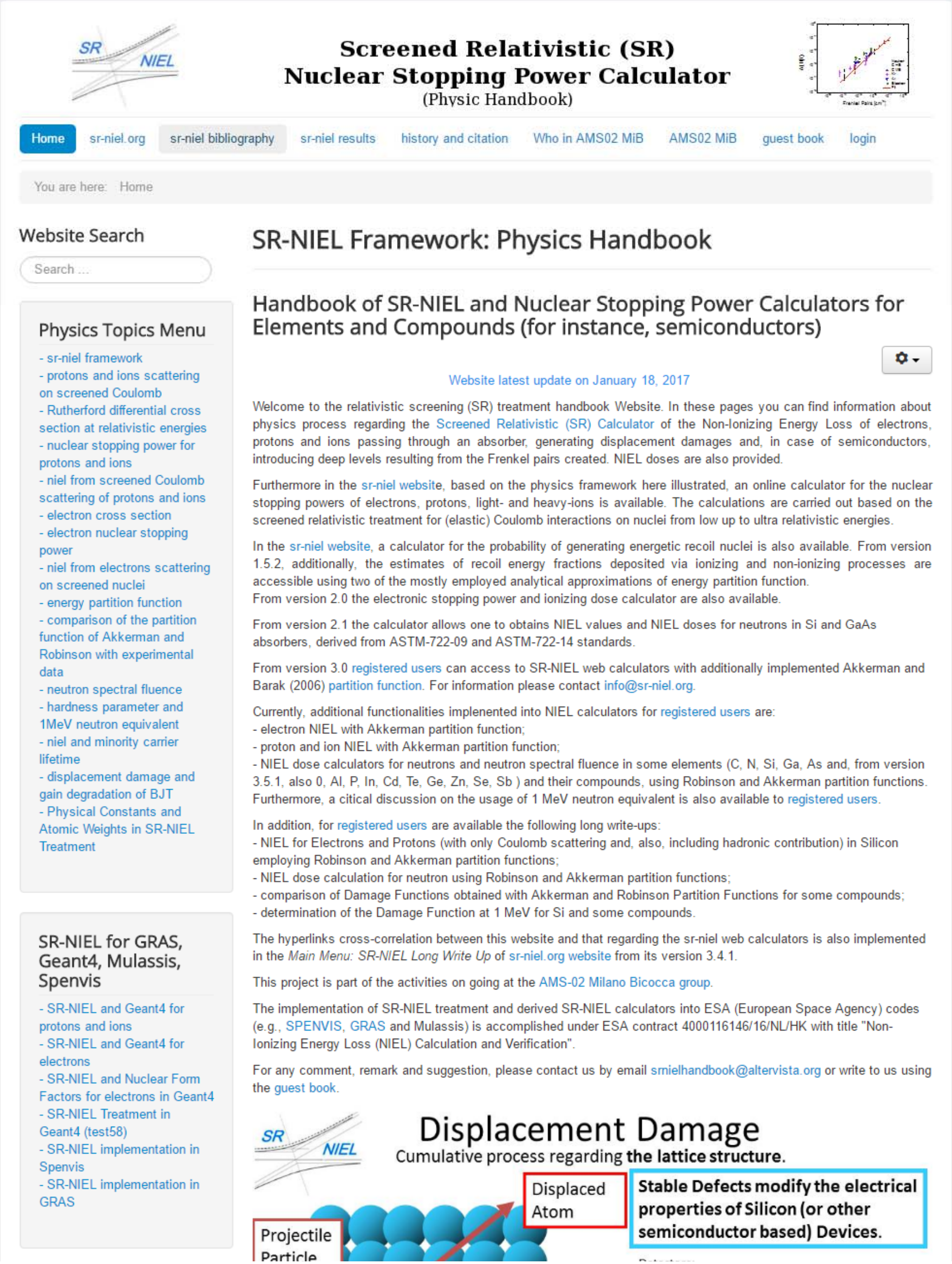
NIEL Dose Calculator using

On line Calculators available at:
www.sr-niel.org

This is a **C++** analytical code and has been developed to calculate the Non Ionizing Energy Loss of electrons, protons and ions with the possibility to change the displacement threshold energy

Moreover is possible to select different **nuclear form factor** for electrons and switch on/off the **hadronic contribution** for protons

The site is continuously updated (now version 3.6.0)



Screened Relativistic (SR)
Nuclear Stopping Power Calculator
(Physic Handbook)

Physics Topics Menu

- sr-niel framework
- protons and ions scattering on screened Coulomb
- Rutherford differential cross section at relativistic energies
- nuclear stopping power for protons and ions
- niel from screened Coulomb scattering of protons and ions
- electron cross section
- electron nuclear stopping power
- niel from electrons scattering on screened nuclei
- energy partition function
- comparison of the partition function of Akkerman and Robinson with experimental data
- neutron spectral fluence
- hardness parameter and 1MeV neutron equivalent
- niel and minority carrier lifetime
- displacement damage and gain degradation of BJT
- Physical Constants and Atomic Weights in SR-NIEL Treatment

SR-NIEL for GRAS, Geant4, Mulassis, Spenvis

- SR-NIEL and Geant4 for protons and ions
- SR-NIEL and Geant4 for electrons
- SR-NIEL and Nuclear Form Factors for electrons in Geant4
- SR-NIEL Treatment in Geant4 (test58)
- SR-NIEL implementation in Spenvis
- SR-NIEL implementation in GRAS

SR-NIEL Framework: Physics Handbook

Handbook of SR-NIEL and Nuclear Stopping Power Calculators for Elements and Compounds (for instance, semiconductors)

Website latest update on January 18, 2017

Welcome to the relativistic screening (SR) treatment handbook Website. In these pages you can find information about physics process regarding the Screened Relativistic (SR) Calculator of the Non-Ionizing Energy Loss of electrons, protons and ions passing through an absorber, generating displacement damages and, in case of semiconductors, introducing deep levels resulting from the Frenkel pairs created. NIEL doses are also provided.

Furthermore in the sr-niel website, based on the physics framework here illustrated, an online calculator for the nuclear stopping powers of electrons, protons, light- and heavy-ions is available. The calculations are carried out based on the screened relativistic treatment for (elastic) Coulomb interactions on nuclei from low up to ultra relativistic energies.

In the sr-niel website, a calculator for the probability of generating energetic recoil nuclei is also available. From version 1.5.2, additionally, the estimates of recoil energy fractions deposited via ionizing and non-ionizing processes are accessible using two of the mostly employed analytical approximations of energy partition function.
From version 2.0 the electronic stopping power and ionizing dose calculator are also available.

From version 2.1 the calculator allows one to obtains NIEL values and NIEL doses for neutrons in Si and GaAs absorbers, derived from ASTM-722-09 and ASTM-722-14 standards.

From version 3.0 registered users can access to SR-NIEL web calculators with additionally implemented Akkerman and Barak (2006) partition function. For information please contact info@sr-niel.org.

Currently, additional functionalities implenented into NIEL calculators for registered users are:
- electron NIEL with Akkerman partition function;
- proton and ion NIEL with Akkerman partition function;
- NIEL dose calculators for neutrons and neutron spectral fluence in some elements (C, N, Si, Ga, As and, from version 3.5.1, also 0, Al, P, In, Cd, Te, Ge, Zn, Se, Sb) and their compounds, using Robinson and Akkerman partition functions.

Furthermore, a citical discussion on the usage of 1 MeV neutron equivalent is also available to registered users.

In addition, for registered users are available the following long write-ups:
- NIEL for Electrons and Protons (with only Coulomb scattering and, also, including hadronic contribution) in Silicon employing Robinson and Akkerman partition functions;
- NIEL dose calculation for neutron using Robinson and Akkerman partition functions;
- comparison of Damage Functions obtained with Akkerman and Robinson Partition Functions for some compounds;
- determination of the Damage Function at 1 MeV for Si and some compounds.

The hyperlinks cross-correlation between this website and that regarding the sr-niel web calculators is also implemented in the *Main Menu: SR-NIEL Long Write Up* of sr-niel.org website from its version 3.4.1.

This project is part of the activities on going at the AMS-02 Milano Bicocca group.

The implementation of SR-NIEL treatment and derived SR-NIEL calculators into ESA (European Space Agency) codes (e.g., SPENVIS, GRAS and Mulassis) is accomplished under ESA contract 4000116146/16/NL/HK with title "Non-Ionizing Energy Loss (NIEL) Calculation and Verification".

For any comment, remark and suggestion, please contact us by email srnielhandbook@altervista.org or write to us using the guest book.

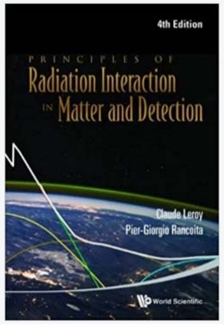
Displacement Damage
Cumulative process regarding **the lattice structure.**

Displaced Atom

Stable Defects modify the electrical properties of Silicon (or other semiconductor based) Devices.

Projectile Particle

As basic sr-niel reference:
C. Leroy and P.G. Rancoita (2016),
Principles of Radiation Interaction in
Matter and Detection - 4th Edition -,
World Scientific (Singapore),
pages 1344.



Brief Version History

www.sr-niel.org

Version 1.5.0 (Nov. 2014)	NIEL calculator for **electrons**, **protons** & **ions** in any kind of target material (compound with Bragg rule)
Version 2.7.1 (Feb 2016)	added NIEL calculator for **neutrons** in **Si** and **GaAs** based on ASTM Standard damage functions (E722-09 and E722-14)
Version 2.8.0 (Feb 2016)	sr-niel handbook available srnielhandbook.altervista.org
Version 3.0.0 (May 2016)	availability of both Robinson and Akkerman partition functions
Version 3.2.0 (July 2016)	added NIEL calculator for **neutrons** in **C**, **N**, **Si**, **Ga**, **As** based on NJOY results (compound with Bragg rule)
Version 3.6.0 Current version (February 2017) update no. 30	calculators available for spectral fluences for electrons, protons, ions and neutrons; cross reference to handbook; hadronic contribution for alpha-particles etc.

SR-NIEL ESA Implementations

	Spenvis	GRAS	Mulassis
SR-NIEL Version	1.5/2.8	2.8	2.8
Status	NIEL Calculator (v 1.5, provided to ESA in 2014); implemented into public SPENVIS v. 4.6.8 in 2016 Intermediate v. 2.8 updated October 2016 on ESA servers; version 3.6 under implementation	Implementation Completed v 2.8 (May 2016); version 3.6 under implementation	v 2.8 made available but never implemented; version 3.6 under implementation
To do	•Transfer to public SPENVIS version (tbd with ESA); under discussion	•Transfer to official GRAS version (tbd by ESA), under discussion	•Transfer to official Mulassis version (tbd by ESA), under discussion

Initial Geant4 Implementation

The scattering calculations we developed, are included in Geant4 and in 2 different physic class:

Since Geant4 version 9.4 (February 2011)

- G4IonCoulumbScatteringModel
- G4IonCoulumbCrossSection

For Protons and Ions Coulomb scattering and for E > 50 keV/nucl

Since Geant4 version 9.5 (October 2012)

- G4eSingleCoulumbScatteringModel
- G4ScreeningMottCrossSection

Electrons Coulomb scattering with *Exponential nuclear form factor*

NIEL calculation is included in the external example **test58**

Geant4 Implementation

Accomplished by IV quarter 2016 / I quarter 2017:

•The classes were updated to match Geant4 v 10.3 (Dec 2016)

•Full Mott cross-section for electron interaction up to Z=92, based on M.J. Boschini et al., (2013) (An expression for the Mott cross section of electrons and positrons on nuclei with Z up to 118, Rad. Phys. Chem. 90, 39-66.)

•Minor bugs where spotted and fixed

•Implement other form factors for electrons cross section (*Gaussian, Uniform nuclear form factors in addition to exponential*)

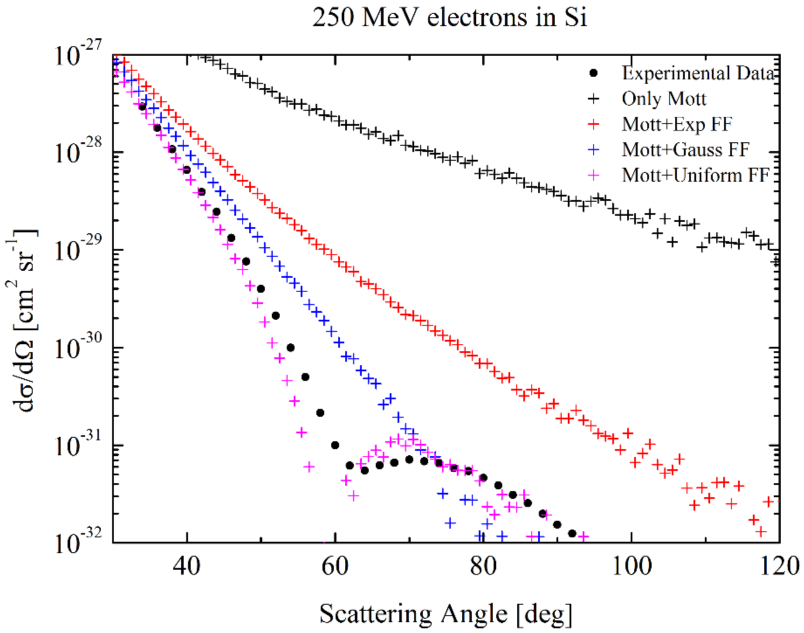
To be done

•Improve computing time of the electrons class

•Implement hadronic contribution for protons & alpha’s (available via test 58)

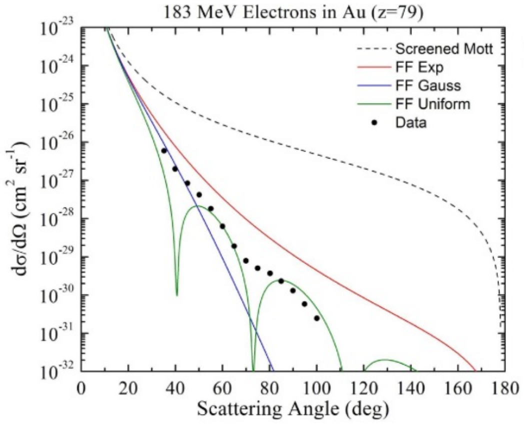
Exs. Geant4 FF implementation

sr-treatment implented in Geant4 simulation from www.sr-niel.org



sr-treatment analytical calculation

183 MeV Electrons in Au (z=79)



Experimental Data From:
B.Hahn et al. Phys. Rev. 101 (1956) 1131

sr-niel framework:

calculation of the differential cross section without and with three form factors

Institutes and Industries using calculators available at www.sr-niel.org

Main Institute and Industries using calculators on www.sr-niel.org

The bulk of web-calculators were gradually posted online by May 2015 (v 1.5 in November 2014)
At present (v. 3.6.0):

Total webpages accessed > 121,000 at the end of Feb 2017

Requested Calculations from external users: **5496** at end of Feb 2017 (**4338** on October 17, 2016)

→ The following slides are based on **2813** requests calculations from Identified Laboratories or Industries

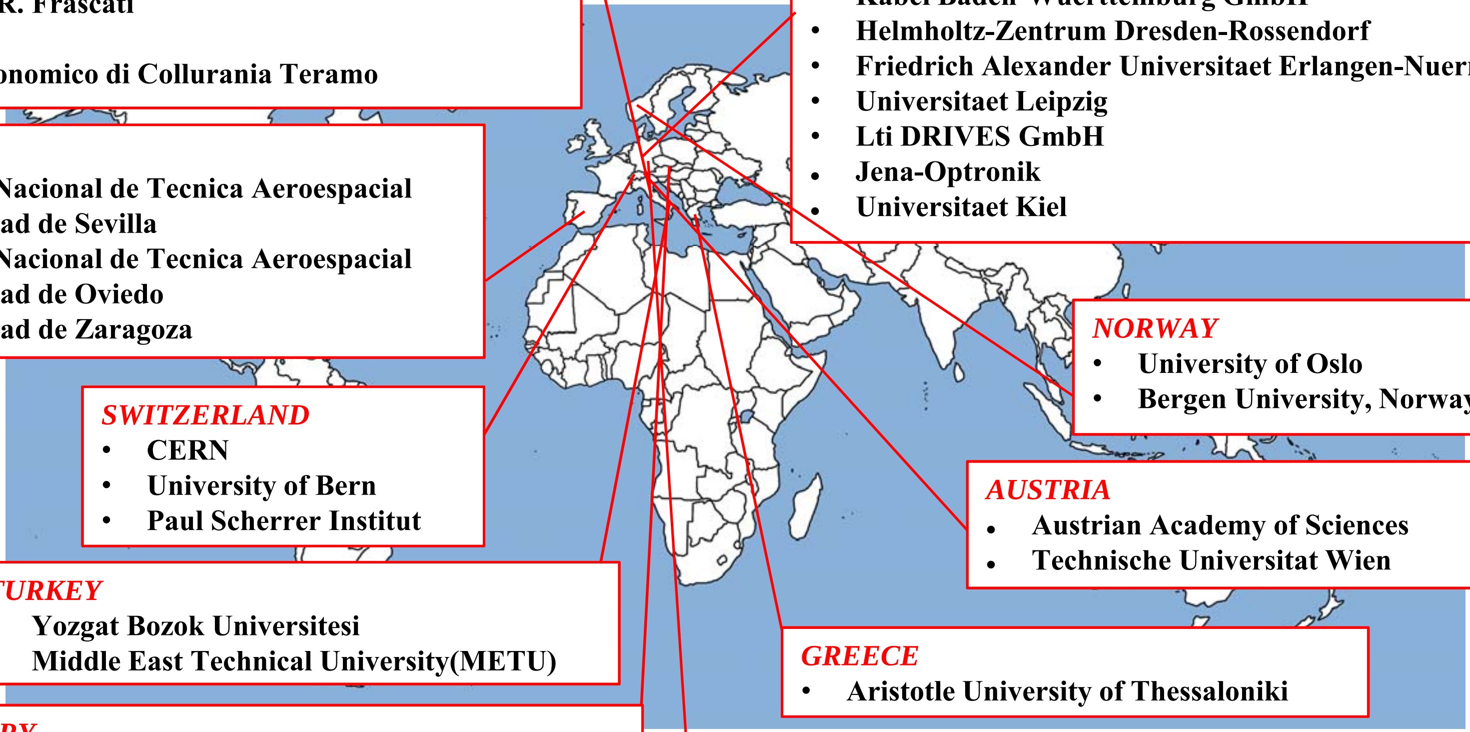
40.3% from USA

Laboratories and Industries with > 50 webcalculator requests:

SANDIA National Laboratories
EADS Deutschland GmbH
Ohio State University
CERN
Cassidian-Optronics-GmbH Germany

ESA
CNES
Ohio State University
University of Louisiana at Lafayette

Europe I



ITALY
- **ESA (ESRIN)**
- **ENEA**
- **INFN**
- **Fondazione Bruno Kessler**
- **LNL Laboratori Nazionali di Legnaro**
- **Università degli studi di Cassino**
- **Università di Trieste**
- **Fondazione San Raffaele del Monte Tabor**
- **Ente per le Nuove Tecnologie, Energia ed Ambiente**
- **ENEA C.R. Frascati**
- **INAF**
- **Oss. Astronomico di Collurania Teramo**

SPAIN
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- **Universidad de Sevilla**
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- **TSBS fuer EADS Deutschland GmbH**
- **Fraunhofer GERMY**
- **AZUR SPACE Solar Power GmbH**
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- **Ruprecht-Karls-Universitaet Heidelberg**
- **GSI Helmholtzzentrum fuer Schwerionenforschung GmbH**
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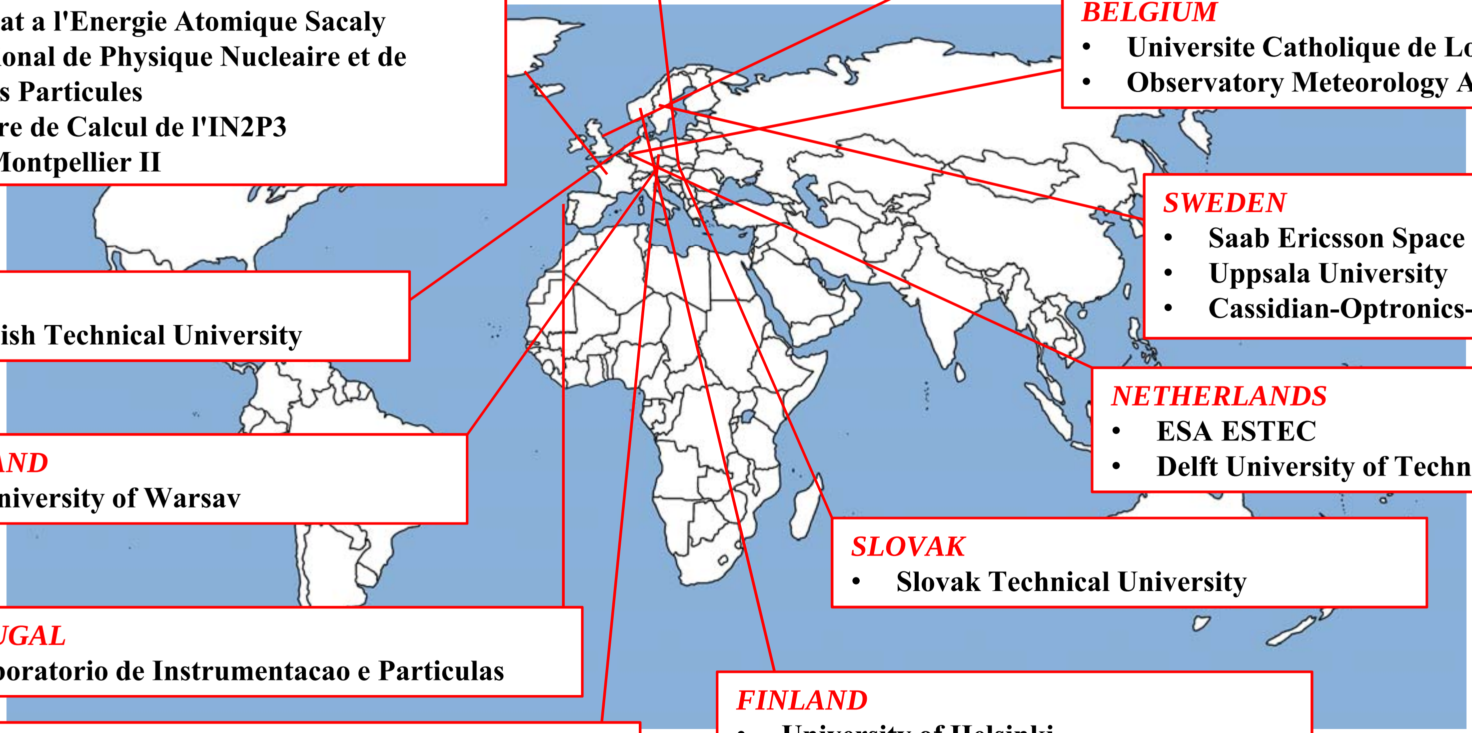
Europe II



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- Commissariat a l'Energie Atomique
- Thales SAS
- TRAD
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- The University of Birmingham
- The University of Manchester
- National Physical Laboratory
- University of Leicester
- Lancaster University
- Loughborough University
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- University of Glasgow
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- University College London

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- Observatory Meteorology Aeronomy

SWEDEN
- Saab Ericsson Space Goteborg
- Uppsala University
- Cassidian-Optronics-GmbH

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- DTU Danish Technical University

NETHERLANDS
- ESA ESTEC
- Delft University of Technology

POLAND
- University of Warsav

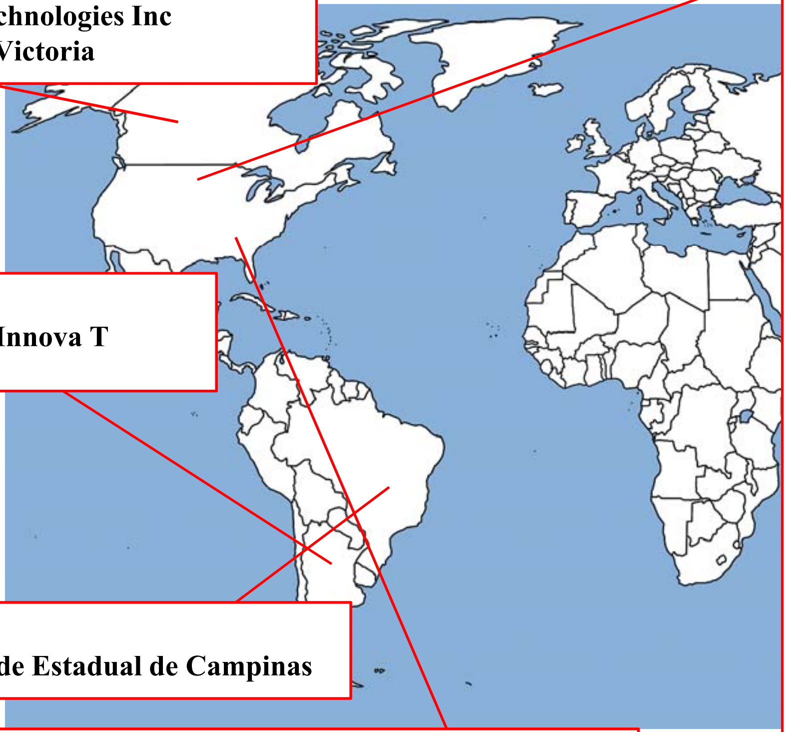
SLOVAK
- Slovak Technical University

PORTUGAL
- Laboratorio de Instrumentacao e Particulas

FINLAND
- University of Helsinki

ROMANIA
- National Institute for Physics and Nuclear Engineering Horia Hulubei

America



CANADA
- **Atomic Energy of Canada Ltd**
- **Iridian Spectral Technologies Ltd**
- **Bell Canada**
- **TekSavvy Solutions, Inc.**
- **University of Winnipeg**
- **Nanowave Technologies Inc**
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- **Solar Junction**
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- **Massachusetts Institute of Technology**
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- **Idaho National Laboratory (INL-12)**
- **Purdue University (PURDUE)**
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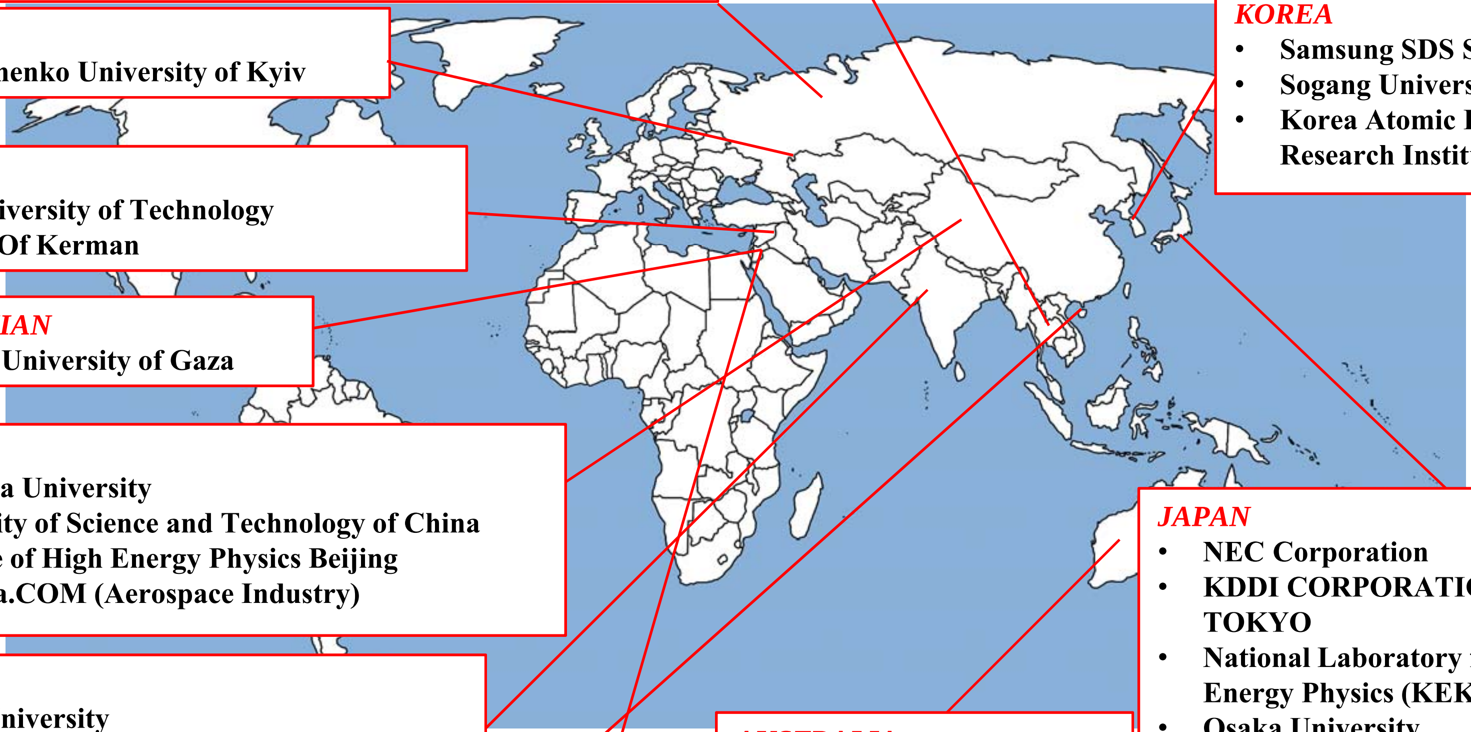

RUSSIA
- **Joint Institute for Nuclear Research DUBNA**
- **Budker Institute of Nuclear Physics Novosibirsk**
- **Ioffe Physical-Techical Institute St.Petersburg**
- **Petersburg Nuclear Physics Institute of RAS**

THAILAND
- **Thailand Institute of Nuclear Technology**

UKRAINE
- **Taras Shevchenko University of Kyiv**

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- **Samsung SDS Seoul**
- **Sogang University**
- **Korea Atomic Energy Research Institute**

IRAN
- **Isfahan University of Technology**
- **University Of Kerman**

PALESTINIAN
- **Islamic University of Gaza**

CHINA
- **Tsinghua University**
- **University of Science and Technology of China**
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INDIA
- **Mysore University**
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- **The University of Hong Kong**

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- **NEC Corporation**
- **KDDI CORPORATION TOKYO**
- **National Laboratory for High Energy Physics (KEK)**
- **Osaka University**
- **Japan Aerospace Exploration Agency**
- **Kyoto University**

Experimental Results

Test Irradiation Campaign

Protons Irradiation

Energy [MeV]	Fluence [cm^{-2}]	Dose [$MeV\ g^{-1}$]	Dose [Gy]
0.7	1.70E+011	1.15E+10	1.85
	3.30E+011	2.24E+10	3.59
	4.50E+011	3.05E+10	4.89
1	4.50E+010	2.23E+09	0.36
	2.30E+011	1.14E+10	1.82
2	4.20E+011	1.12E+10	1.79
	8.40E+011	2.23E+10	3.58

Irradiated at CSNSM Orsay (France)

Electrons Irradiation

Energy [MeV]	Fluence [cm^{-2}]	Dose [$MeV\ g^{-1}$]	Dose [Gy]
1	1.00E+014	1.11E+09	0.18
	5.00E+014	5.56E+09	0.89
	1.00E+015	1.11E+10	1.78
1.5	5.00E+014	1.00E+10	1.60
	1.00E+015	2.00E+10	3.21
3	2.00E+014	7.48E+09	1.20
	4.00E+014	1.50E+10	2.40

Irradiated at Delft (The Netherlands)

Dose in calculated with SR-NIEL (v. 2.8) in GaAs (Ed=21eV, Robinson PF) as target material

The radiation behaviour is very important for EOL performances estimation

- To deeply analyse the behaviour of CTJ30 solar cells after proton and electron irradiation, not only the triple junction but all subcell was irradiated and annealed following the schema below.
- For each conditions the following cells (2x2 cm2) were irradiated:
  - 3 CTJ30, InGaP/GaAs/Ge
  - 3 TOP, InGaP
  - 3 MID (In)GaAs (with InGaP filter)
  - 3 Bottom Ge (with InGaP and InGaAs filter)

- Solar cells were measured at CESI under solar simulator dual source immediately after irradiation
- 2 out of three samples for each irradiation conditions and each solar cells type were annealed (8 hours under 1 sun, 60 °C)
- 1 sample will be measured in three months to analyse self annealing

	Energy (MeV)	Fluences (p/cm2)
proton	0.7	1.70E+11
	0.7	3.30E+11
	0.7	4.50E+11
	1	4.50E+10
	1	2.30E+11
	2	4.20E+11
	2	8.40E+11

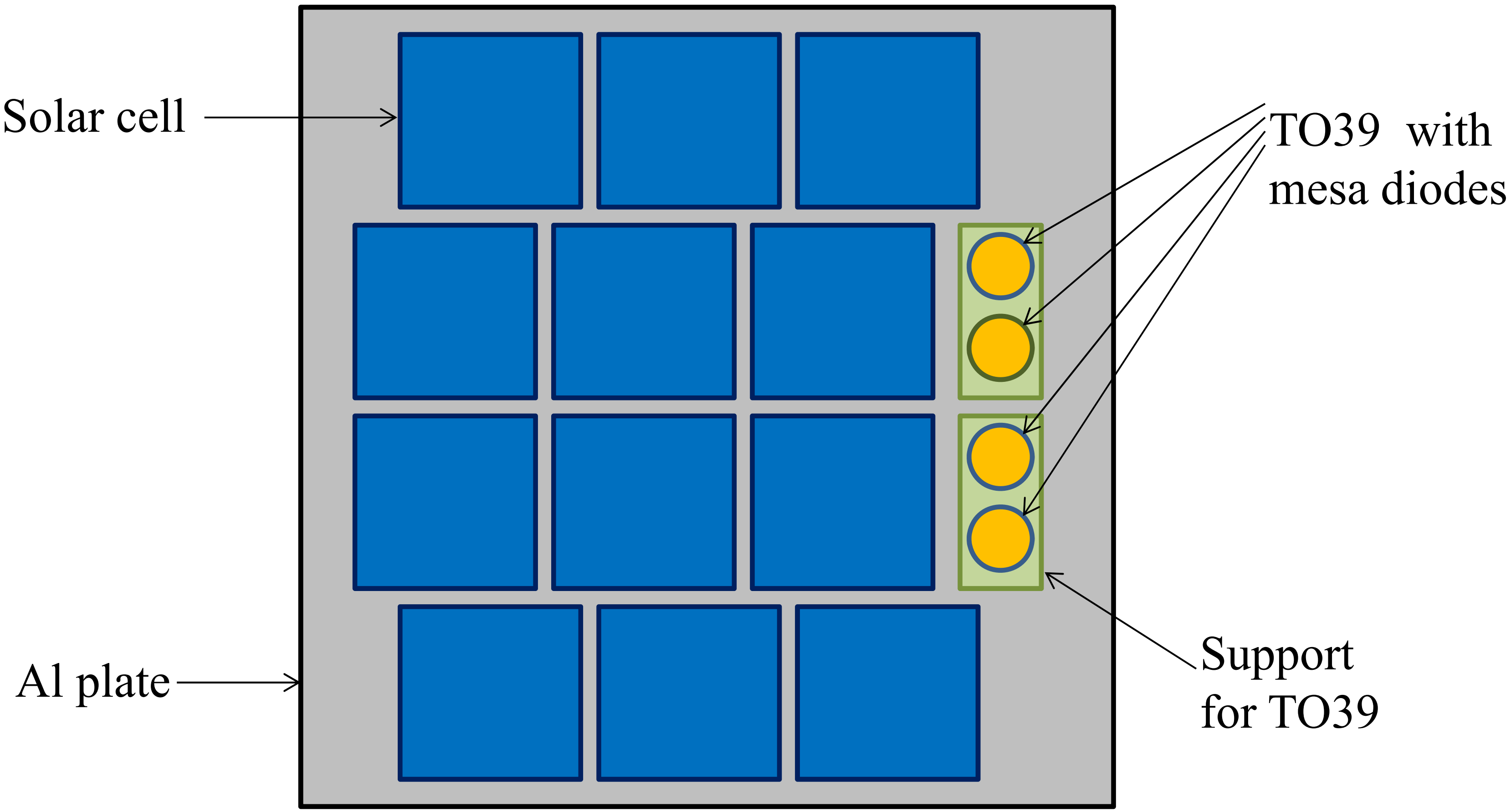
	Energy (MeV)	Fluences (e/cm2)
electron	1	1.00E+14
		5.00E+14
		1.00E+15
	1.5	5.00E+14
		1.00E+15
	3	2.00E+14
		4.00E+14

Total irradiated samples

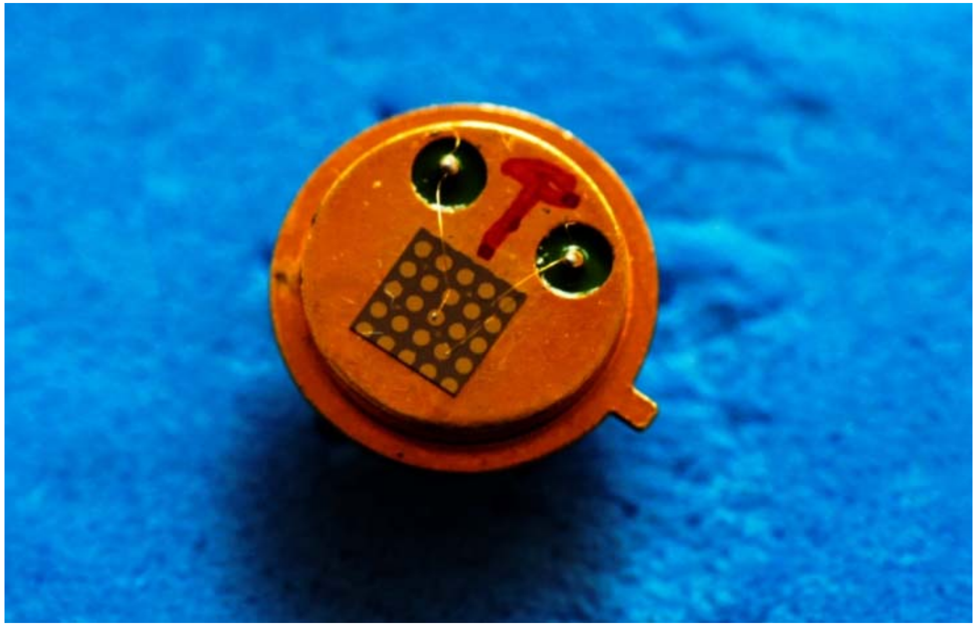
3J solar cells : 14 fluences x 3 samples = 42 samples
1J solar cells : 14 fluences x 3 types x 3 samples = 126 samples
Diodes for DLTS: 14 fluences x 2 types x 2 samples = 56 samples x 25 diodes = 1400

Solar cells 2 cm x 2 cm
Diodes 500 micron diameter (obtained with MESA technology)
Total number of devices : 1568

Arrangement of solar cells and diodes on Al plate for proton irradiation



Sample for DLTS measurements mounted on TO39 holder



Photograph of a top junction sample, 3.3x3.3 mm^2, mounted on a TO-39 holder. The dots correspond to the AuGeNi top contacts (0.4 mm in diam). Two mesa diodes are connected to the isolated pins with gold wires. The back ohmic contact is soldered to the case by silver paste.

3J and 1J solar cells

Self annealing:

4 weeks protons, 2.5 weeks electrons

(after Irradiation)

Annealing:

in addition to self annealing,

8 hours under sun simulator, 60 °C

in all calculations, we used the stoichiometry (and layer thicknesses) from CESI

In this analysis
the optimization is carried out accounting for, simultaneously,
P/P_{max}, I_{sc}, V_{oc}
obtained from all irradiations of electrons and protons

NIEL doses are obtained from sr-niel as a function of E_d

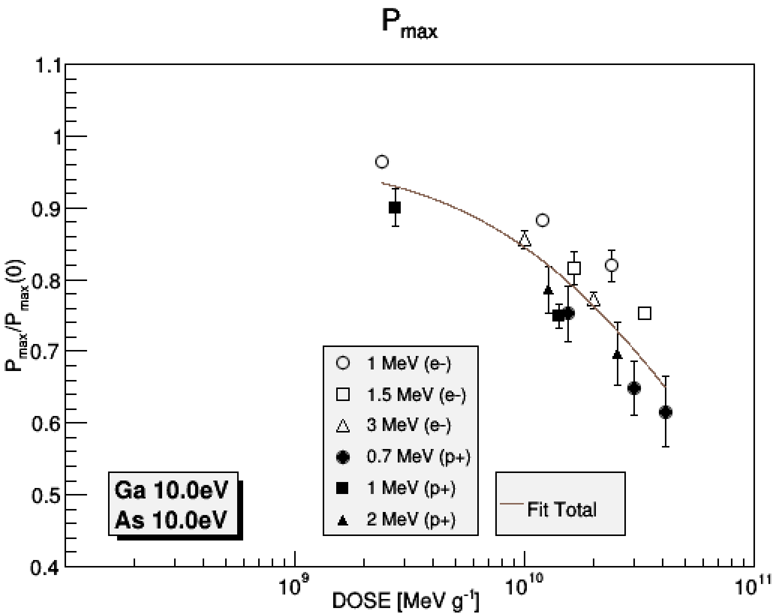
Used the standard semi-empirical expression with an additional constant term from C. Baur et al. (2005) 31 IEEE Photovoltaic Specialists Conference:

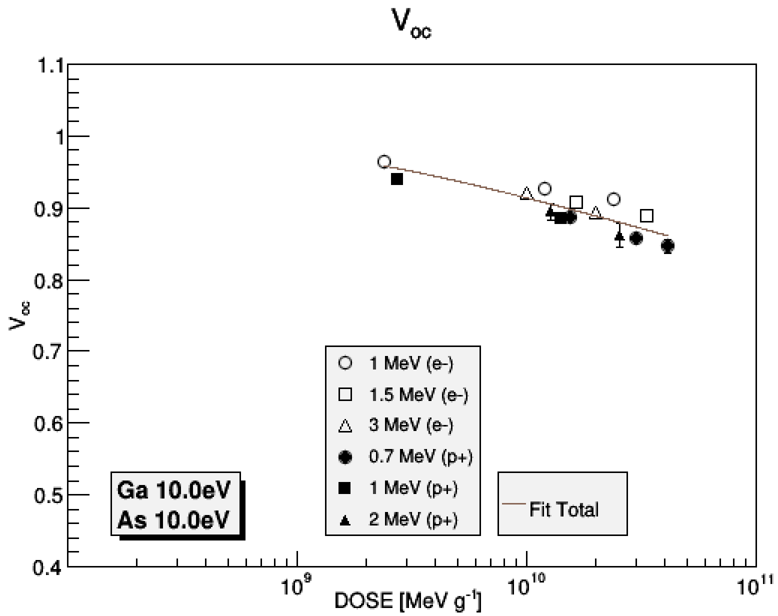
$$(1-\mathrm{par2})-\mathrm{par0}\cdot\log_{10}(1+\mathrm{par1}\cdot\mathrm{Dose})$$

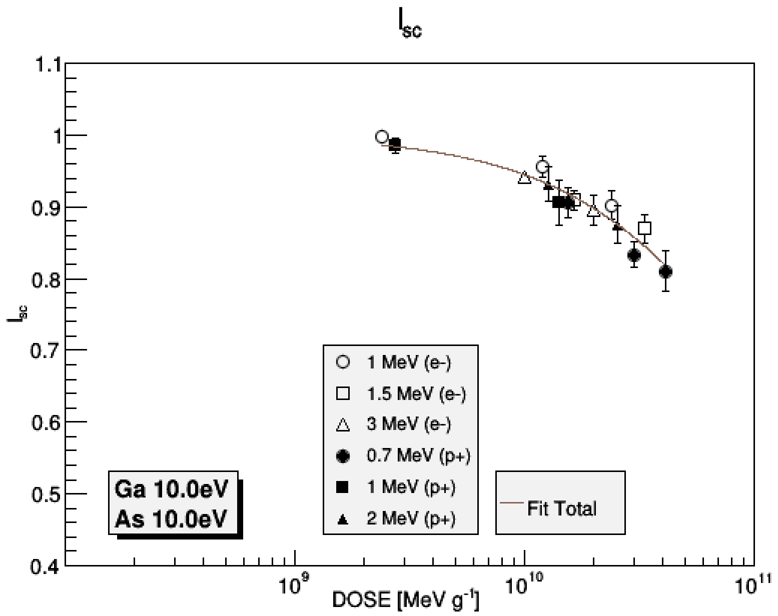
That reduce to the usual one if par2=0 (as found for for 3J, 1J Top, 1J Mid)

$$1-\mathrm{par0}\cdot\log_{10}(1+\mathrm{par1}\cdot\mathrm{Dose})$$

GaAs NIEL with Ed=10 eV and Robinson partition function (self-annealing)

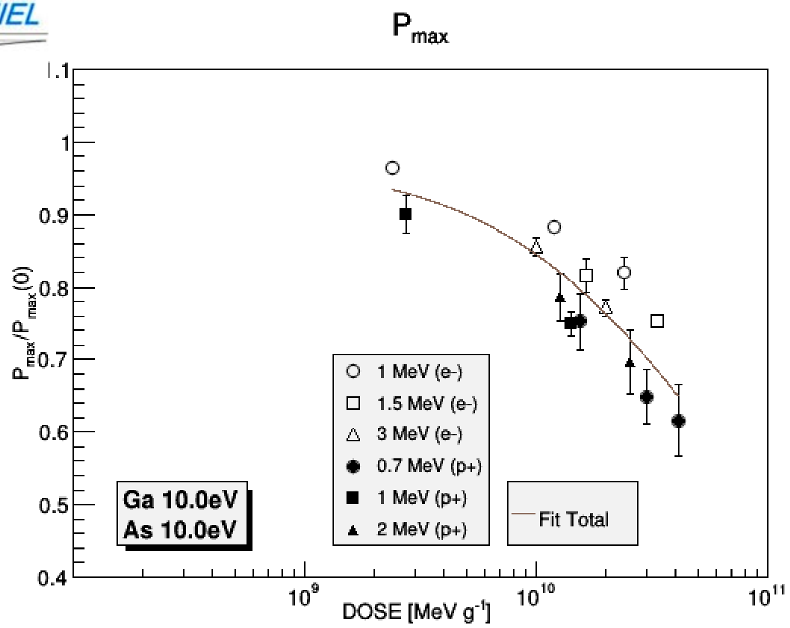


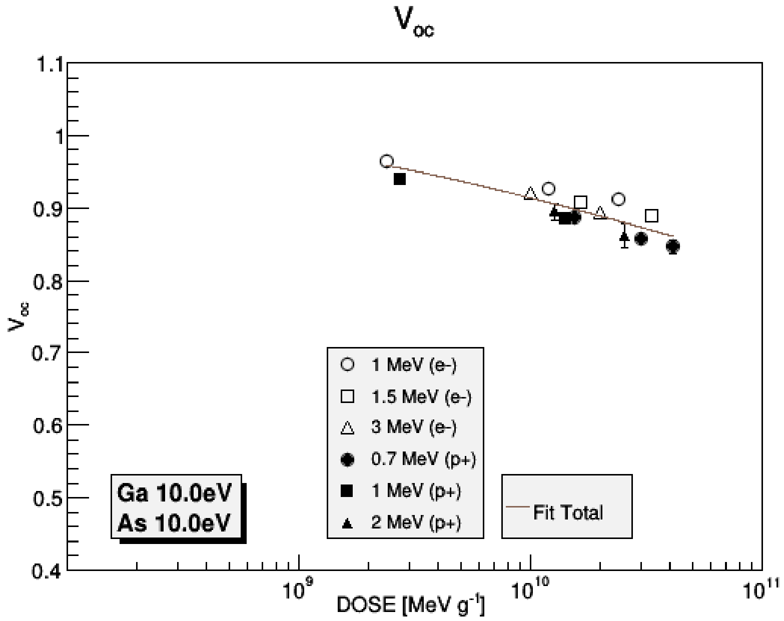


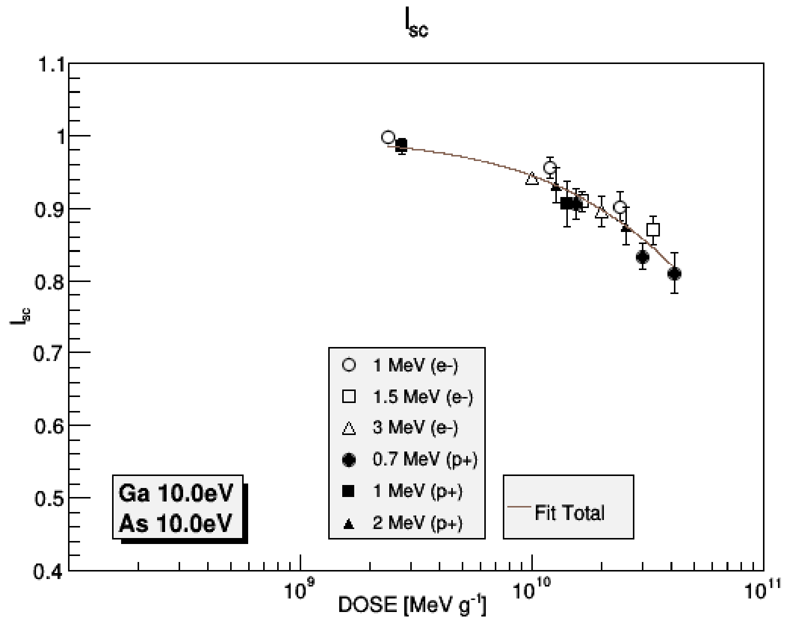


10 eV, suggested in Sect. 4.1.2 of
B.E. Anspaugh, GaAs Solar Cell Radiation Handbook,
NASA, JPL Publication 96-9, (1996).

3J cells:
Search for best Ed value
for 10 < Ed < 30 eV

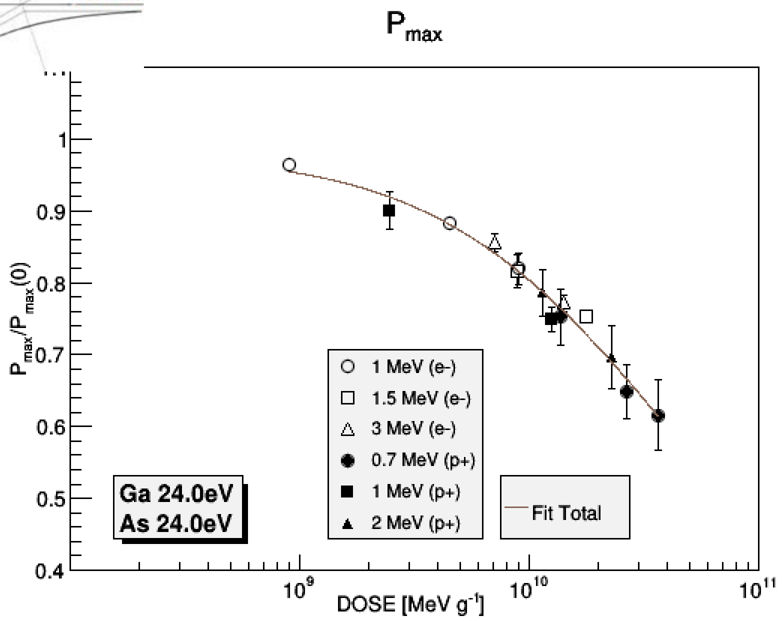


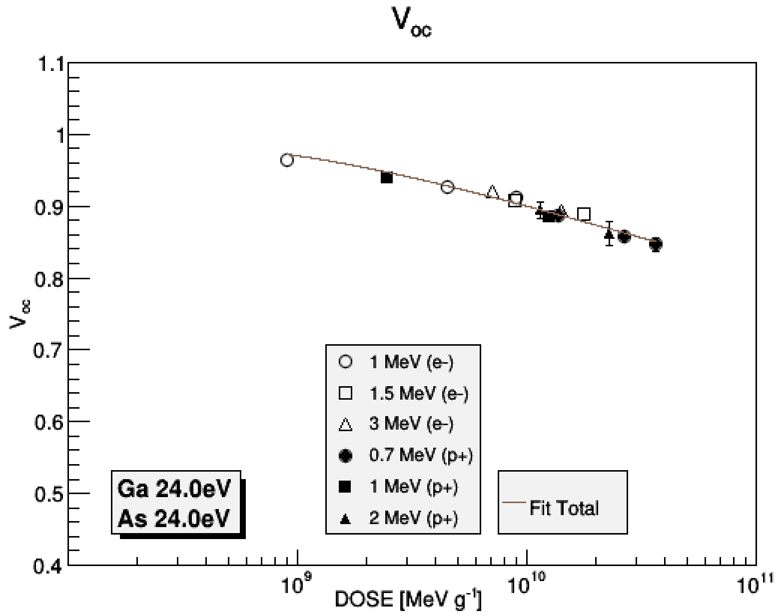


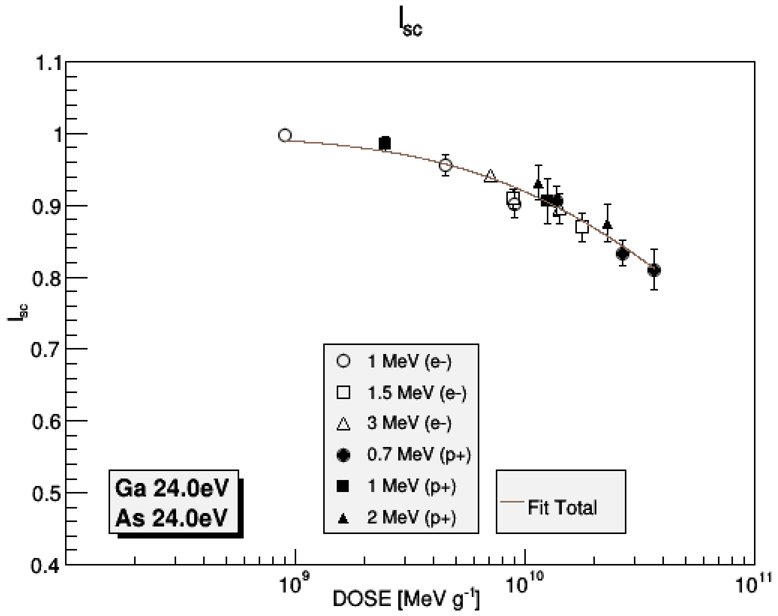


3J solar cell

GaAs NIEL with Ed=24 eV and Robinson partition function (self-annealing)



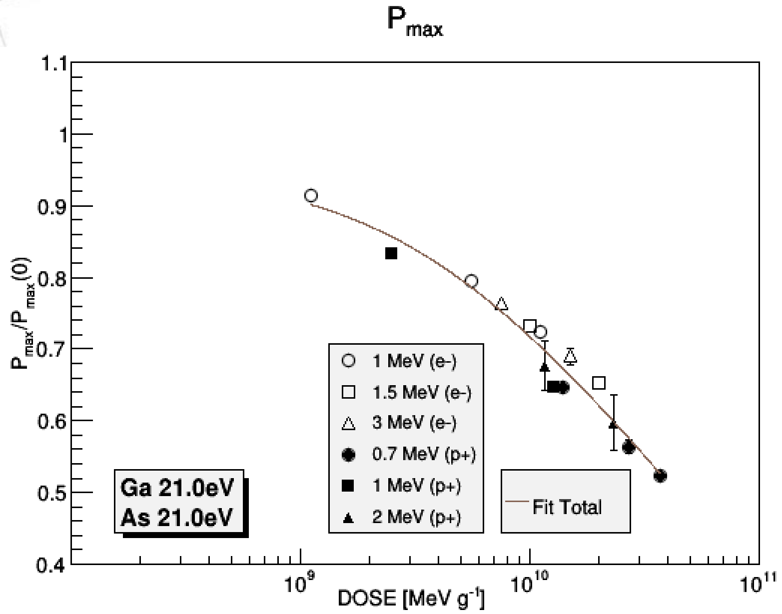


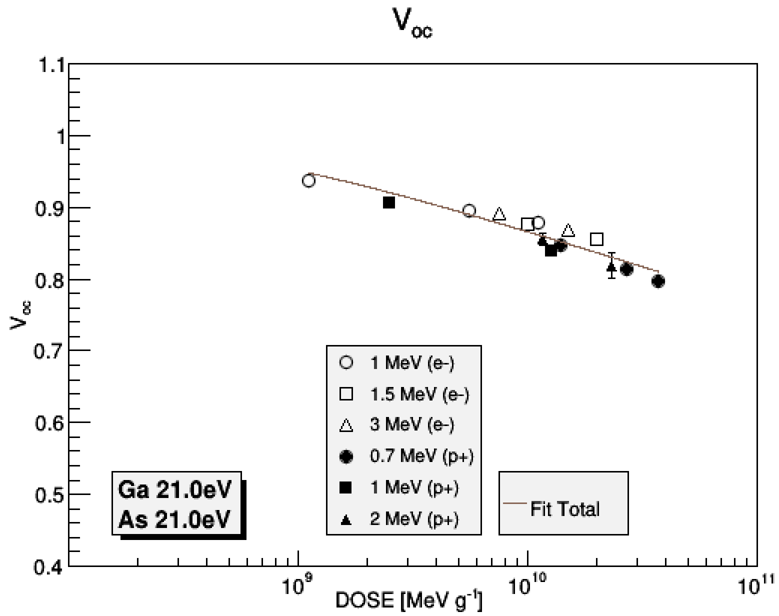


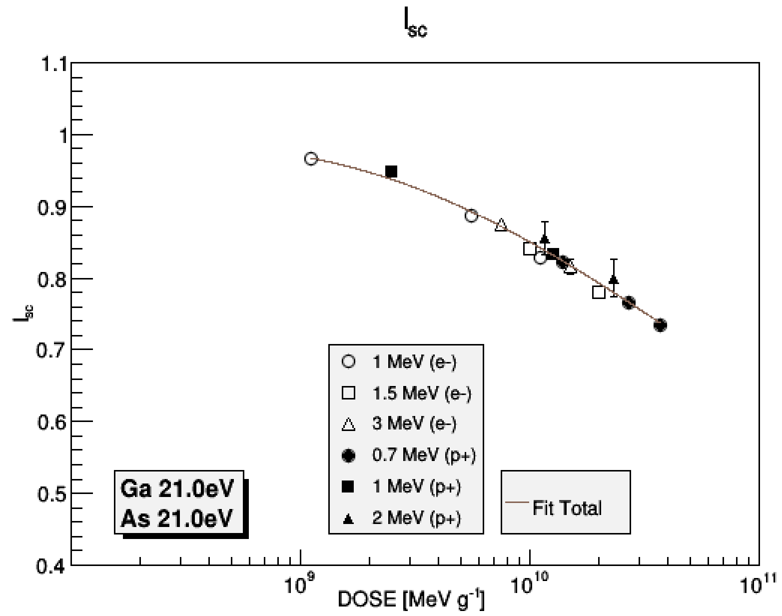
3J solar cell

1J mid cells:
Search for best Ed value for Ga and As
for 10 < Ed < 30 eV

GaAs NIEL with Ed=21 eV and Robinson partition function (self-annealing)



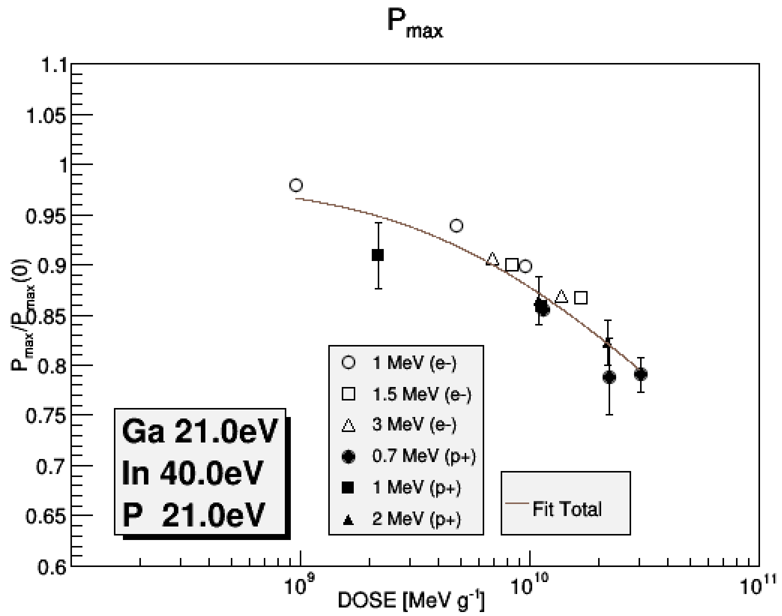


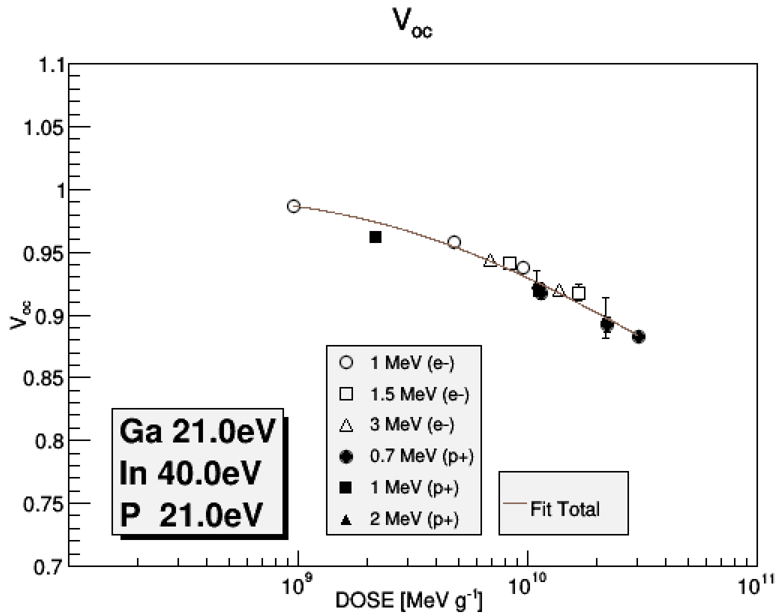


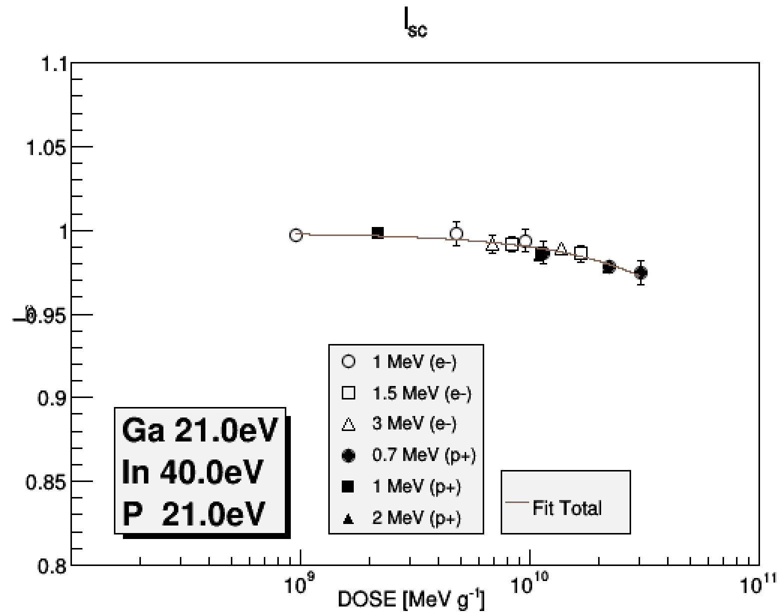
1J mid cells

1J top cells:
Fixed Ed = 21 for Ga and P
Search for best Indium Ed value
for 30 < Ed < 50 eV

GaP (Ed=21 eV), In (Ed=40 eV) NIEL and Robinson partition function (self-annealing)


P$_{max}$

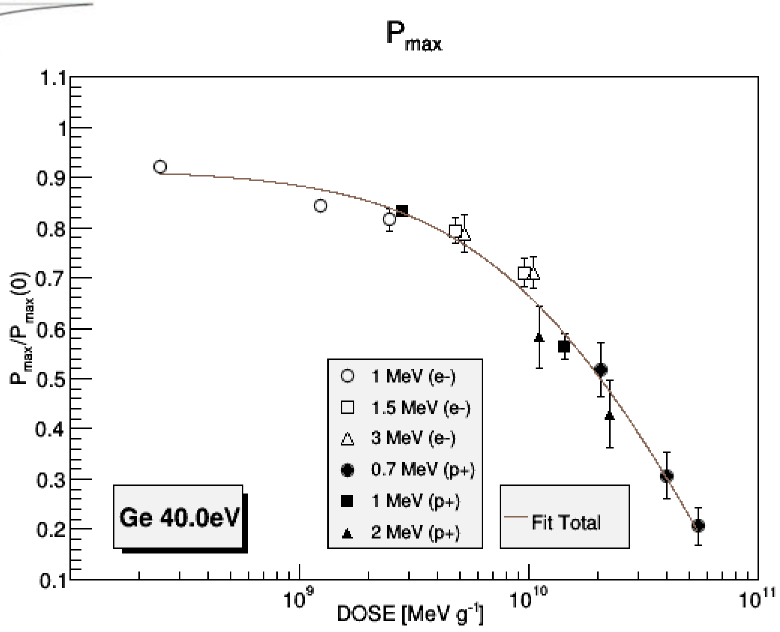

V$_{oc}$

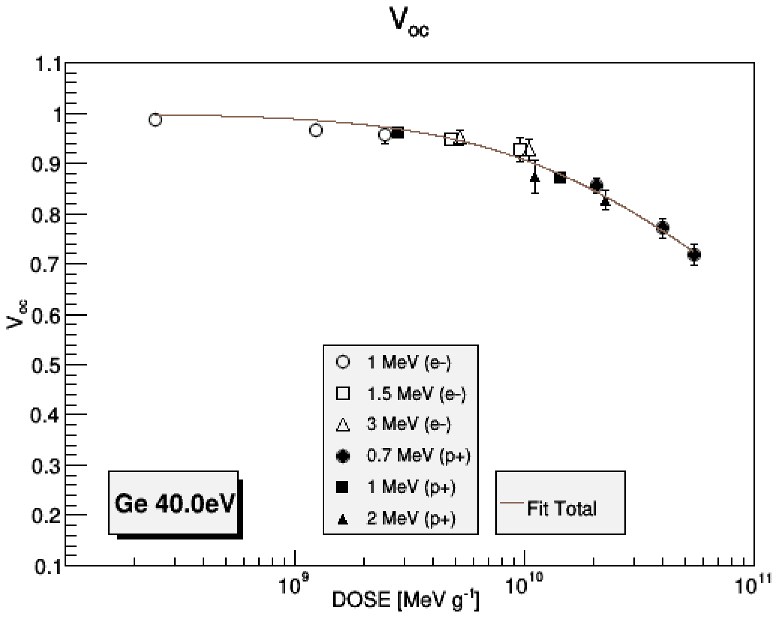

I$_{sc}$

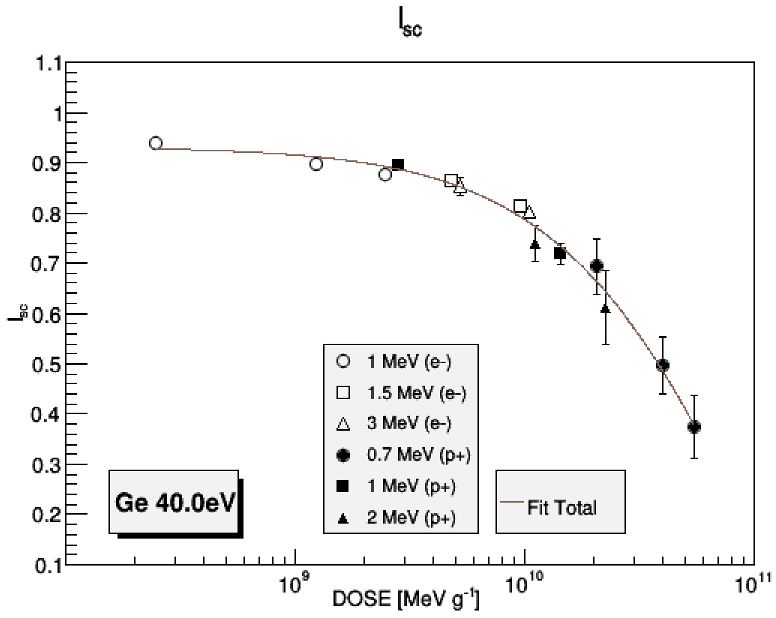
1J top cell

1J bottom cells:
Search for best Ed value
for 30 < Ed < 50 eV

Ge NIEL with Ed=40 eV and Robinson partition function (self-annealing)







1J bottom cell

P/P_{max} After Annealing

Protons Irradiation

Energy [MeV]	Variation [%]
0.7	5.1 ± 1.6
1	2.4 ± 0.5
2	3.7 ± 1.0

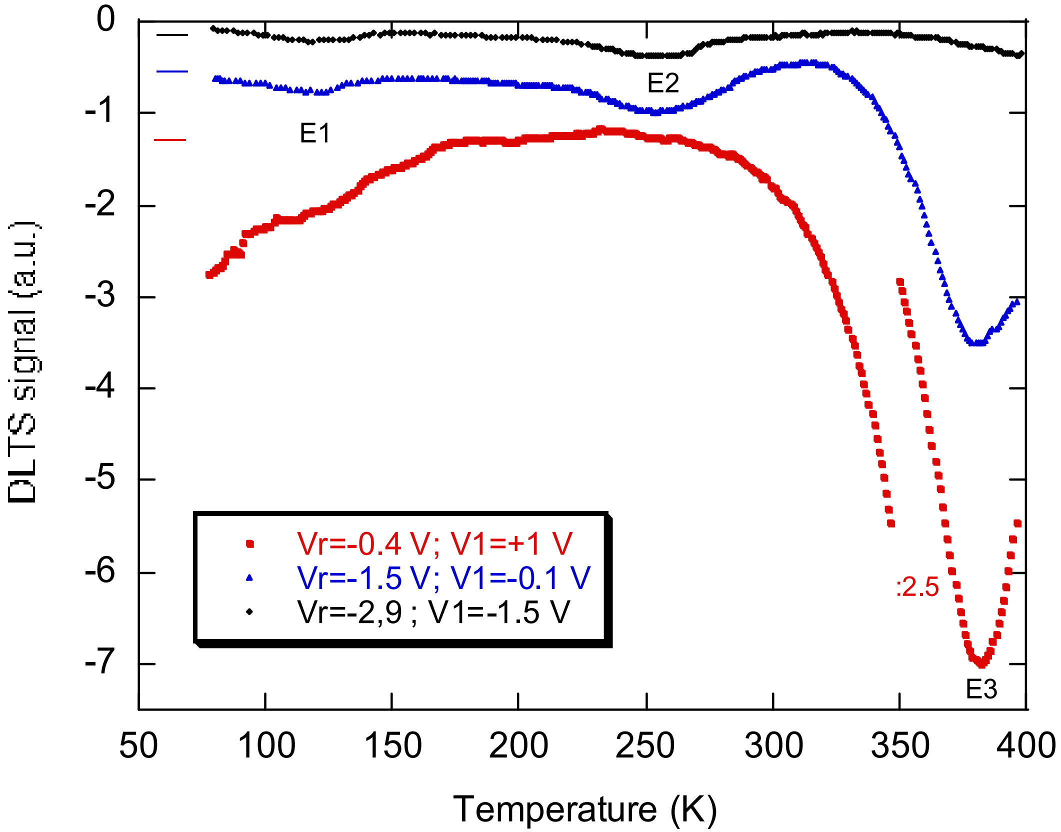
Electrons Irradiation

Energy [MeV]	Variation [%]
1	3.2 ± 1.7
1.5	4.7 ± 0.4
3	4.9 ± 1.0

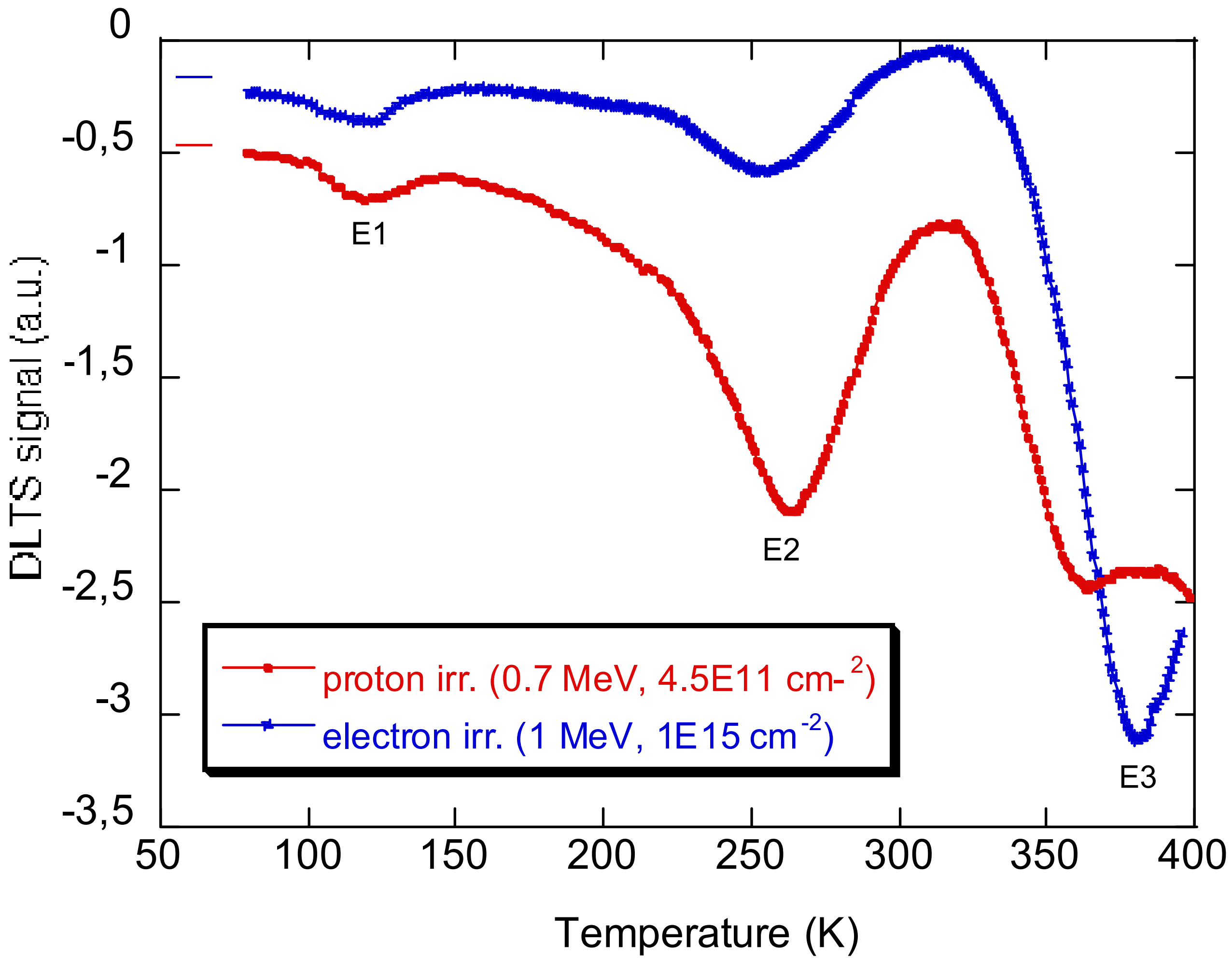
DLTS Preliminary Results

DLTS spectra obtained on a middle junction irradiated with electrons (1 MeV at a fluence of 10^{15} cm^{-2}) using different reverse voltage Vr at fixed pulse amplitude of 1.4 V.

Emission rate =46 s^{-1}, pulse width=500 µs, V1=pulse voltage.



DLTS spectrum (Vr= -1.5 V) of a middle cell diode irradiated with
protons (energy 0.7 MeV and fluence 4.5×10^{11} cm^{-2})
is compared to that of a middle cell diode irradiated with
electrons (energy 1 MeV and fluence 1×10^{15} cm^{-2}).
NIEL dose ratio (proton/electron) = 2.74



Preliminary Remarks on DLTS

i) Three main DLTS peaks, from the top of the valence band labelled as E1 (0.21 eV), E2 (0.45 eV) and E3 (0.71 eV), and a broad low temperature shoulder of E2 are observed in both electron and proton irradiated samples.

ii) The E3 peak, that is mainly located at the p/n interface and is also present in the non-irradiated sample, has been associated to interface defects.

iii) E1, E2 (and related shoulder) have been attributed to irradiation induced defects since: i) they are uniformly distributed in the region of the depletion layer investigated by DLTS, ii) their density increases with absorbed dose and iii) they are not detected in non-irradiated samples

Preliminary Remarks on Comparison between electron and proton irradiated samples

i) An additional DLTS peak at a temperature of about 365 K is observed for intermediate reverse voltage (Vr=-1.5 V) in the proton irradiated sample. Since this peak disappears for higher reverse voltage and is not observed in non-irradiated samples, it is attributed to defects induced by proton irradiation near the interface. *These defects might be newly formed defects by the proton irradiation, or due to interaction between the proton irradiation and already present interface defects.*

ii) The peak amplitude RATIO E2/E1 is observed to be larger for the proton irradiated sample than for the electron irradiated one

iii) While the NIEL dose ratio protons/electrons is 2.74, the ratio of the defect concentrations (protons/electrons) derived from E2 is slightly larger (3.4). The ratio of defect concentrations (protons/electrons) derived from E1, on the contrary, is slightly lower (about 2.2)

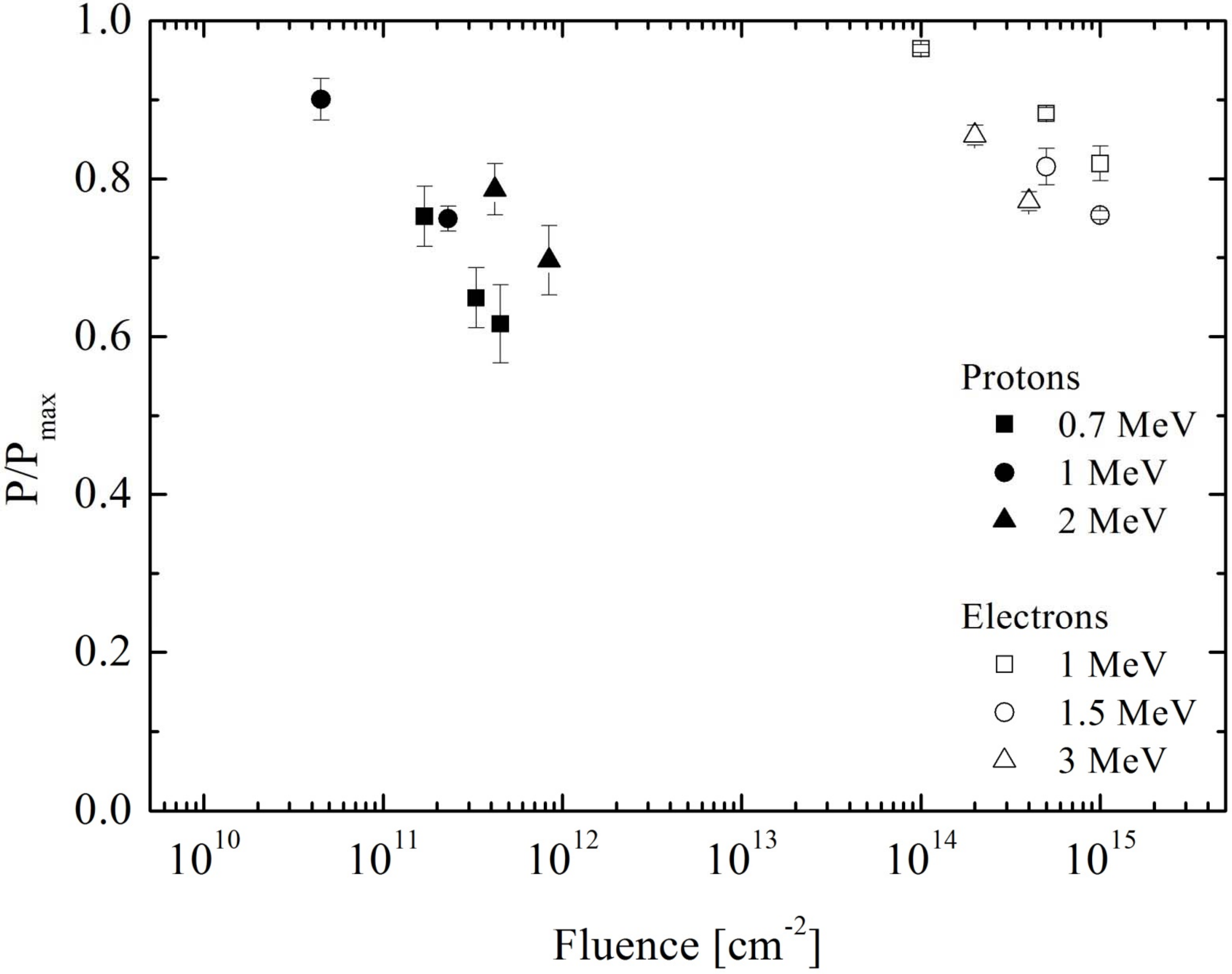
Preliminary remarks (symmary) mostly regarding self-annealing data

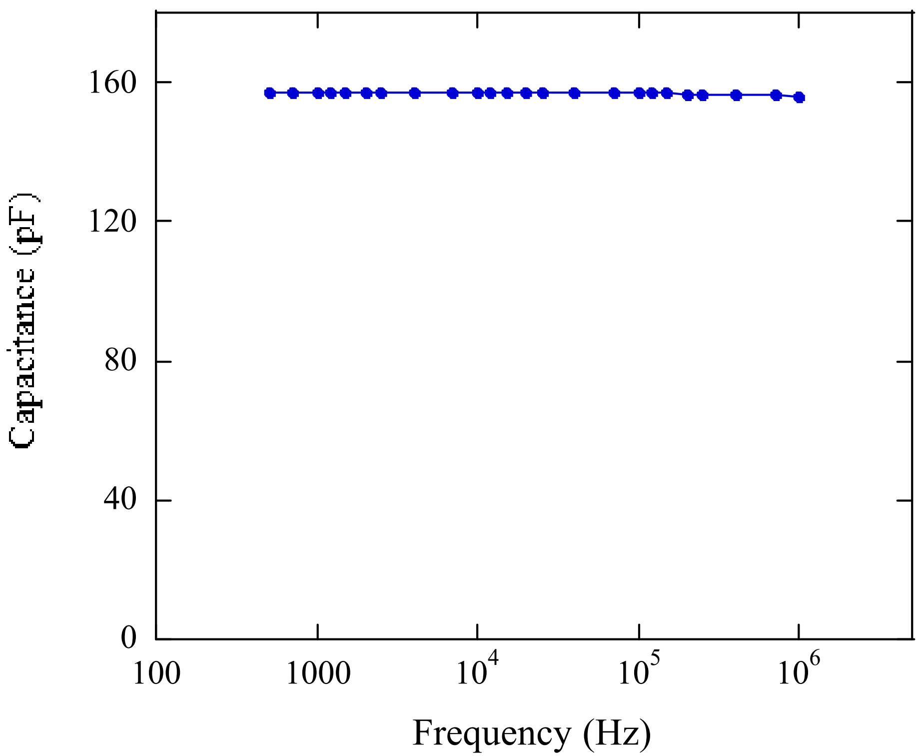
- From a global fit on P/Pmax, Isc, Voc self annealing data for electrons and protons, Ed ≈ 21 eV for Ga and As (for 1J solar cells) is already reached after a few weeks (of self-annealing time). For 3J the effective Ed for Ga and As can be affected by modelling the 3J solar cell as a 1J GaAs cell.
- 10 eV displacement threshold energy is not appropriate for "GaAs based" solar cells.
- Doses are calculated using sr-niel (v. 3.6).
- the ratio protons/electrons of the peak amplitudes E2 (E1) is observed to be larger (smaller) with respect to NIEL Dose ratio (2.74)

Two abstracts submitted:
To IEEE NSREC
Displacement Damage dose and DLTS Analyses on Triple and Single Junction
solar cells irradiated with electrons and protons, Carsten Baur5, Roberta Campesato1,
Mariacristina Casale1, Massimo Gervasi 2,3, Enos Gombia 4, Erminio Greco1, Aldo Kingma4, P.G. Rancoita2, Davide Rozza2, Mauro Tacconi2,3
To IEEE PVSEC
NIEL DOSE Analysis on Triple Junction cells 30% efficient and related single junctions, Roberta Campesato 1, Erminio Greco1, , Mariacristina Casale1, Massimo Gervasi 2,3,
P.G. Rancoita2, Davide Rozza2, Mauro Tacconi2,3, Enos Gombia 4, Aldo Kingma4, Carsten Baur5

Back up

Self Annealing 3J cells



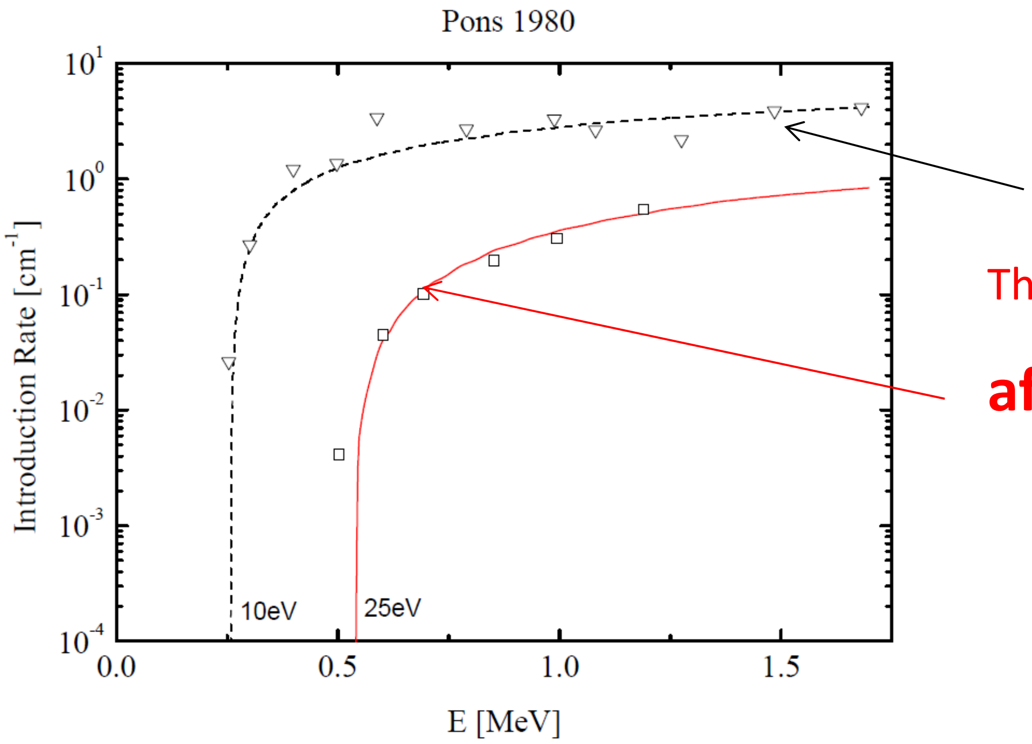


Capacitance vs frequency of a mesa structure obtained on the middle cell.

Displacement threshold energy in GaAs

Determined based on overall rates of defects introduction using DLTS measurements

Data points from Pons et al, J. Appl. Phys. 51, 2038 (1980) for **electron irradiated GaAs** with **superimposed current NIEL calculations** with 10 and 25 eV *displacement threshold energy* **normalized to the highest energy point**



Pons Data (1980)

after irradiation 10 eV

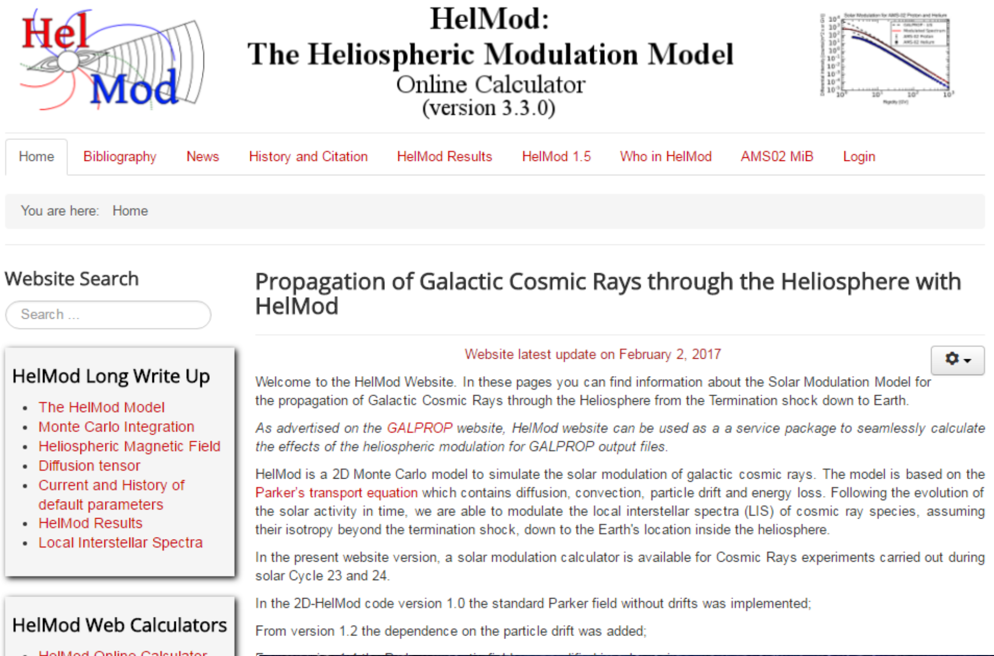
Thommen et al, Rad. Effects 2,201 (1970).

after II stages annealing: 25 eV

annealing procedure
(stage I at 235 K and stage II at 280 K)

the (self-) annealing effect is **expected to cause a shift of the damage energy threshold to a value larger than 10 eV**. In that paper, the authors correctly remarked about a possible disappearing of divacancies. (see C.Baur et al. (2014), NIEL dose dependence for solar cells irradiated with electrons and protons, Proc. of the 14th ICATPP, September 23--27 2013, Villa Olmo, Como, Italy, World Scientific, Singapore, 698-713; ISBN: 978-981-4603-15-7)

Correlated sites I: www.helmod.org



HelMod:
The Heliospheric Modulation Model
Online Calculator
(version 3.3.0)

Home | Bibliography | News | History and Citation | HelMod Results | HelMod 1.5 | Who in HelMod | AMS02 MiB | Login

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Website Search

Search ...

HelMod Long Write Up

- The HelMod Model
- Monte Carlo Integration
- Heliospheric Magnetic Field
- Diffusion tensor
- Current and History of default parameters
- HelMod Results
- Local Interstellar Spectra

HelMod Web Calculators

- HelMod Online Calculator
- HelMod Solar Modulator
- Stand-Alone Module (offline)

Related Link

- GALPROP
- Wilcox Solar Observatory
- SILSO
- OMNIWeb
- Geomagsphere
- SR-NIEL web calculator
- SR-NIEL physics handbook
- INFN Milano-Bicocca
- IEP-SAS Kosice
- INFN
- CERN
- ASI
- ESA
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Visitor Statistics

Articles View Hits
36040

Visitors Statistics from Sept 1, 2016

Today	69
This week	589
This month	267
Total	22829

Propagation of Galactic Cosmic Rays through the Heliosphere with HelMod

Website latest update on February 2, 2017

Welcome to the HelMod Website. In these pages you can find information about the Solar Modulation Model for the propagation of Galactic Cosmic Rays through the Heliosphere from the Termination shock down to Earth.

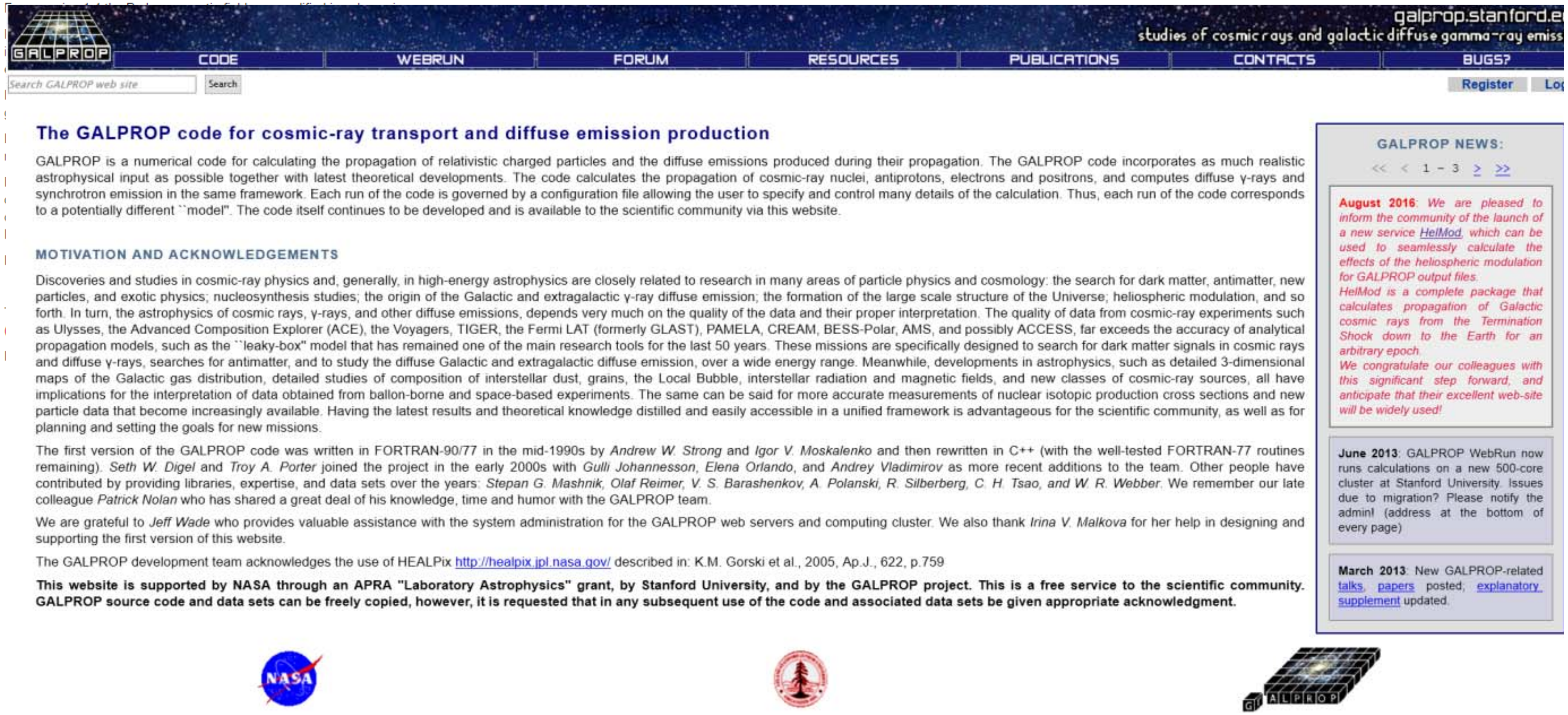
As advertised on the GALPROP website, HelMod website can be used as a a service package to seamlessly calculate the effects of the heliospheric modulation for GALPROP output files.

HelMod is a 2D Monte Carlo model to simulate the solar modulation of galactic cosmic rays. The model is based on the Parker's transport equation which contains diffusion, convection, particle drift and energy loss. Following the evolution of the solar activity in time, we are able to modulate the local interstellar spectra (LIS) of cosmic ray species, assuming their isotropy beyond the termination shock, down to the Earth's location inside the heliosphere.

In the present website version, a solar modulation calculator is available for Cosmic Rays experiments carried out during solar Cycle 23 and 24.

In the 2D-HelMod code version 1.0 the standard Parker field without drifts was implemented;

From version 1.2 the dependence on the particle drift was added;



The GALPROP code for cosmic-ray transport and diffuse emission production

GALPROP is a numerical code for calculating the propagation of relativistic charged particles and the diffuse emissions produced during their propagation. The GALPROP code incorporates as much realistic astrophysical input as possible together with latest theoretical developments. The code calculates the propagation of cosmic-ray nuclei, antiprotons, electrons and positrons, and computes diffuse γ-rays and synchrotron emission in the same framework. Each run of the code is governed by a configuration file allowing the user to specify and control many details of the calculation. Thus, each run of the code corresponds to a potentially different ``model". The code itself continues to be developed and is available to the scientific community via this website.

MOTIVATION AND ACKNOWLEDGEMENTS

Discoveries and studies in cosmic-ray physics and, generally, in high-energy astrophysics are closely related to research in many areas of particle physics and cosmology: the search for dark matter, antimatter, new particles, and exotic physics; nucleosynthesis studies; the origin of the Galactic and extragalactic γ-ray diffuse emission; the formation of the large scale structure of the Universe; heliospheric modulation, and so forth. In turn, the astrophysics of cosmic rays, γ-rays, and other diffuse emissions, depends very much on the quality of the data and their proper interpretation. The quality of data from cosmic-ray experiments such as Ulysses, the Advanced Composition Explorer (ACE), the Voyagers, TIGER, the Fermi LAT (formerly GLAST), PAMELA, CREAM, BESS-Polar, AMS, and possibly ACCESS, far exceeds the accuracy of analytical propagation models, such as the ``leaky-box" model that has remained one of the main research tools for the last 50 years. These missions are specifically designed to search for dark matter signals in cosmic rays and diffuse γ-rays, searches for antimatter, and to study the diffuse Galactic and extragalactic diffuse emission, over a wide energy range. Meanwhile, developments in astrophysics, such as detailed 3-dimensional maps of the Galactic gas distribution, detailed studies of composition of interstellar dust, grains, the Local Bubble, interstellar radiation and magnetic fields, and new classes of cosmic-ray sources, all have implications for the interpretation of data obtained from ballon-borne and space-based experiments. The same can be said for more accurate measurements of nuclear isotopic production cross sections and new particle data that become increasingly available. Having the latest results and theoretical knowledge distilled and easily accessible in a unified framework is advantageous for the scientific community, as well as for planning and setting the goals for new missions.

The first version of the GALPROP code was written in FORTRAN-90/77 in the mid-1990s by *Andrew W. Strong* and *Igor V. Moskalenko* and then rewritten in C++ (with the well-tested FORTRAN-77 routines remaining). *Seth W. Digel* and *Troy A. Porter* joined the project in the early 2000s with *Gulli Johannesson*, *Elena Orlando*, and *Andrey Vladimirov* as more recent additions to the team. Other people have contributed by providing libraries, expertise, and data sets over the years: *Stepan G. Mashnik, Olaf Reimer, V. S. Barashenkov, A. Polanski, R. Silberberg, C. H. Tsao, and W. R. Webber*. We remember our late colleague *Patrick Nolan* who has shared a great deal of his knowledge, time and humor with the GALPROP team.

We are grateful to *Jeff Wade* who provides valuable assistance with the system administration for the GALPROP web servers and computing cluster. We also thank *Irina V. Malkova* for her help in designing and supporting the first version of this website.

The GALPROP development team acknowledges the use of HEALPix http://healpix.jpl.nasa.gov/ described in: K.M. Gorski et al., 2005, Ap.J., 622, p.759

This website is supported by NASA through an APRA "Laboratory Astrophysics" grant, by Stanford University, and by the GALPROP project. This is a free service to the scientific community. GALPROP source code and data sets can be freely copied, however, it is requested that in any subsequent use of the code and associated data sets be given appropriate acknowledgment.

GALPROP NEWS:

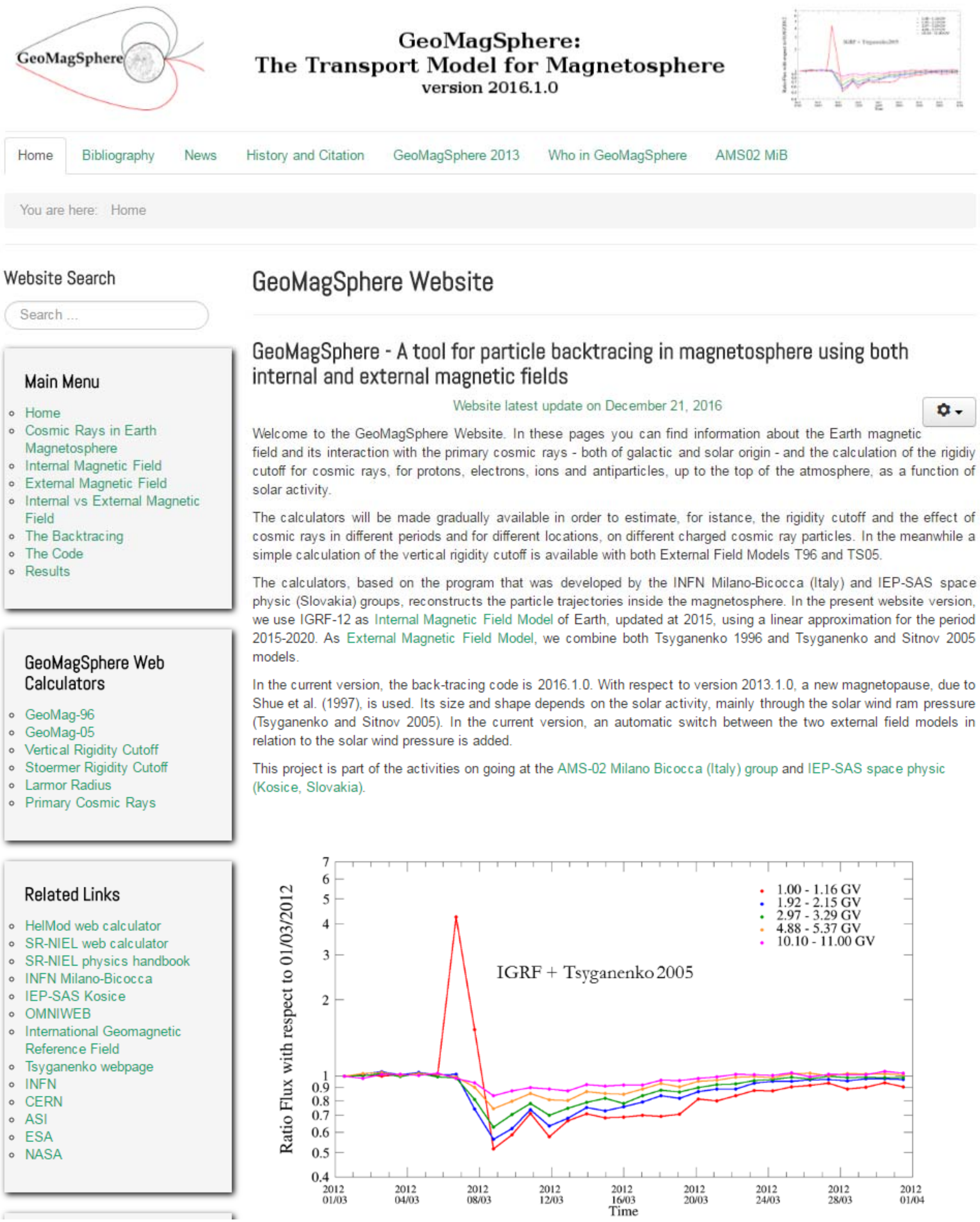
<< < 1 - 3 > >>

August 2016: *We are pleased to inform the community of the launch of a new service HelMod, which can be used to seamlessly calculate the effects of the heliospheric modulation for GALPROP output files.*
HelMod is a complete package that calculates propagation of Galactic cosmic rays from the Termination Shock down to the Earth for an arbitrary epoch.
We congratulate our colleagues with this significant step forward, and anticipate that their excellent web-site will be widely used!

June 2013: GALPROP WebRun now runs calculations on a new 500-core cluster at Stanford University. Issues due to migration? Please notify the admin! (address at the bottom of every page)

March 2013: New GALPROP-related talks, papers posted; explanatory supplement updated.

Correlatd sites II:
www.geomagsphere.org
under full revision



GeoMagSphere Website

GeoMagSphere - A tool for particle backtracing in magnetosphere using both internal and external magnetic fields

Website latest update on December 21, 2016

Welcome to the GeoMagSphere Website. In these pages you can find information about the Earth magnetic field and its interaction with the primary cosmic rays - both of galactic and solar origin - and the calculation of the rigidiy cutoff for cosmic rays, for protons, electrons, ions and antiparticles, up to the top of the atmosphere, as a function of solar activity.

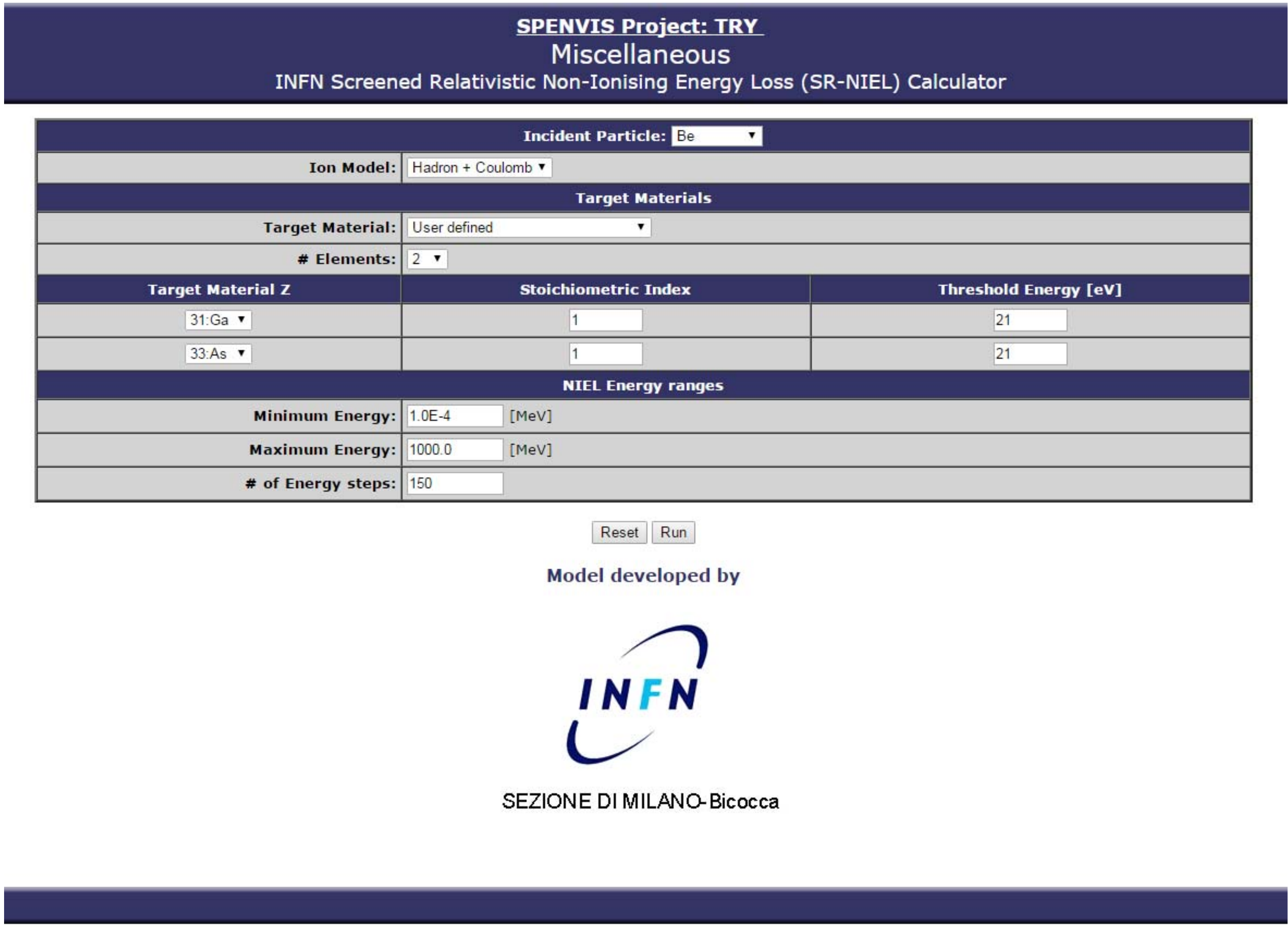
The calculators will be made gradually available in order to estimate, for istance, the rigidity cutoff and the effect of cosmic rays in different periods and for different locations, on different charged cosmic ray particles. In the meanwhile a simple calculation of the vertical rigidity cutoff is available with both External Field Models T96 and TS05.

The calculators, based on the program that was developed by the INFN Milano-Bicocca (Italy) and IEP-SAS space physic (Slovakia) groups, reconstructs the particle trajectories inside the magnetosphere. In the present website version, we use IGRF-12 as Internal Magnetic Field Model of Earth, updated at 2015, using a linear approximation for the period 2015-2020. As External Magnetic Field Model, we combine both Tsyganenko 1996 and Tsyganenko and Sitnov 2005 models.

In the current version, the back-tracing code is 2016.1.0. With respect to version 2013.1.0, a new magnetopause, due to Shue et al. (1997), is used. Its size and shape depends on the solar activity, mainly through the solar wind ram pressure (Tsyganenko and Sitnov 2005). In the current version, an automatic switch between the two external field models in relation to the solar wind pressure is added.

This project is part of the activities on going at the AMS-02 Milano Bicocca (Italy) group and IEP-SAS space physic (Kosice, Slovakia).

Spenvis Implementation



SPENVIS Project: TRY

Miscellaneous

INFN Screened Relativistic Non-Ionising Energy Loss (SR-NIEL) Calculator

Incident Particle: Be

Ion Model:	Hadron + Coulomb

Target Materials

Target Material:	User defined
# Elements:	2

Target Material Z	Stoichiometric Index	Threshold Energy [eV]
31:Ga	1	21
33:As	1	21

NIEL Energy ranges

Minimum Energy:	1.0E-4 [MeV]
Maximum Energy:	1000.0 [MeV]
# of Energy steps:	150

Model developed by

INFN

SEZIONE DI MILANO-Bicocca

Screenshot of the SR-NIEL Calculator input mask in SPENVIS v. 4.6.8