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

Key people involved:

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

General Support Technology Programme (GSTP)
Contract No.: 4000116146/16/NL/HK
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Project Manager: Massimo Gervasi
ESA Technical Officer: Petteri Nieminem
Contract Duration: 17-12-2015 - December 2017

P.G. Rancoita, ESTEC 15 May, 2018

Tasks
(kick-off date Dec 16, 2015: up to → 16 Dec. 2017)

Task 1: Consolidation and Further Development of SR-NIEL model for Implementation into Software Frameworks, Treatment of Neutron and Heavy Ions (1st year)
Task 4: NIEL Data Analyses, Model and Software Framework Updates, Recommendations (2nd year)
Task 5: Maintenance (2nd year)
(Univ. and INFN Milano-Bicocca)

Task 2: Test plan and Experimental Irradiation Test Campaigns (1st year)
Task 3 : DLTS measurements of Irradiated Test Samples (2nd year)
(Univ. and INFN Milano-Bicocca, IMEN-CNR, CESI)

Outline

Sr-niel: physics elements and displacement damage
code and its implementations
world usage

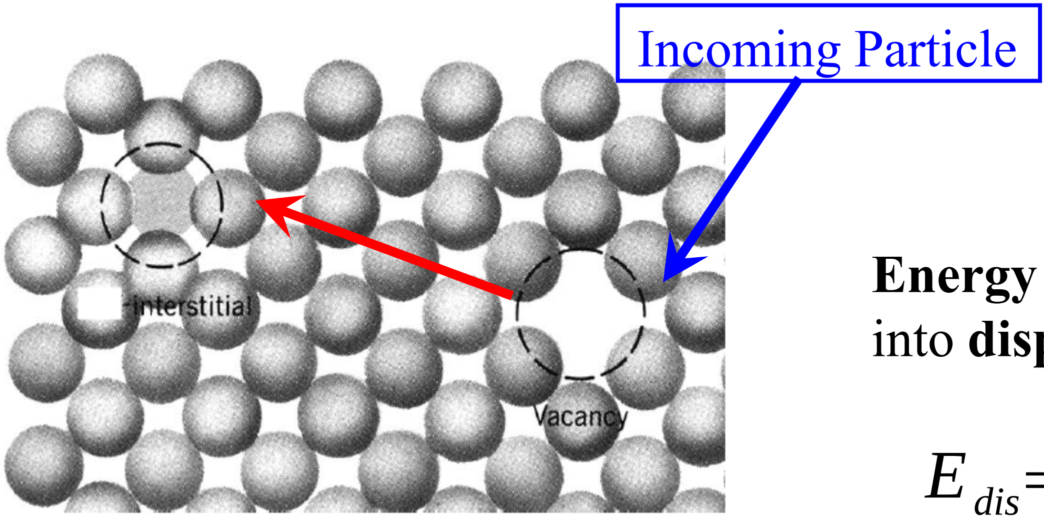
Experimental results from electrons, protons (2017)
3J and 1J solar cells
DLTS results

Preliminary experimental results from neutrons (2018)
carried out under ASIF framework

Remarks

SR-NIEL
physics elements and displacement damage

Displacement Damage and NIEL



Frenkel-pairs:

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

Displacement threshold energy

Energy density which goes into **displacement** [MeV/cm³]:

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

E_{min}: 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)

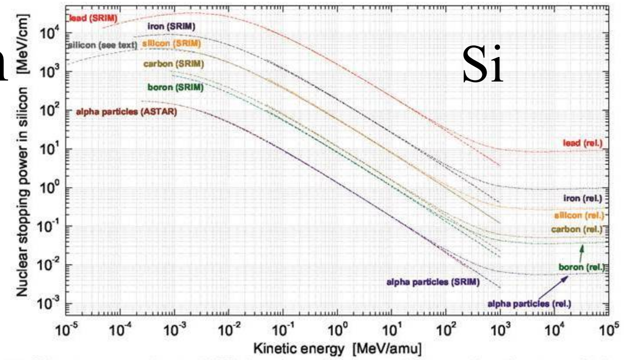


Fig. 2.23 Nuclear stopping powers (in units of MeV/cm) in a silicon medium for α-particles, boron-, carbon-, silicon-, iron- and lead-ions function of the kinetic energy of incoming ions in units of MeV/amu. The data for α-particles (ASTAR) are from [Berger, Coursey, Zucker a Chang (2010)]; those indicated as "silicon (see text)" are calculated using Eq. (2.79) for incoming ^{28}Si ions; the data for ^{208}Pb ("lead"), ^{56} ("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

$$\frac{d\sigma(\theta)}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{pc\beta}\right)^2 \frac{1}{(2A_s + 1 - \cos\theta)^2}$$

m_1, m_2 are the rest masses of the two particles
$M_{1,2}$ is the invariant mass

$$\frac{1}{\beta^2} = 1 + \left(\frac{\mu c^2}{pc}\right)^2$$

$$\mu = \frac{m_1 m_2}{M_{1,2}}$$

with Moliere screening parameter

$$A_s = \frac{1}{4}\left(\frac{\eta}{p a_{TF,un}}\right)^2 \left[1.13 + 3.76\left(\frac{\alpha Z_1 Z_2}{\beta}\right)^2\right]$$

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

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

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

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

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/nuc, 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

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

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**

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

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

References:
- Ziegler, J.F., Biersack, J.P. and Littmark, U. (1985) (a). The Stopping Range of Ions in Solids, Vol. 1, Pergamon Press, New York.

- 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

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

Rutherford in the center of mass:

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

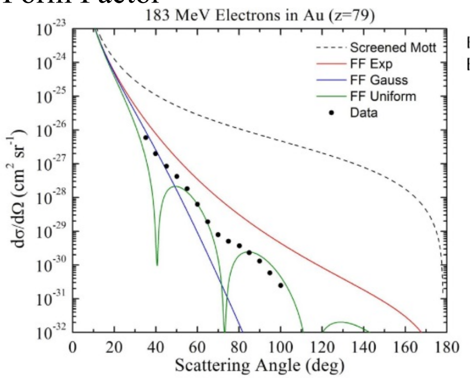
Molier's Screening Coefficient:

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

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

Nuclear Form Factor

183 MeV Electrons



Ratio of
Mott cross section over Rutherford

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

Practical interpolated expressions

Mott Cross Section fit:

$$R = \sum_{j=0}^{4} a_j (1-\cos\theta)^{j/2}$$

$b_{j,k}$ 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 NTID 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 2016 (from Los Alamos) as INFN-ENEA collaboration within ASIF framework.

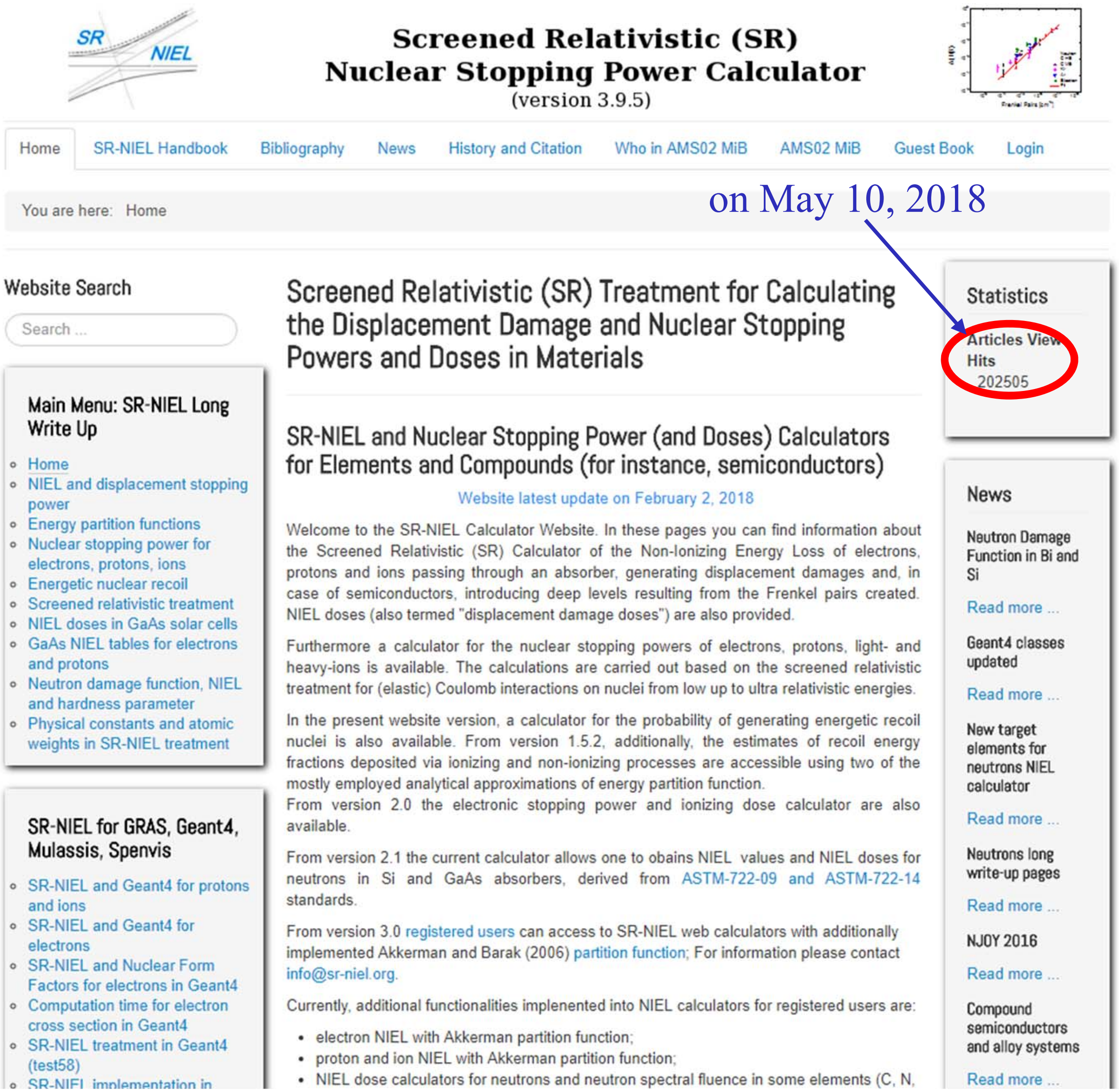
In addition, in sr-niel website users can find the
electronic stopping power (and, thus, estimated TID doses).

- 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%.

SR-NIEL
code and implementations

Code for NIEL Calculation

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



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 <u>change the displacement threshold energy</u>

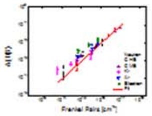
Moreover is possible to select different **nuclear form factor** for electrons and switch on/off the **hadronic contribution** for protons

The site is continuously updated (now version 3.9.5)

SR NIEL

Screened Relativistic (SR) Nuclear Stopping Power Calculator

(Physic Handbook)



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Website Search

Search ...

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
- hadronic NIEL contribution for protons and alpha particles
- 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
- neutron damage function in Bi and Si
- 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 Framework: Physics Handbook

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

Website latest update on February 2, 2018

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 (also termed "displacement damage 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, from version 3.5.1 0, Al, P, In, Cd, Te, Ge, Zn, Se, Sb, from version 3.9 Cu, Hg, Pb, S, Sn and from version 3.9.2 also B, Bi, Cl, Tl) 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.

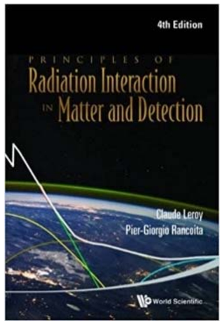
In addition, for registered users are available the following long write-ups:
- NIEL for Electrons and Protons (with only Coulomb scattering and, also, including hadronic contribution) in Silicon employing Robinson and Akkerman partition functions;
- NIEL dose calculation for neutron using Robinson and 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

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 first NIEL calculators for **neutrons** based on NJOY results (compound with Bragg rule)
Version 3.9.5 Current version (February 2018) update no. 42	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	1.5/3.7	3.7	3.7
Status	NIEL Calculator (v 1.5, provided to ESA in 2014); implemented into public SPENVIS v. 4.6.8 in 2016 version 3.7 implemented in November 2017 on ESA servers	version 3.7 implemented in November 2017 on ESA servers	version 3.7 implemented in November 2017 on ESA servers
To do	•Transfer to public SPENVIS version (tbd with ESA)	•Transfer to official GRAS version (tbd by ESA)	•Transfer to official Mulassis version (tbd by ESA)

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 2017:

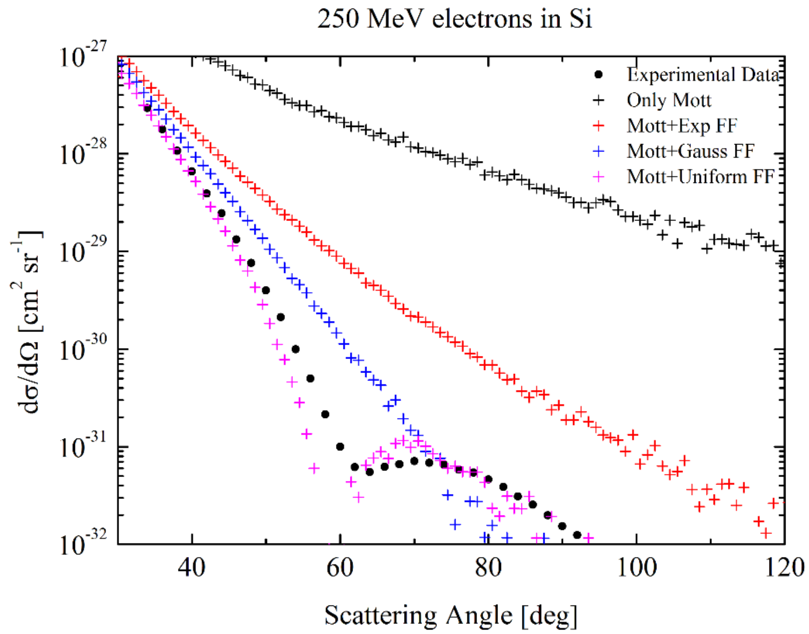
- The classes were updated to match latest Geant4
- Full Mott cross-section for electron interaction up to Z=92, based on M.J. Boschini et al., (2013) (An expression for the Mott cross section of electrons and positrons on nuclei with Z up to 118, Rad. Phys. Chem. 90, 39-66.)
- Minor bugs where spotted and fixed
- Implemented all nuclear form factors (FF) for electrons cross section (*Gaussian, Uniform nuclear form factors in addition to exponential*)
- Version without FF also available
- Improved computing time of the electrons class (about a factor 200)

Further activity in 2018

- The Coulomb sr-niel contribution for compounds was revised by January 2018.
- FROM APRIL 2018, test58 includes the sr-niel HADRONIC CONTRIBUTION FOR COMPOUNDS

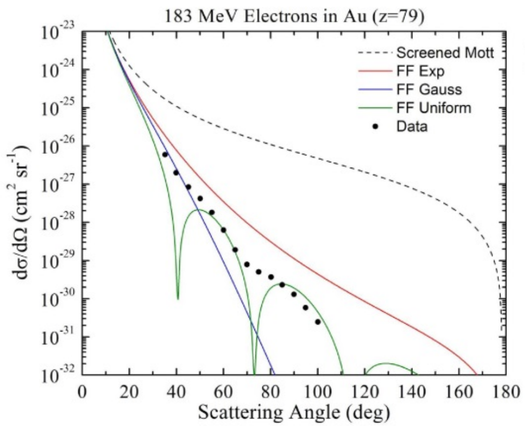
Exs. Geant4 FF implementation

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



sr-treatment analytical calculation

183 MeV Electrons in Au (z=79)

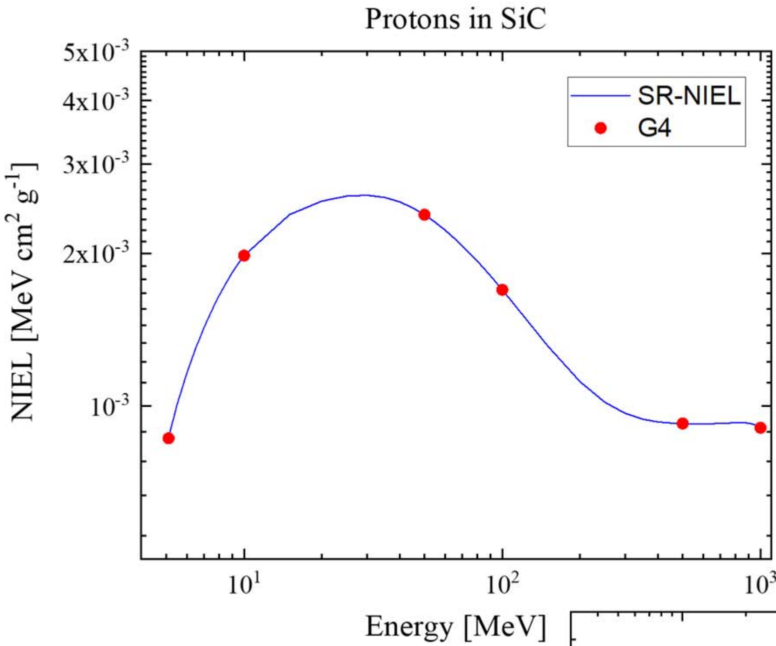


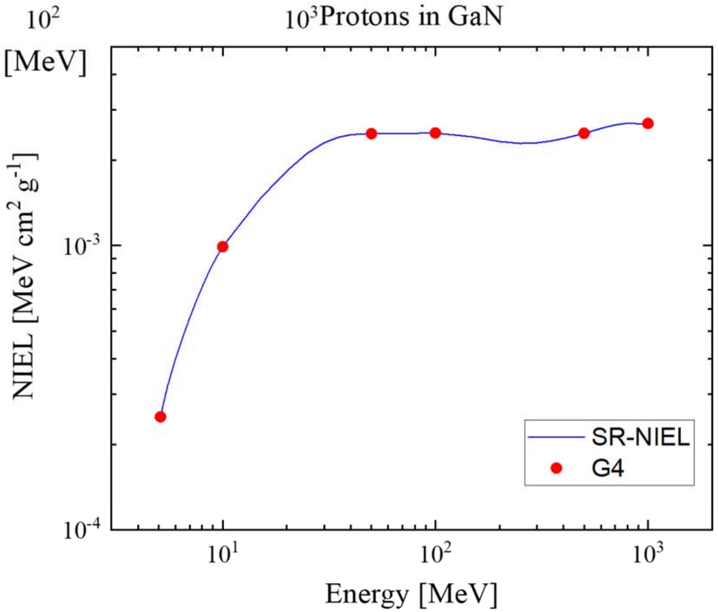
Experimental Data From:
B.Hahn et al. Phys. Rev. 101 (1956) 1131

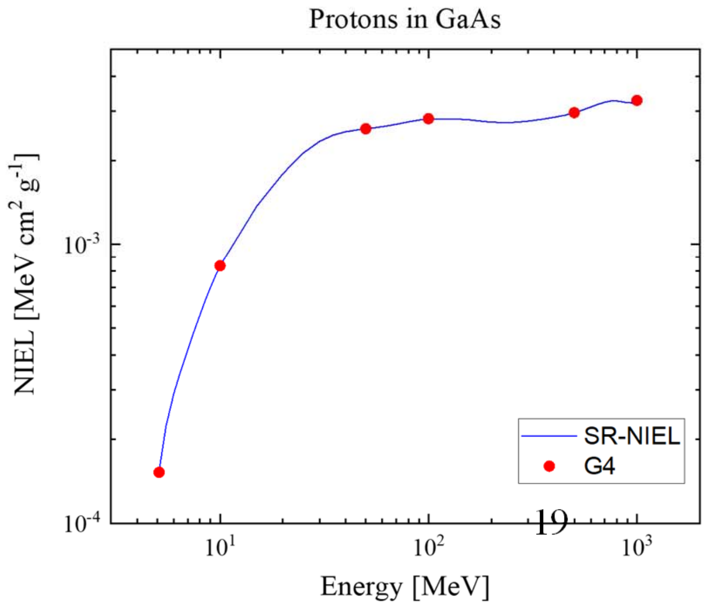
sr-niel framework:

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

NIEL (hadronic contributions) for Compounds in test 58 of GEANT4







SR-NIEL: world usage

Institutions and Companies using calculators available at www.sr-niel.org

Main Institutions and Companies 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. 3.9.5)

Total webpages accessed > 199,000 on May 4, 2018 (>170,000 December 2017)

Requested Calculations from external users: 9335 on May 4, 2018

(8375 on March 14, 2018; 7950 December 4, 2017; 7320 October 4, 2017; 6127 end of May 2017, 5410 end of Feb 2017; 4357 on October 17, 2016; 3392 May 13, 2016; 2015 Oct 31, 2015; 419 Jan 31, 2015)

→ The following slides are based on **5439** requests calculations from well known Institutions or Companies (May 1st 2018)

39% from USA (92% in case of registered users)

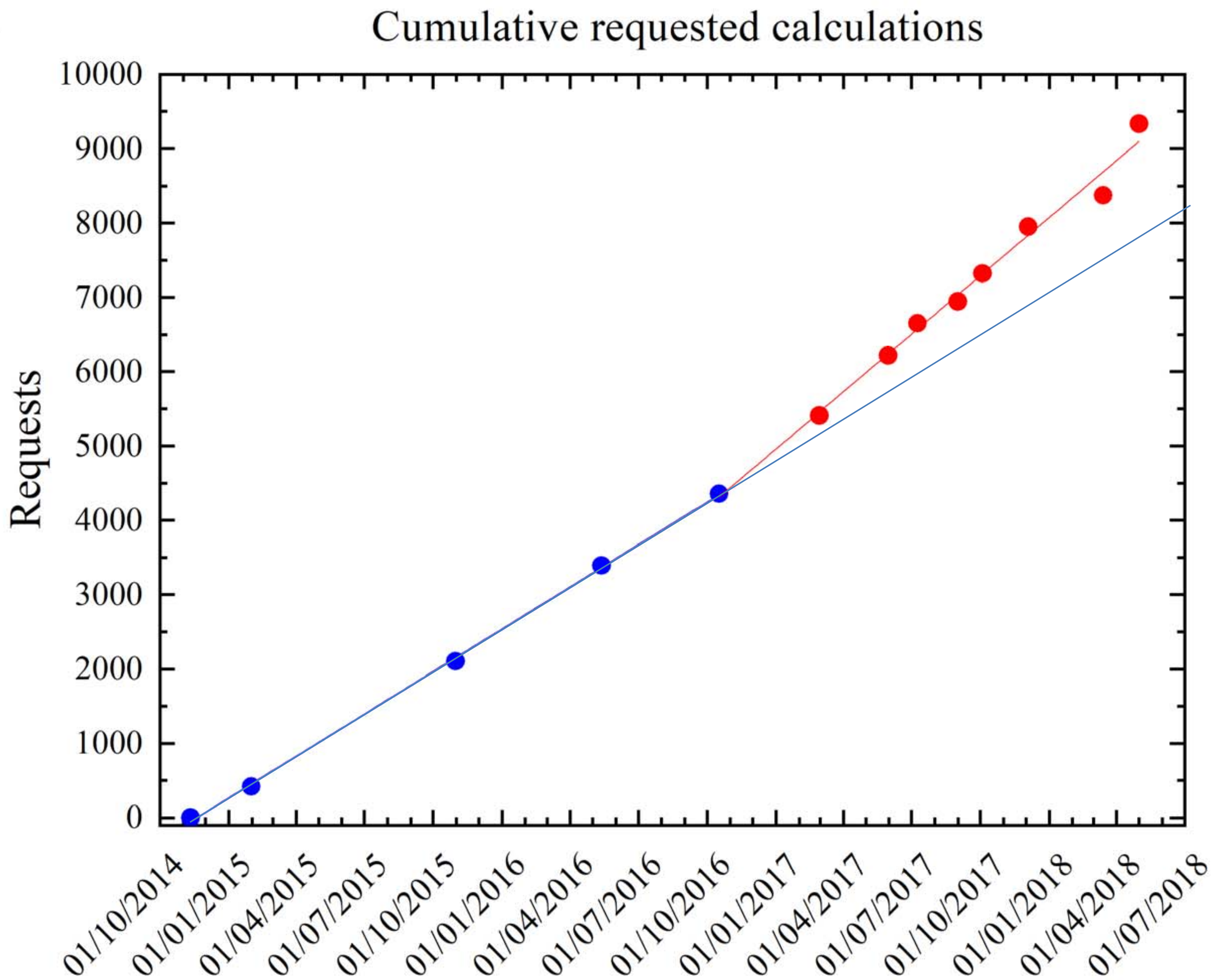
Laboratories and Industries with > 50 webcalculator requests:

ESA
EADS Deutschland GmbH
Cassidian-Optronics-GmbH
CERN
University of Bern
CNES
Office National d'Etudes et de Recherches Aeronautiques
Commissariat a l'Energie Atomique
Joint Institute for Nuclear Research DUBNA

Japan Aerospace Exploration Agency

SANDIA National Laboratories
US Navy & Department of Defense
NASA
Ohio State University
The Aerospace Corporation LA USA
Northrop Grumman Corp.
University of Massachusetts Lowell
California Institute of Technology
University of Louisiana at Lafayette

Requested Calculations from external users: 9335 on May 4, 2018



Europe I

ITALY

- ESA (ESRIN)
- INFN
- Napoli University
- ENEA
- Università di Trieste
- Fondazione Bruno Kessler
- INFN-Laboratori Nazionali del Sud
- LNL Laboratori Nazionali di Legnaro
- Università degli studi di Cassino
- Milano Bicocca University
- Fondazione San Raffaele del Monte Tabor
- ESA-ISECG
- INFN-TIFPA Trento
- Ente per le Nuove Tecnologie, Energia ed Ambiente
- INAF
- Università degli studi di Pisa
- ENEA C.R. Frascati
- Universita' degli Studi di Udine
- Politecnico di Milano
- INFN-LNF Frascati (Italy)
- Trento University
- Oss. Astronomico di Collurania Teramo
- Universita' degli Studi di Padova
- Universita' degli Studi di Roma La Sapienza

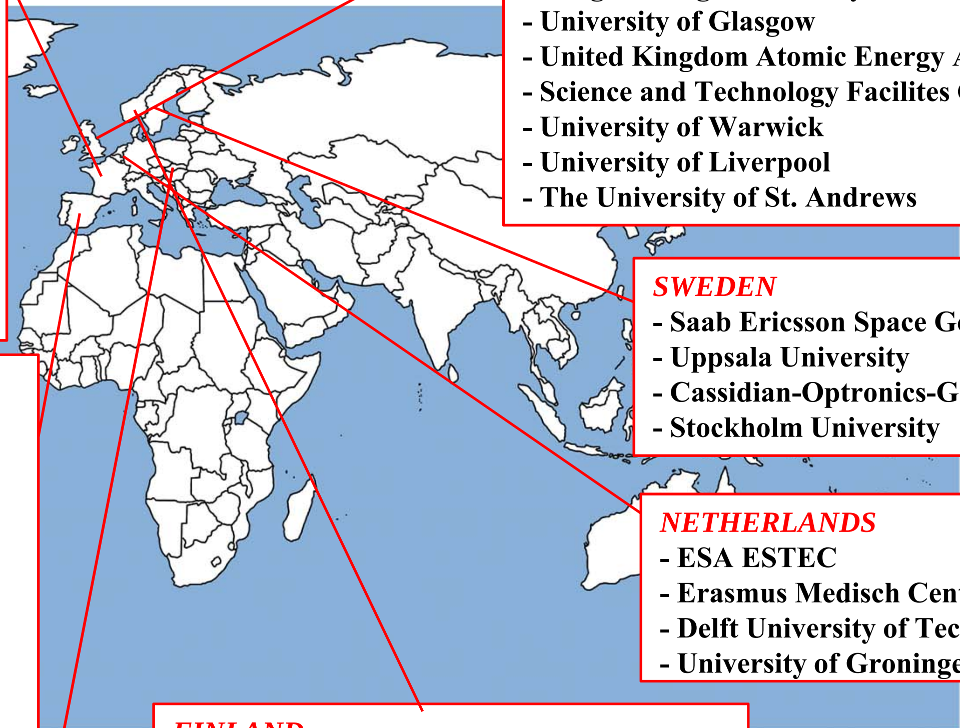
SWITZERLAND

- CERN
- University of Bern
- Paul Scherrer Institut
- Swiss Federal Institute of Technology Zurich
- Mercury Systems
- Ecole Polytechnique Federale de Lausanne
- University of Geneva
- RUAG Services AG

GERMANY

- EADS Deutschland GmbH
- Eberhard Karls Universitaet Tuebingen
- DIEHL Aerosystems
- Cassidian-Optronics-GmbH
- GWD Goettingen
- GSI Helmholtzzentrum fuer Schwerionenforschung GmbH
- AZUR SPACE Solar Power GmbH
- Ludwig-Maximilians-Universitaet Muenchen
- TSBS fuer EADS Deutschland GmbH
- Fraunhofer GERMY
- Friedrich-Schiller-Universitaet Jena
- OHB System AG
- Ruprecht-Karls-Universitaet Heidelberg
- Technische Universitat Munchen
- Karlsruhe Institute of Technology (KIT)
- Johann Wolfgang Goethe-Universitaet Frankfurt
- Airbus DS Optronics GmbH
- Max-Planck-Institut fuer Plasmaphysik
- Rheinische Friedrich-Wilhelms-Universitaet Bonn
- Johannes Gutenberg-Universitaet, Mainz
- Friedrich Alexander Universitaet Erlangen-Nuernberg
- TESAT Spacecom
- Universitaet Kiel
- Universitaet der Bundeswehr Muenchen
- DESY
- Georg-August Universitaet Goettingen
- Helmholtz-Zentrum Dresden-Rossendorf
- Technische Universitaet Dresden
- Max Planck Institute for Human Cognitive and Brain Sciences
- ASP-Equipment GmbH
- Kabel Baden-Wuerttemburg GmbH
- GRS – Global Research for Safety
- Universitaet Leipzig
- Helmholtz-Zentrum Berlin fuer Materialien und Energie GmbH
- Lti DRIVES GmbH
- Jena-Optronik
- Universitaet Duisburg-Essen
- DLR German Aerospace Center
- etc...

Europe II



FRANCE

- CENTRE NATIONAL D'ETUDES SPATIALES Toulouse
- Office National d'Etudes et de Recherches Aeronautiques
- Commissariat a l'Energie Atomique
- Thales SAS
- ASTRIUM SAS Toulouse
- Institut National de Physique Nucleaire et de Physique des Particules
- TRAD
- Commissariat a l'Energie Atomique Sacaly
- Ecole Polytechnique
- Ecole Nationale Superieure d`Ingenieur des Constructions Aeronautiques
- Universite de Strasbourg
- Universite Pierre et Marie Curie – Paris
- CNRS Centre de Calcul de l'IN2P3
- Airbus Defence and Space
- Universite Montpellier II
- Erems

SPAIN

- Instituto Nacional de Tecnica Aeroespacial
- Alter Technology Tuv Nord S.A.U.
- Universidad de Sevilla
- Universitat Autonoma de Barcelona
- Research Centre for Energy, Environment and Technology
- Universidad de Oviedo
- Universidad Politecnica de Madrid
- Universidad de Zaragoza

SLOVAK

- Slovak Technical University

UNITED KINGDOM

- Open University
- The University of Manchester
- The University of Birmingham
- ASTRIUM Ltd
- University of Leicester
- Imperial College London
- Statumen International
- University of York
- Queens University Belfast
- National Physical Laboratory
- Dpt. Physcs University of Oxford
- University College London
- Lancaster University
- Loughborough University
- University of Glasgow
- United Kingdom Atomic Energy Authority
- Science and Technology Facilites Council
- University of Warwick
- University of Liverpool
- The University of St. Andrews

SWEDEN

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

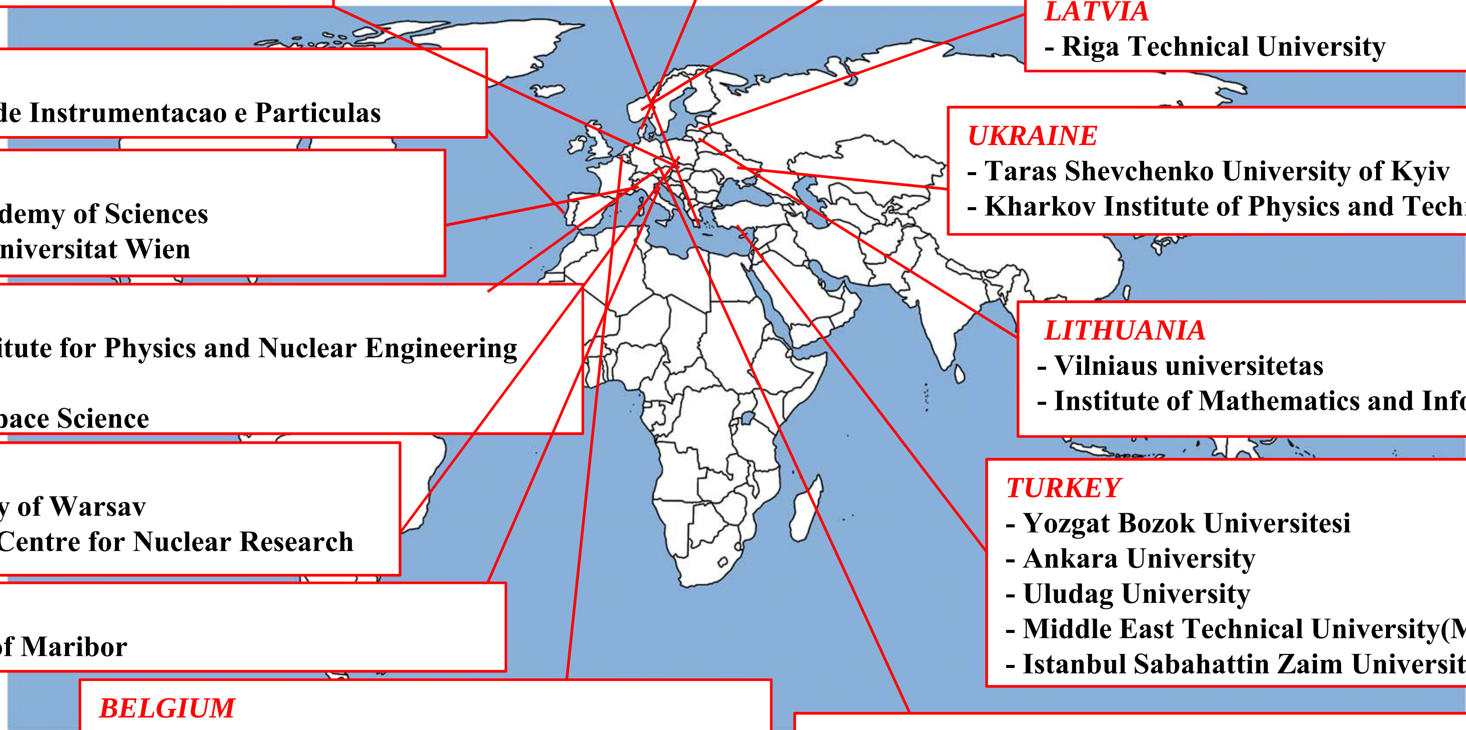
NETHERLANDS

- ESA ESTEC
- Erasmus Medisch Centrum
- Delft University of Technology
- University of Groningen

FINLAND

- University of Helsinki
- University of Jyvaskyla
- University of Turku

Europe III



GREECE
- Aristotle University of Thessaloniki
- University of Crete
- National Center of Scientific Research DEMOKRITOS

DENMARK
- DTU Danish Technical University
- Terma A/S

CZECH REPUBLIC
- Czech Technical University Prague
- ON Semiconductor
- Unis s.r.o.
- Charles University Prague

NORWAY
- University of Oslo
- Bergen University, Norway

LATVIA
- Riga Technical University

PORTUGAL
- Laboratorio de Instrumentacao e Particulas

UKRAINE
- Taras Shevchenko University of Kyiv
- Kharkov Institute of Physics and Technology

AUSTRIA
- Austrian Academy of Sciences
- Technische Universitat Wien

ROMANIA
- National Institute for Physics and Nuclear Engineering Horia Hulubei
- Institute of Space Science

LITHUANIA
- Vilniaus universitetas
- Institute of Mathematics and Informatics

POLAND
- University of Warsav
- National Centre for Nuclear Research

TURKEY
- Yozgat Bozok Universitesi
- Ankara University
- Uludag University
- Middle East Technical University(METU)
- Istanbul Sabahattin Zaim Universitesi

SLOVENIA
- University of Maribor

BELGIUM
- Universite Catholique de Louvain
- Observatory Meteorology Aeronomy
- Facultes Universitaires Notre Dame de la Paix
- Delta Air Transport

HUNGARY
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USA

Requests from USA: 39% (92% registered)

USA

- University of Alaska
- Argonne National Laboratory (ANLB)
- Purdue University (PURDUE)
- North Carolina Central University (NCCU)
- SLAC National Accelarator Laboratory
- Idaho National Laboratory (INL-12)
- Le Moyne College
- Vanderbilt University (VANDER)
- Los Alamos National Laboratory
- Food and Drug Administration
- Boise State University (BSU)
- Stanford University
- National Space Science and Technology Center – University of Alabama
- Solar Junction
- Charles Stark Draper Laboratory, Inc.
- TRIDENT SPACE & DEFENSE
- Space Exploration Technologies Corporation (SPACEX)
- Rochester Institute of Technology (RIT-3)
- Auburn University
- University of Colorado
- Northern Arizona University
- Austin Peay State University (APSU)
- Harris Corporation (HARRIS-6)
- Montana State University
- Ominivision
- University of Michigan
- Princeton University
- etc….

USA

- SANDIA National Laboratories
- US Navy & Department of Defence
- NASA
- The Aerospace Corporation LA USA
- Ohio State University
- Northrop Grumman Corp. (NGC-1)
- University of Massachusetts Lowell
- California Institute of Technology
- University of Louisiana at Lafayette
- Micropac Industries Inc
- FERMILAB
- US Army – 754th Electronic Systems Group (7ESG)
- Teledyne Brown Engineering (TBE)
- University of California
- RMD Inc.
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- Cal State Fullerton (CSUF)
- General Dynamics Advanced Information Systems, Inc
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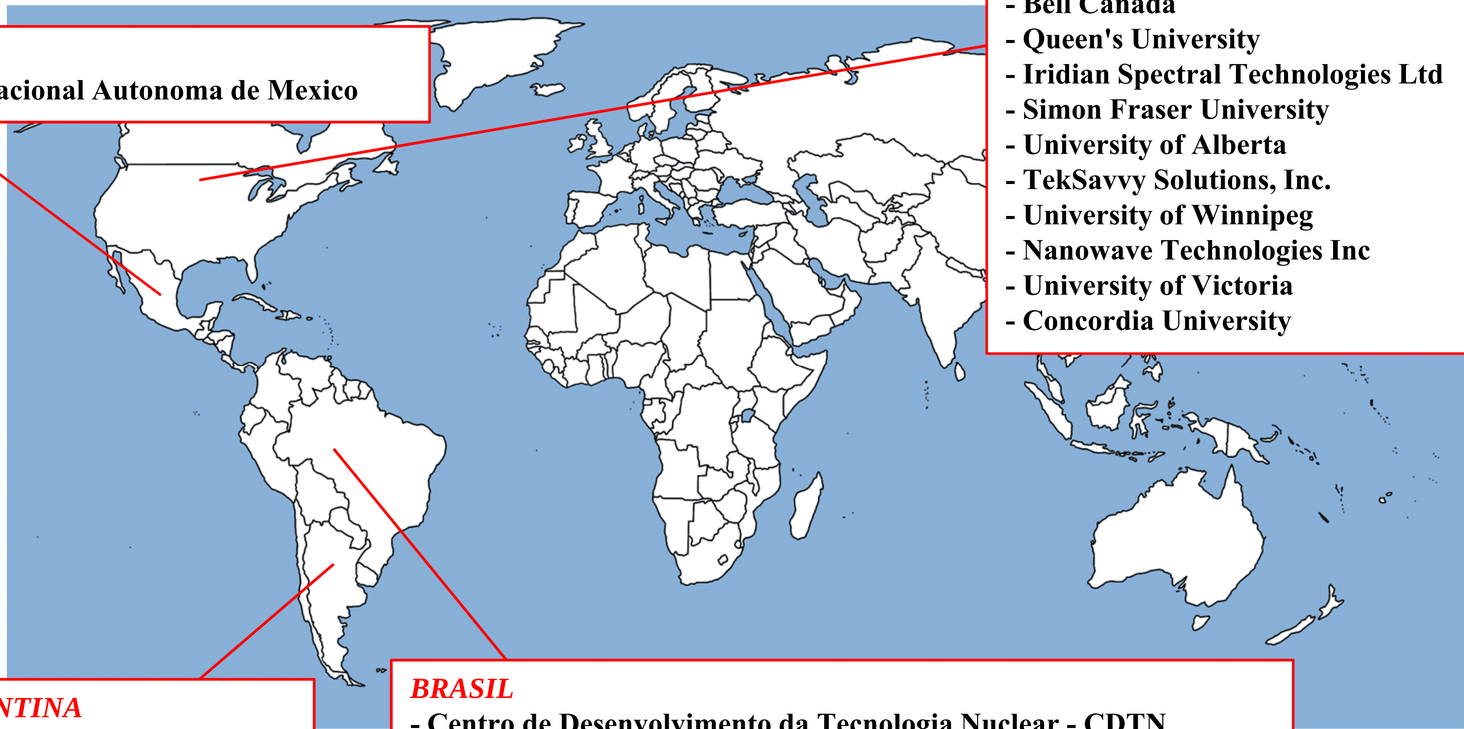
- Pacific Northwest National Laboratory (PNNL-Z)
- Raytheon Company (RAYTHE)
- The Boeing Company
- Louisiana Tech University (LTU-1)
- Lawrence Berkeley National Laboratory
- California State University
- Massachusetts Institute of Technology
- Virginia Commonwealth University (VCU-Z)
- Mayo Foundation for Medical Education and Research
- Case Western Reserve University
- Ball Corporation (BALLCO)
- Michigan State University
- Lockheed Martin Corporation
- Georgia Institute of Technology
- AHS-Hillcrest-Medical-Center
- Microchip Techonology Inc.
- Millennium Space Systems

America's except USA



MEXICO
- **Universidad Nacional Autonoma de Mexico**

CANADA
- **University of Waterloo**
- **TRIUMF (Tri-University Meson Facility)**
- **Atomic Energy of Canada Ltd**
- **Bell Canada**
- **Queen's University**
- **Iridian Spectral Technologies Ltd**
- **Simon Fraser University**
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- **University of Winnipeg**
- **Nanowave Technologies Inc**
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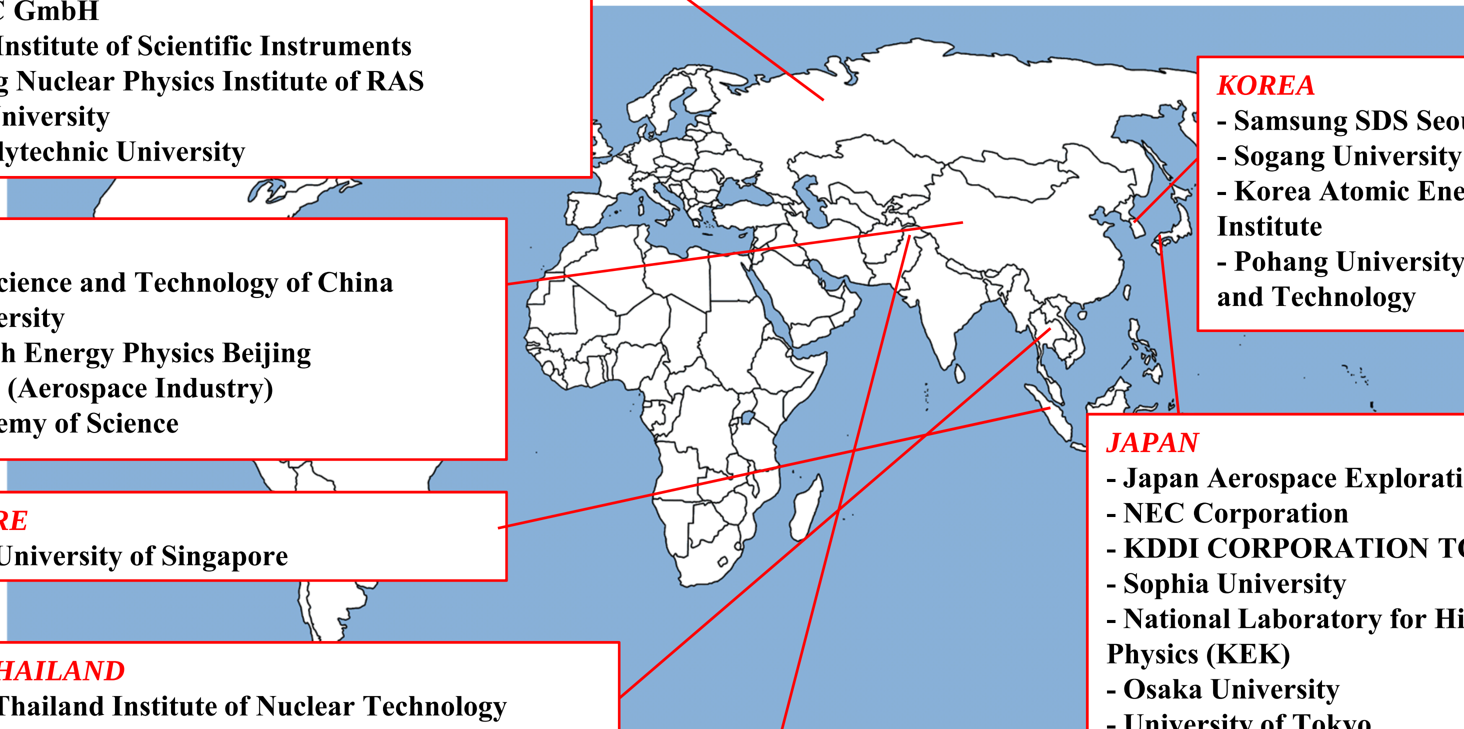
ARGENTINA
- **Fondation Innova T**

BRASIL
- **Centro de Desenvolvimento da Tecnologia Nuclear - CDTN**
- **Universidade Estadual de Campinas**

Asia



RUSSIA
- Joint Institute for Nuclear Research DUBNA
- ISS Reshetnev
- JSC "NIIP"
- Russian Academy of Sciences
- Budker Institute of Nuclear Physics Novosibirsk
- Ioffe Physical-Techical Institute St.Petersburg
- RITVERC GmbH
- Research Institute of Scientific Instruments
- Petersburg Nuclear Physics Institute of RAS
- Moscow University
- Tomsk Polytechnic University

KOREA
- Samsung SDS Seoul
- Sogang University
- Korea Atomic Energy Research Institute
- Pohang University of Science and Technology

CHINA
- University of Science and Technology of China
- Tsinghua University
- Institute of High Energy Physics Beijing
- Cogenda.COM (Aerospace Industry)
- Chinese Accademy of Science

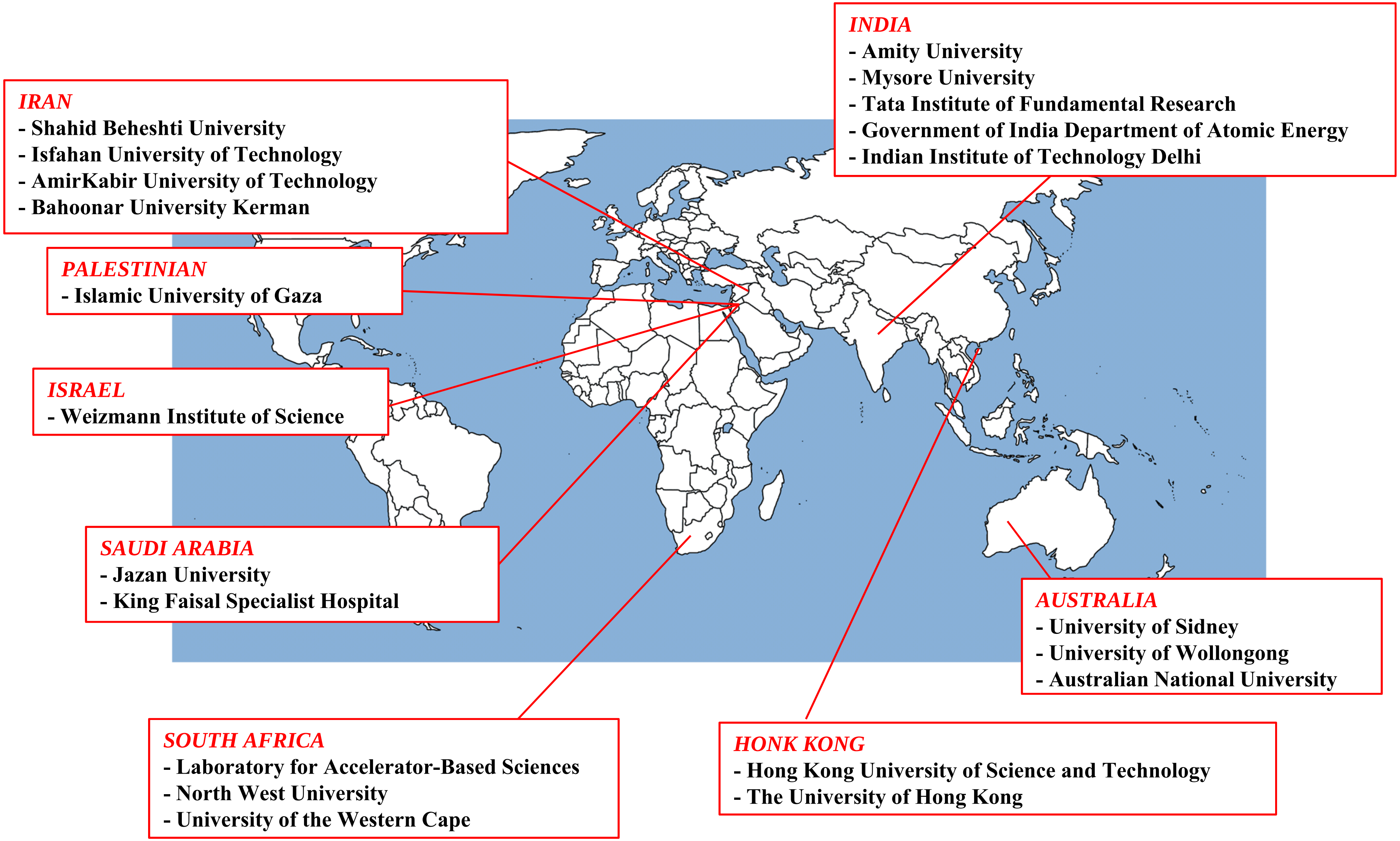
JAPAN
- Japan Aerospace Exploration Agency
- NEC Corporation
- KDDI CORPORATION TOKYO
- Sophia University
- National Laboratory for High Energy Physics (KEK)
- Osaka University
- University of Tokyo
- Japan Atomic Energy Agency
- RIKEN
- Kyoto University

SINGAPORE
- National University of Singapore

THAILAND
- Thailand Institute of Nuclear Technology

PAKISTAN
- National University of Science and Technology

Asia, Africa, Oceania



Experimental Results

Test Irradiation Campaign

Protons Irradiation

Energy [MeV]	Fluence [cm^{-2}]	Dose [MeV g^{-1}]	Dose [Gy]
0.7	1.70E+011	1.40E+10	2.24
	3.30E+011	2.71E+10	4.35
	4.50E+011	3.70E+10	5.93
1	4.50E+010	2.50E+09	0.40
	2.30E+011	1.28E+10	2.05
2	4.20E+011	1.16E+10	1.86
	8.40E+011	2.32E+10	3.71

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. 3.9) in GaAs (mid cell 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)

	Energy (MeV)	Fluences (p/cm2)
Incoming 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

- Solar cells were measured at CESI under solar simulator dual source 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

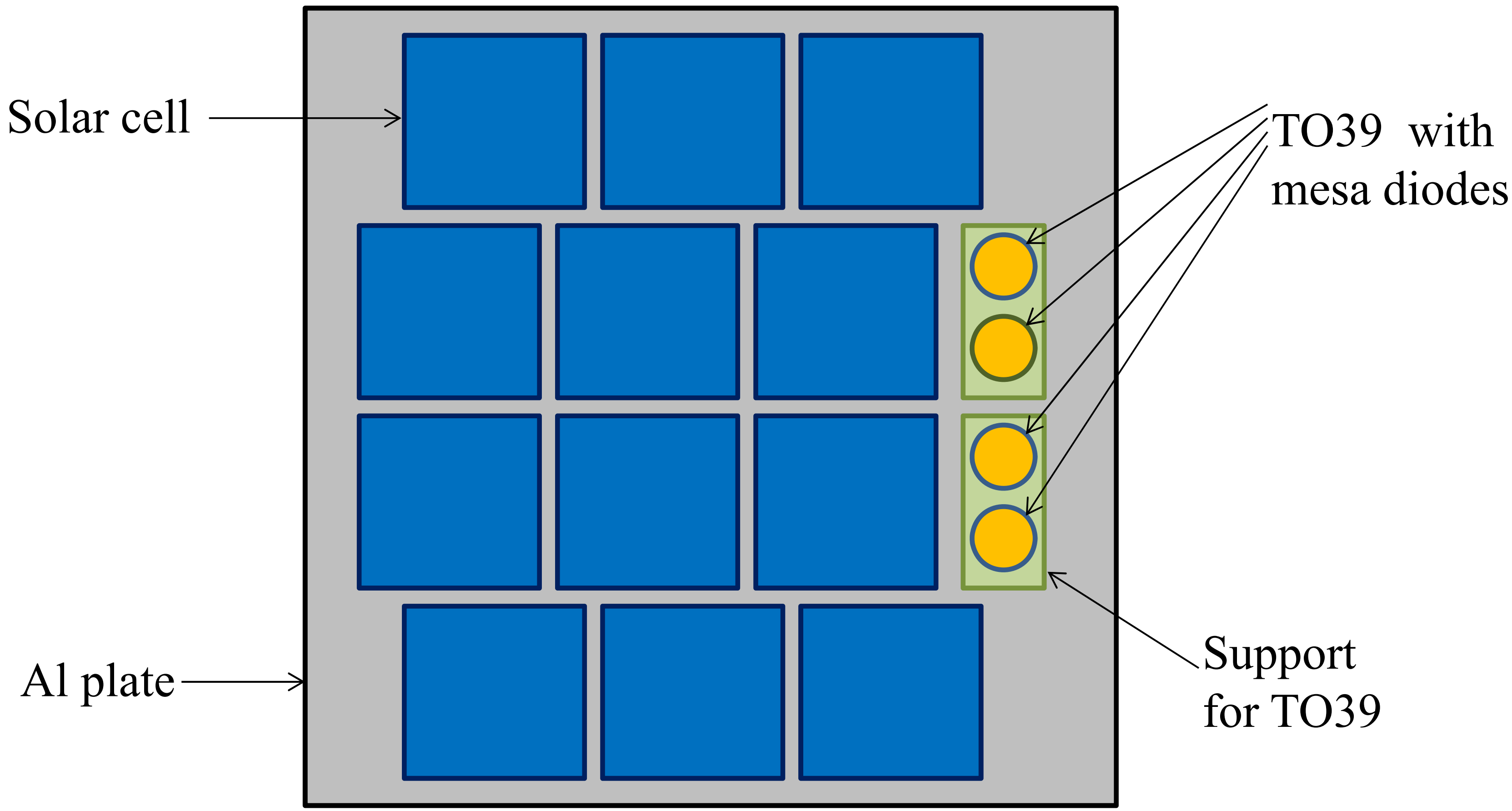
	Energy (MeV)	Fluences (e/cm2)
Incoming electron	1	1.00E+14
		5.00E+14
		1.00E+15
	1.5	5.00E+14
		1.00E+15
	3	2.00E+14
		4.00E+14

Total irradiated samples

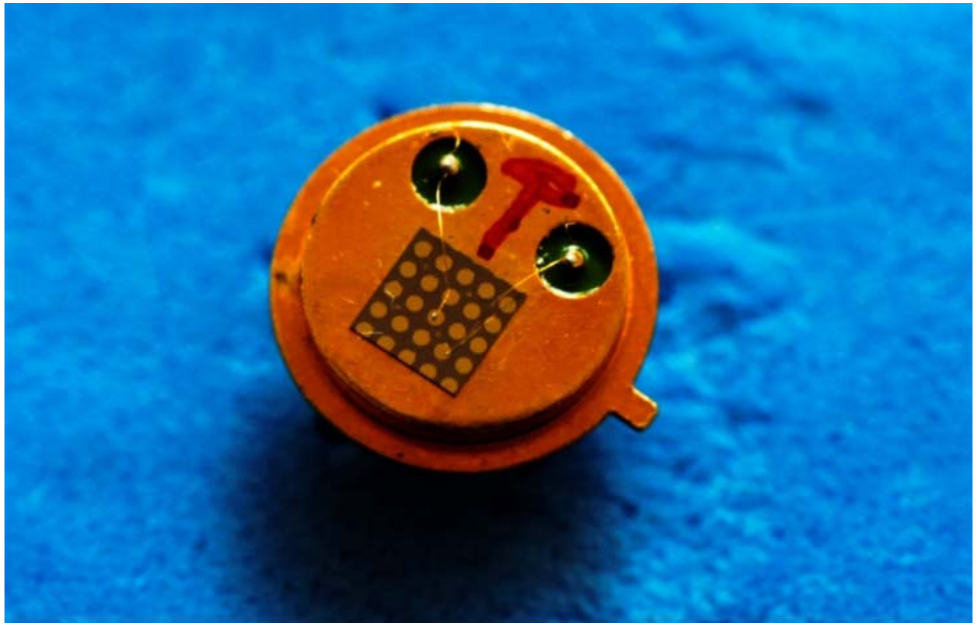
3J solar cells : 14 fluences x 3 samples = 42 samples
1J solar cells : 14 fluences x 3 types x 3 samples = 126 samples
Diodes for DLTS: 14 fluences x 2 types x 2 samples = 56 samples x 25 diodes = 1400

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



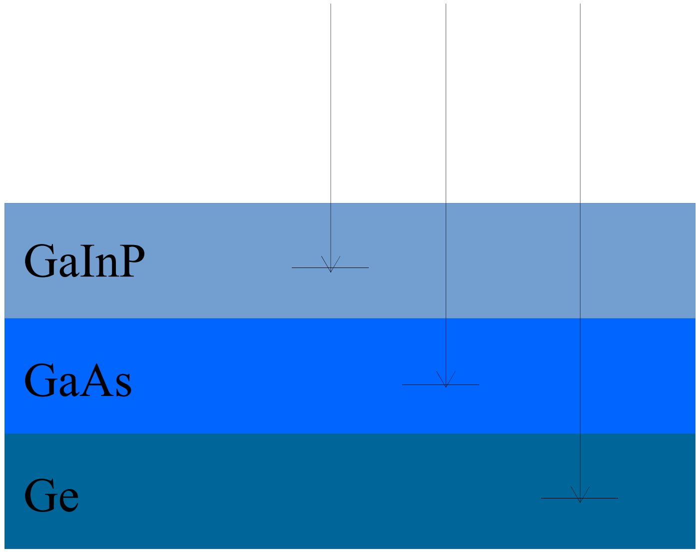
Sample for DLTS measurements mounted on TO39 holder



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. 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

Energy Loss



Energy loss was taken into account for **protons for determining the proton incoming energy in each cell.**
For **electrons** such a correction is negligible .

The real thicknesses provided by CESI w used.

For **single cells** NIEL was calculated using the energy of the particle at the middle of the junction.

For the **3J solar cell** GaAs NIEL was used with energy in the middle of the GaAs junction.

Particle Energies for NIEL calculation

Protons

Incoming Energy [MeV]	Top Cell	Mid Cell	Bottom Cell	3J Solar Cell
0.70	0.68	0.55	0.30	0.55
1.00	0.98	0.88	0.68	0.88
2.00	2.00	1.92	1.79	1.92

Electrons

Incoming Energy [MeV]	Top Cell	Mid Cell	Bottom Cell	3J Solar Cell
1.00	1.00	1.00	1.00	1.00
1.50	1.50	1.50	1.50	1.50
3.00	3.00	3.00	3.00	3.00

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

P/P_{max} After Annealing

Protons Irradiation

Energy [MeV]	Variation [%]
0.7	5.1 ± 1.6
1.0	2.4 ± 0.5
2.0	3.7 ± 1.0

Electrons Irradiation

Energy [MeV]	Variation [%]
1.0	3.2 ± 1.7
1.5	4.7 ± 0.4
3.0	4.9 ± 1.0

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)

vs

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

The fitted expression is the standard semi-empirical – which relates via two parameters P/P_{max}, I_{sc}, V_{oc} to the $Dose^{NIEL}(Ed)$ –, with an additional third term correcting the constant value, i.e., (1-A) from C. Baur et al. (2005) 31 IEEE Photovoltaic Specialists Conference:

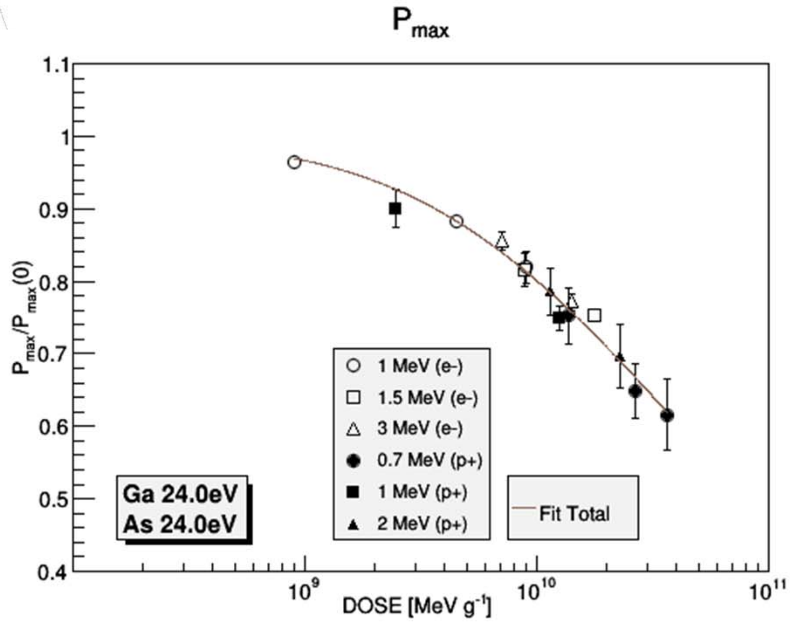
$$(1-\mathrm{A})-\mathrm{B}\cdot\log_{10}\left[1+\mathrm{C}\cdot NIEL\mathrm{Dose}(Ed)\right]$$

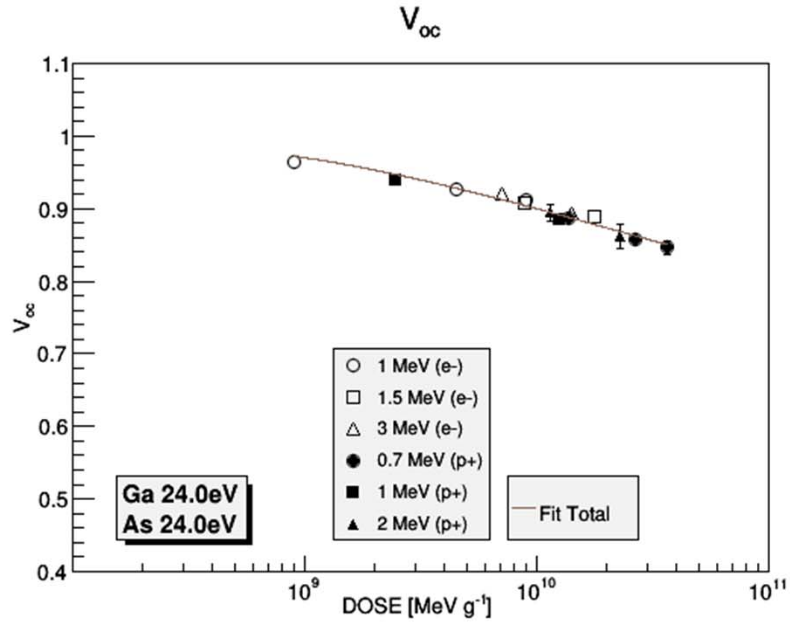
That reduce to the usual one if A=0 (as found for for 3J, 1J Top, 1J Mid):

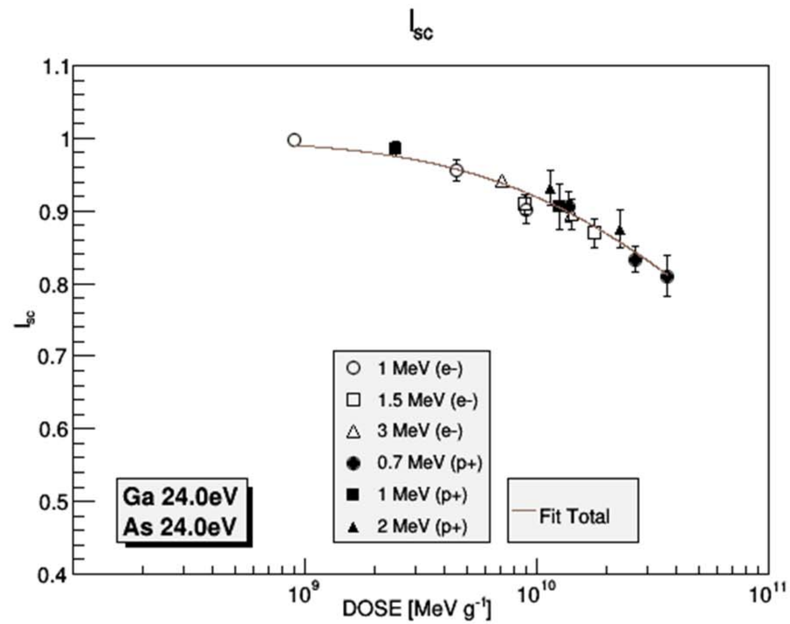
$$1-\mathrm{B}\cdot\log_{10}\left[1+\mathrm{C}\cdot NIEL\mathrm{Dose}(Ed)\right]$$

3J cells:
Search for best Ed value
for 10 < Ed < 50 eV

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

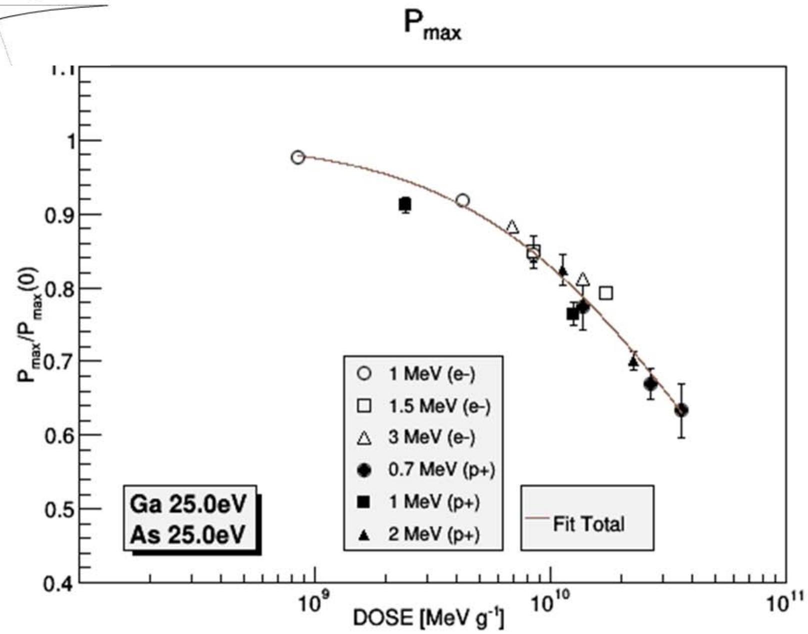


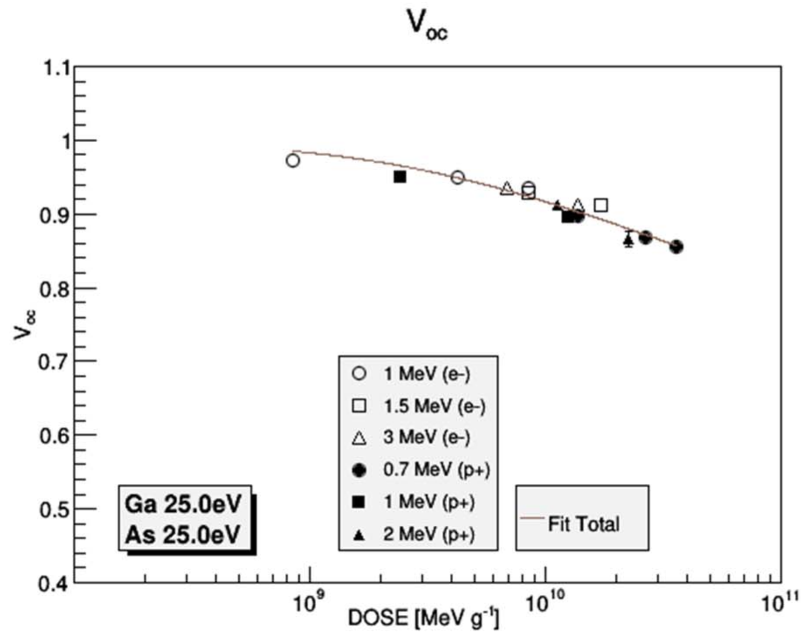


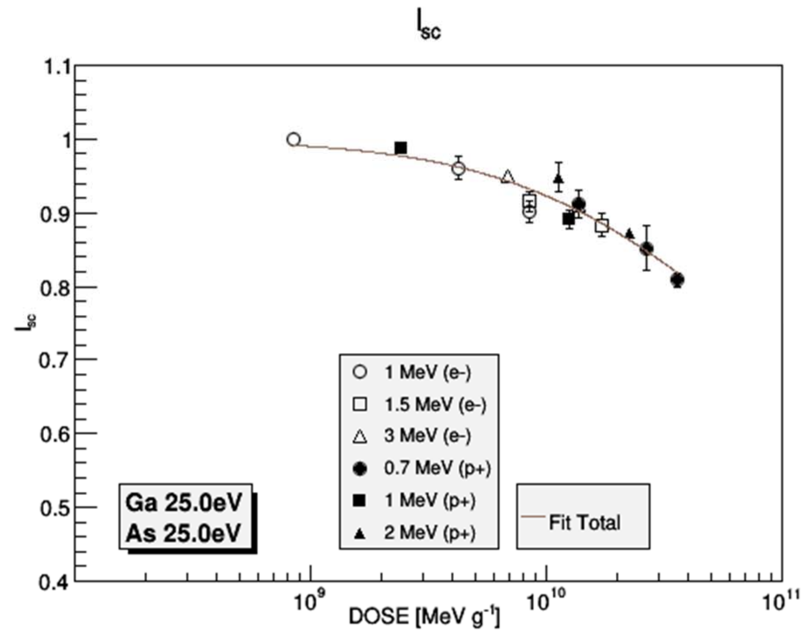


3J Solar Cell

Self-Annealed

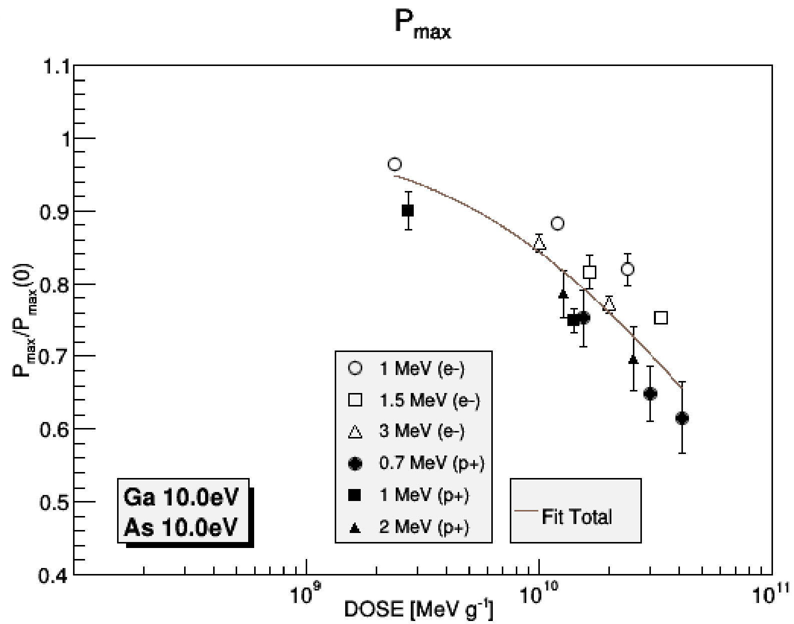


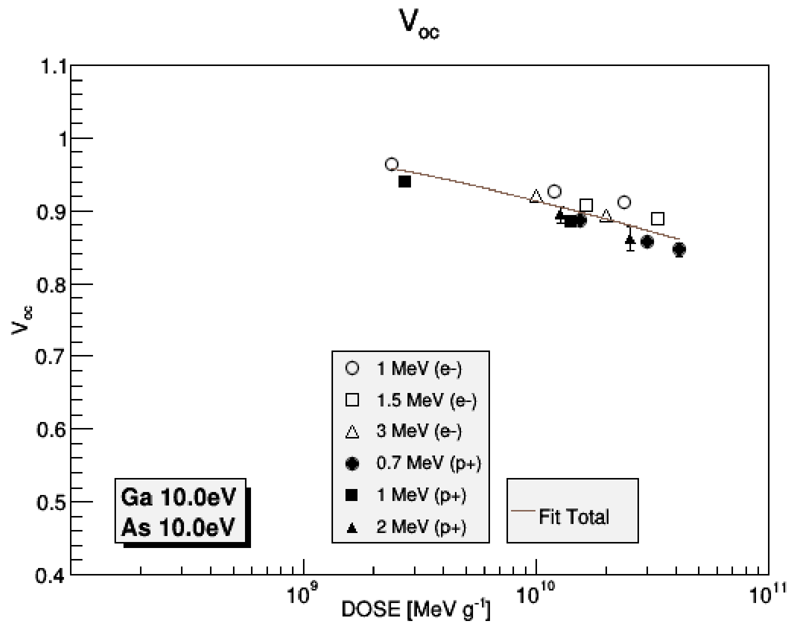


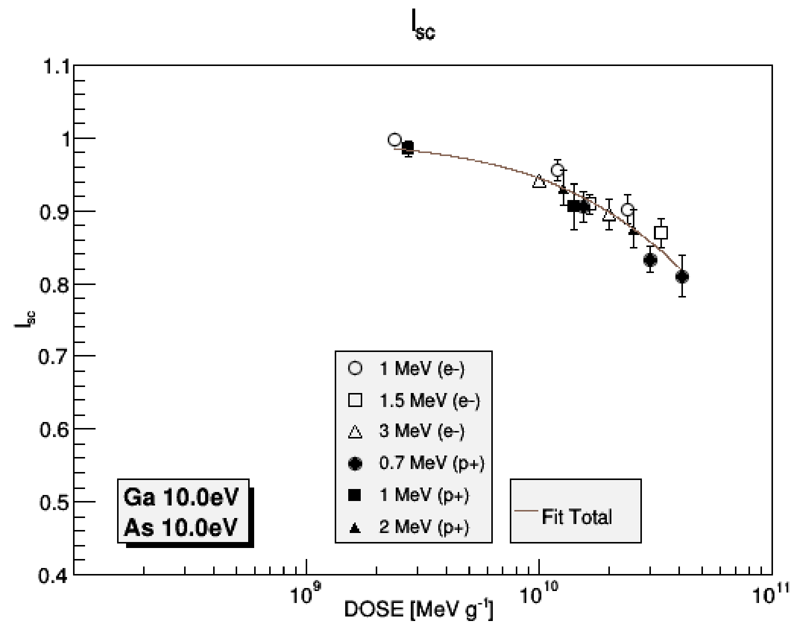


3J Solar Cell

After Annealing





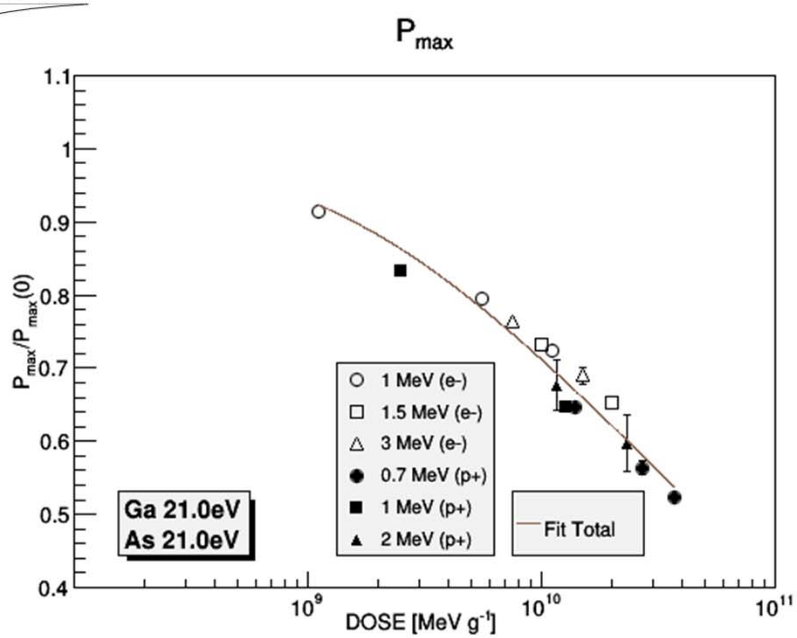


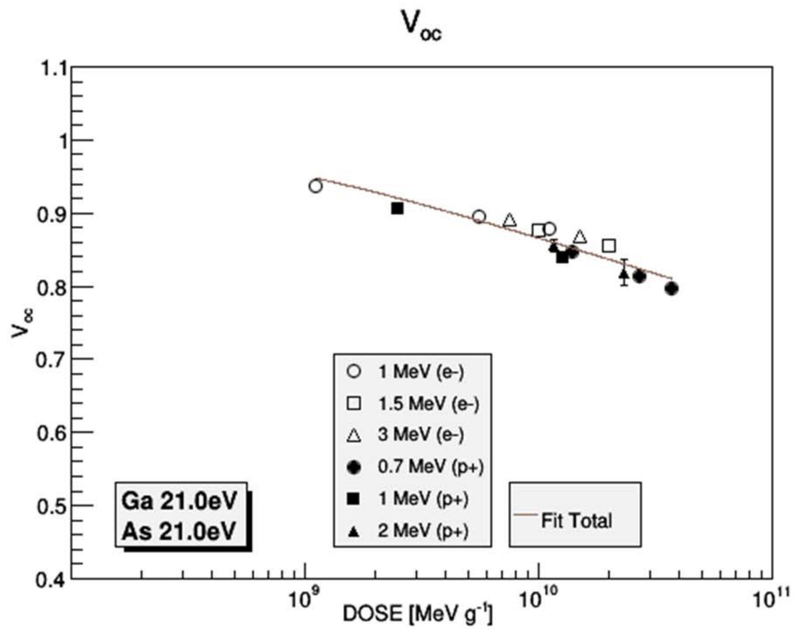
3J solar cell
Self-Annealed

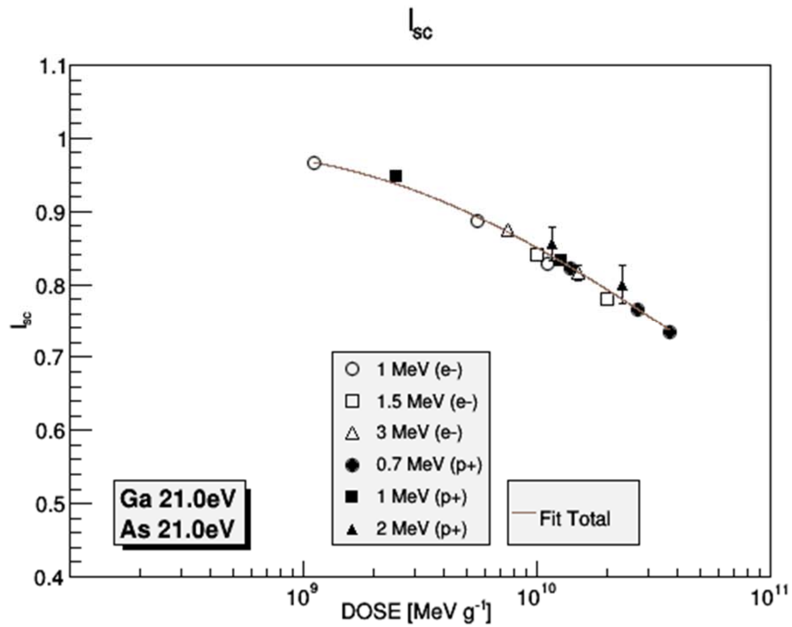
Using 10 eV for Ed as suggested by NASA Handbook

1J mid cells:
Search for best Ed value for Ga and As
for 10 < Ed < 50 eV

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

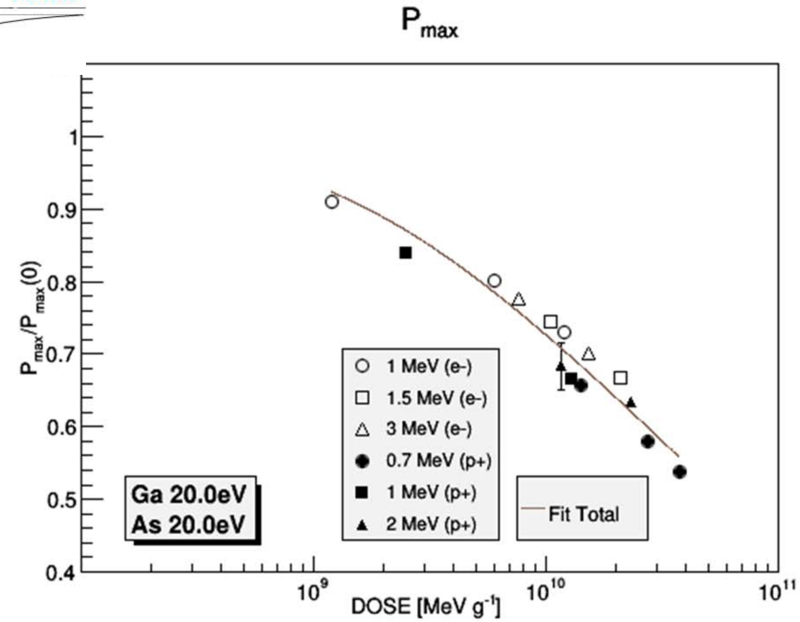


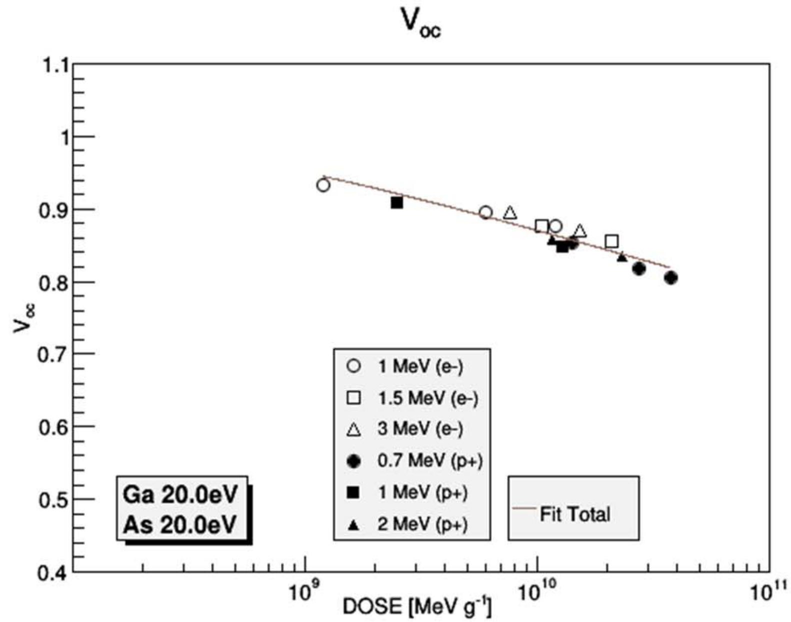


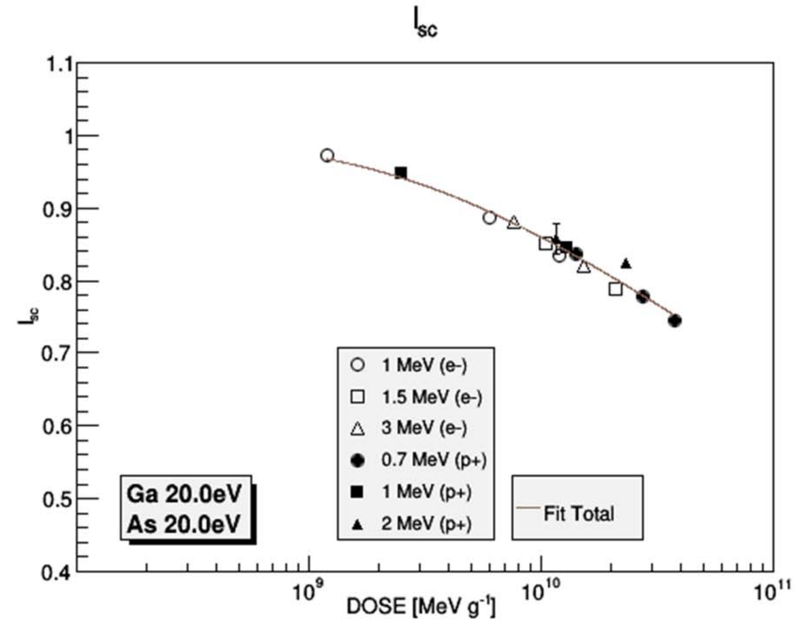


Mid Cell

Self-Annealed





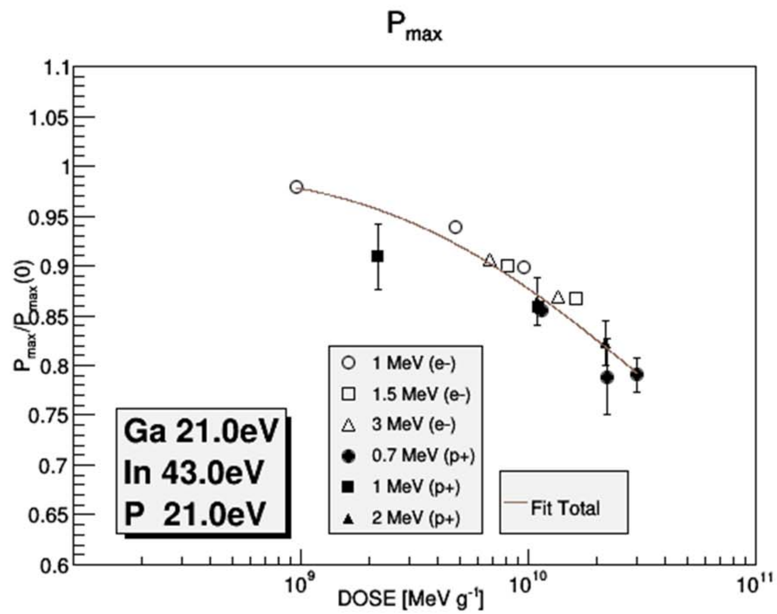


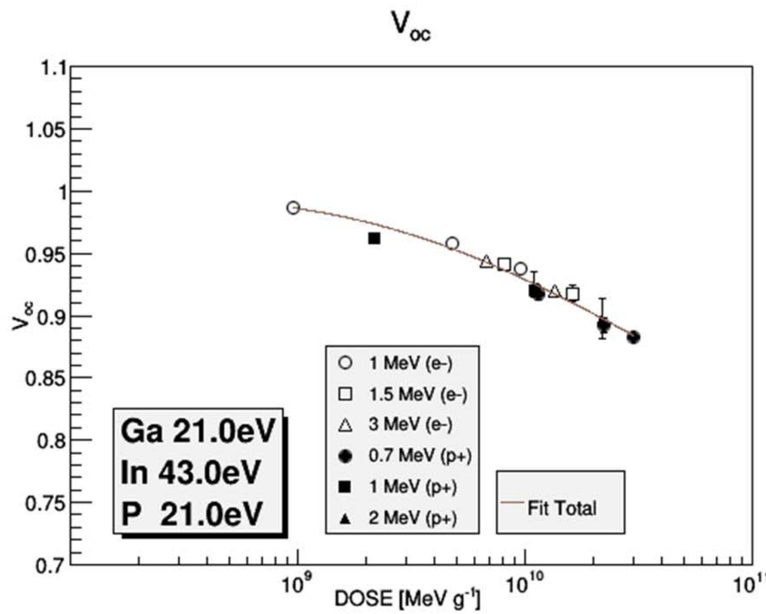
Mid Cell

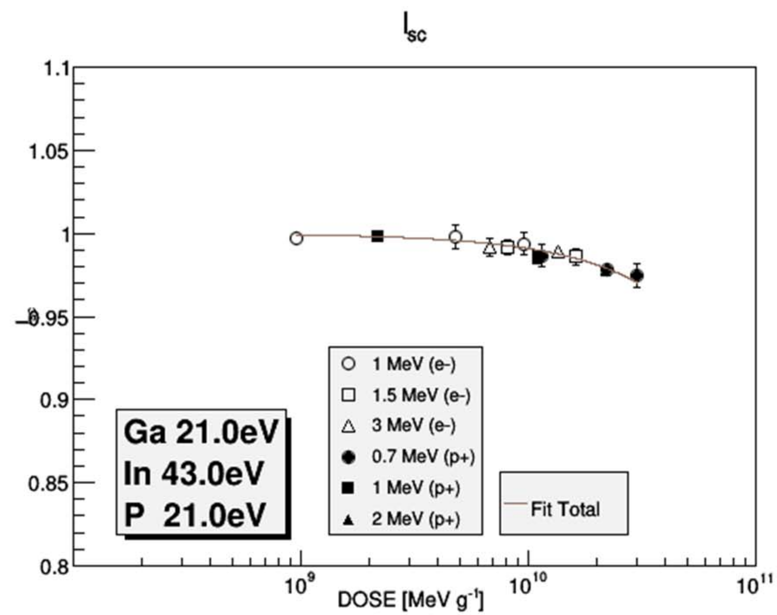
After Annealing

1J top cells:
Fixed Ed = 21 for Ga and P
Search for best Indium Ed value
for 10 < Ed < 70 eV

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

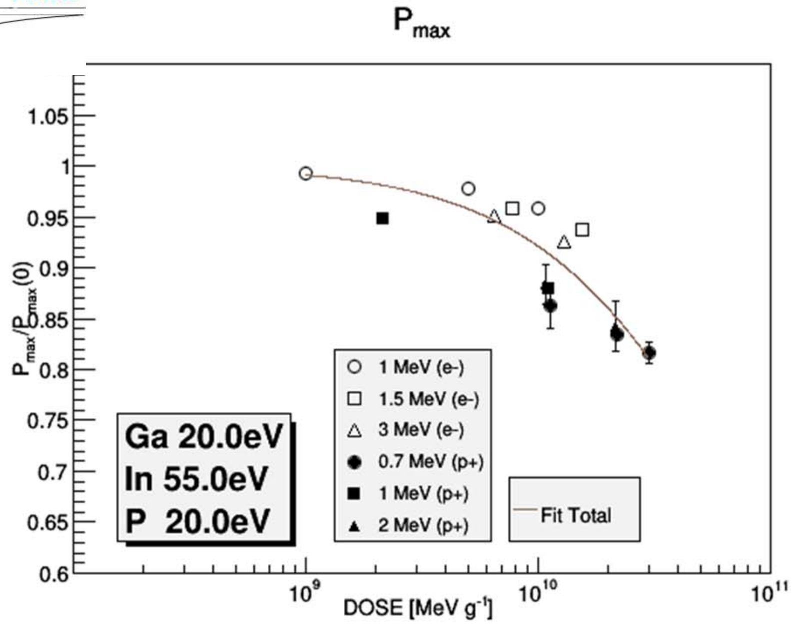


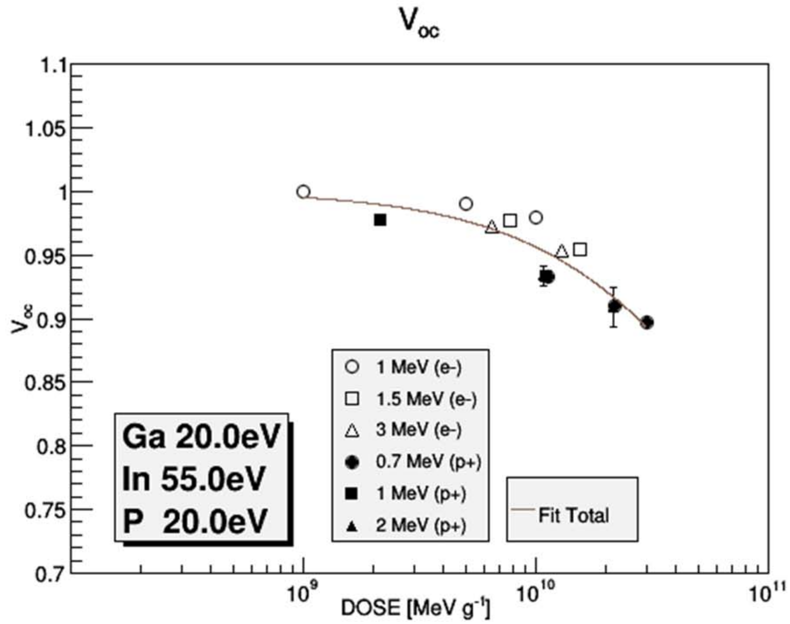


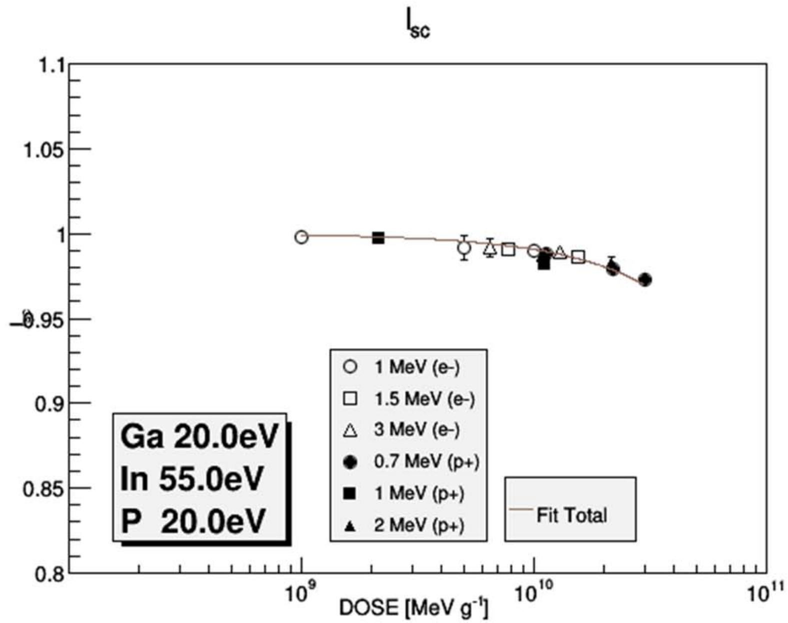


Top Cell

Self-Annealed





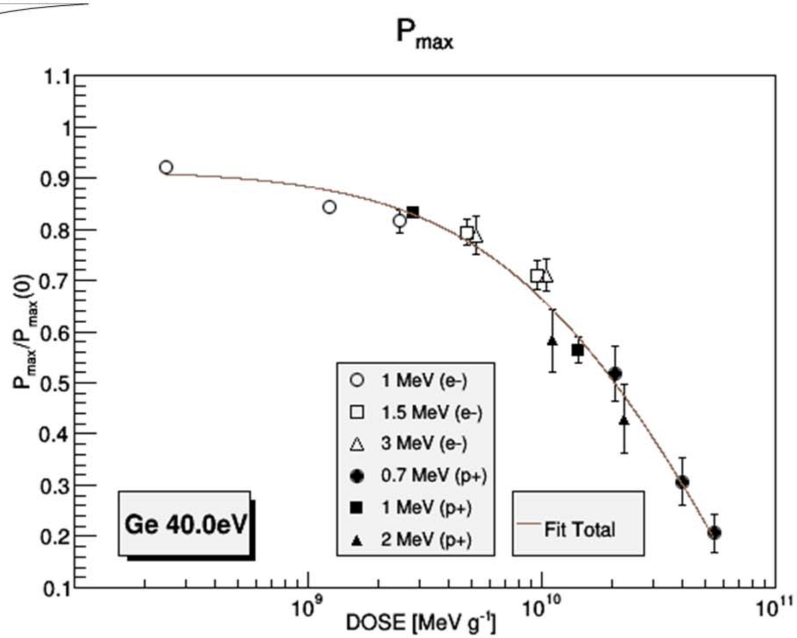


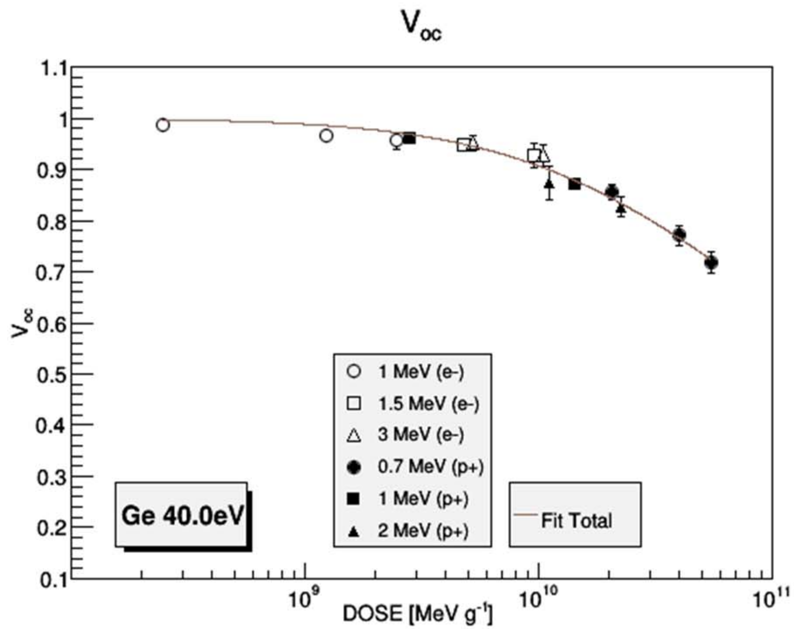
Top Cell

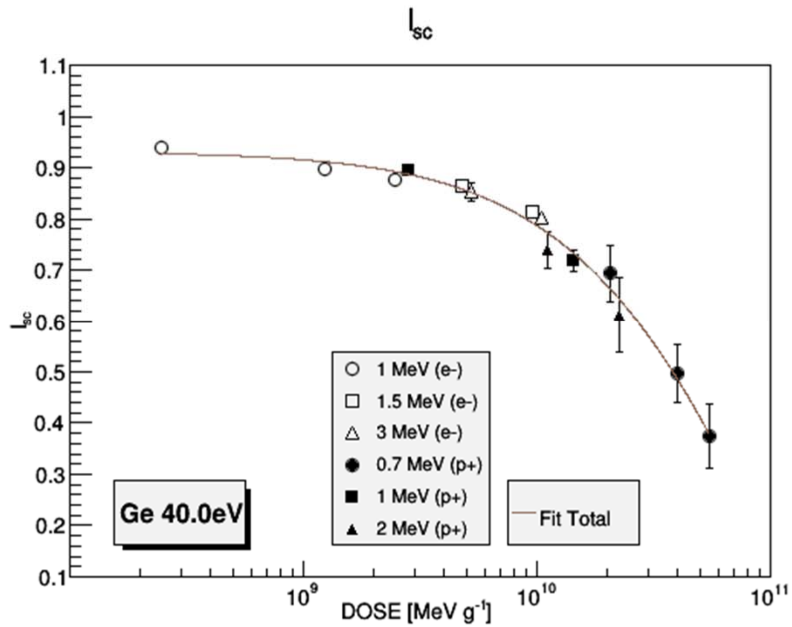
After Annealing

1J bottom cells:
Search for best Ed value
for $10 < Ed < 50$ eV

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

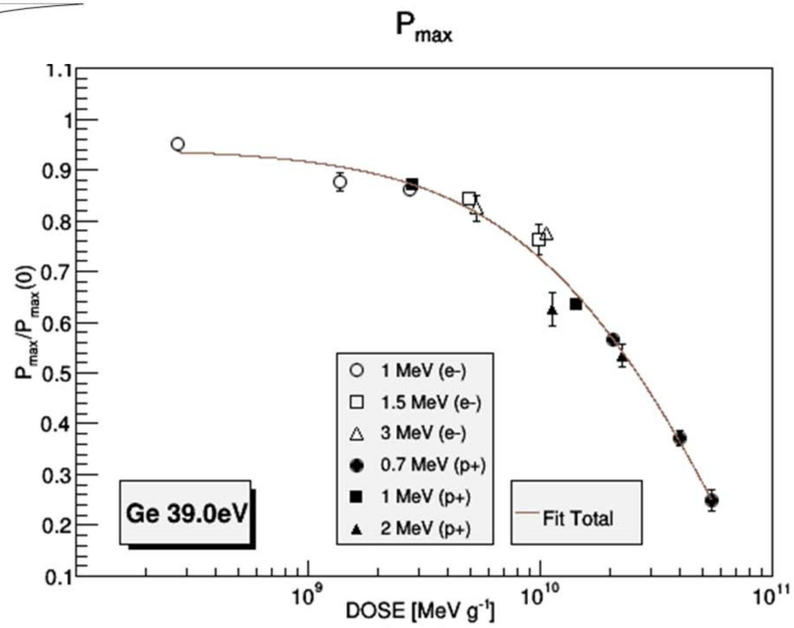


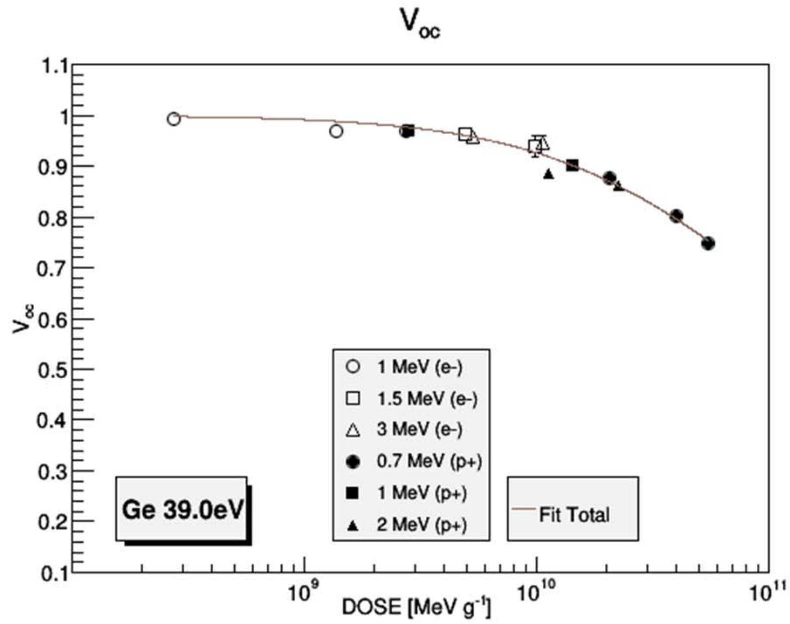


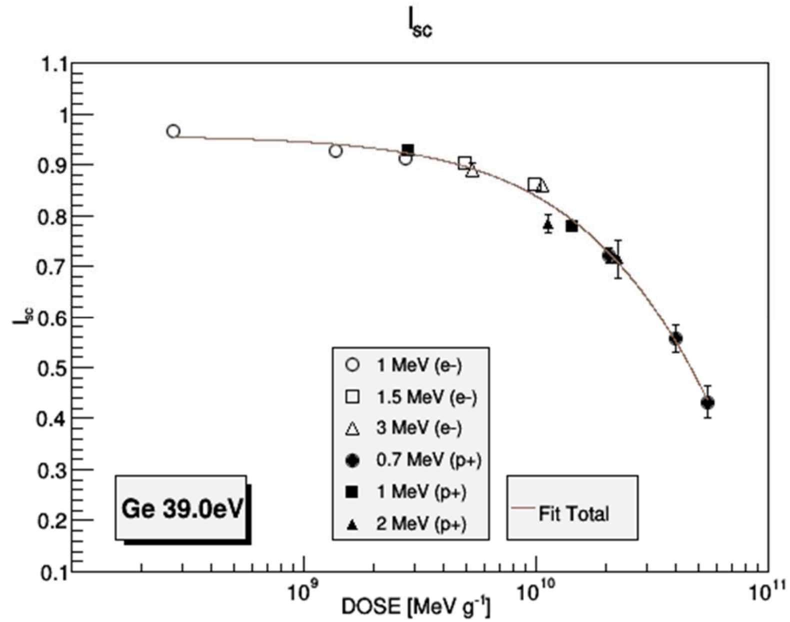


Bottom Cell

Self-Annealed







Bottom Cell

After Annealing

DLTS Results

CNR DLTS measurements on MESA diode from CESI solar cell technology

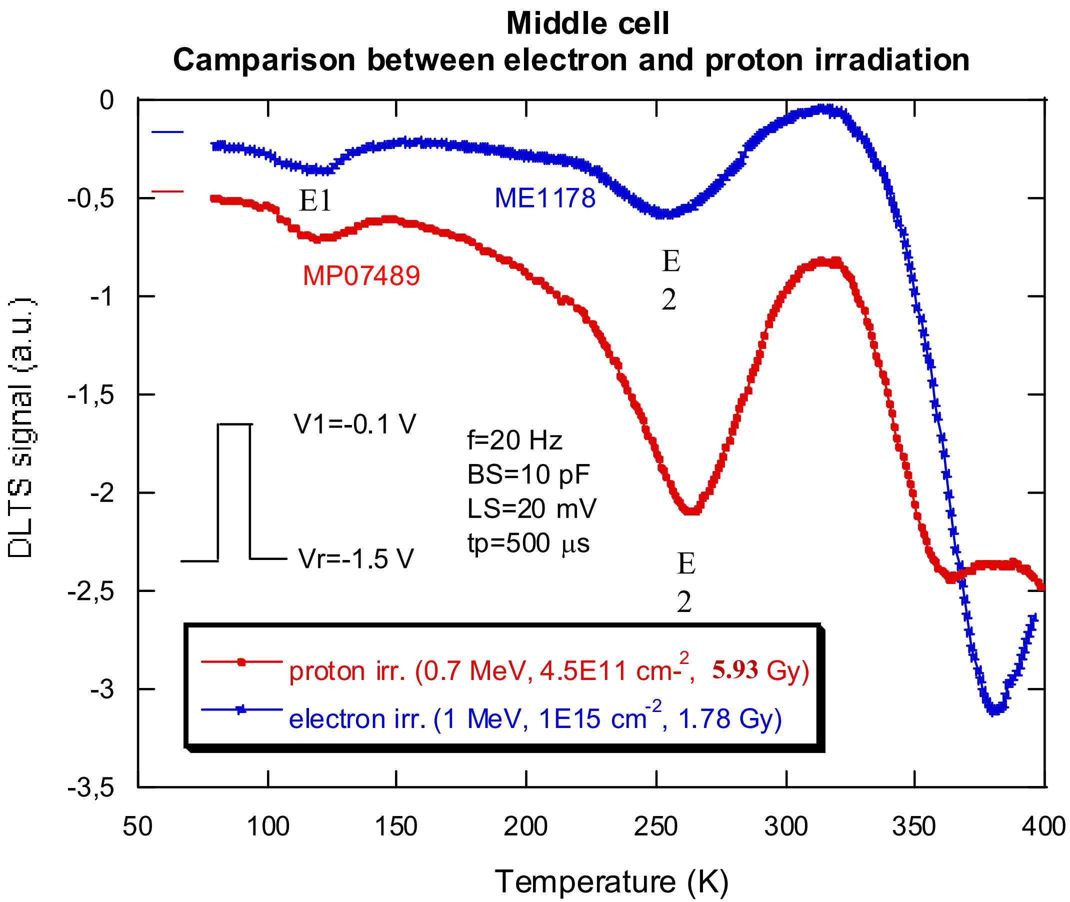
a) Top and Middle cells (0.5 mm in diam) by photolithographic techniques and metal evaporation. More than 100 DLTS measurements have been carried out on irradiated and non-irradiated diodes in the 77-400 K temperature range (time requested by a single DLTS measurement and sample preparation about 2 h): *further measurements are likely to be done in the future*.

a) Top Cell (InGaP): due to the relatively high free carrier concentration of the top cell and the low reverse bias that can be applied to it (about 1 V) it was only possible to investigate regions near the junction interface dominated by high densities of interface states. These restrictions prevented a detailed study of bulk deep levels on both irradiated and non-irradiated samples.

b) Middle cell (GaAs) irradiated with electrons: three deep levels, labelled as E1 (0.21 eV), E2 (0.45 eV) and E3 (0.71 eV more a band peak of interface states than a level), have been identified on the mid cell. These levels have been identified as majority carrier traps in the p-type bulk base since majority carrier pulses have been used in the DLTS measurements. As a consequence their energy must be referred to the top of the valence band.

c) Middle cell irradiated with protons showed the same E1 and E2 levels. However, E2 level exhibits a trap concentration only slightly smaller (or similar) for protons at the same NIEL dose; while E1 is substantially smaller. Moreover (with protons), the high temperature peak exhibits a more complex distribution of levels with respect to the peak E3 observed in the cells irradiated with electrons.

DLTS spectrum (Vr= -1.5 V) of a middle cell diode irradiated with protons (energy 0.7 MeV and fluence $4.5x10^{11}$ cm^{-2}) is compared to that of a middle cell diode irradiated with electrons (energy 1 MeV and fluence $1x10^{15}$ cm^{-2}).



Niel doses in GaAs are from sr-niel with Ed = 21 eV

NIEL dose ratio (proton/electron) = 3.3

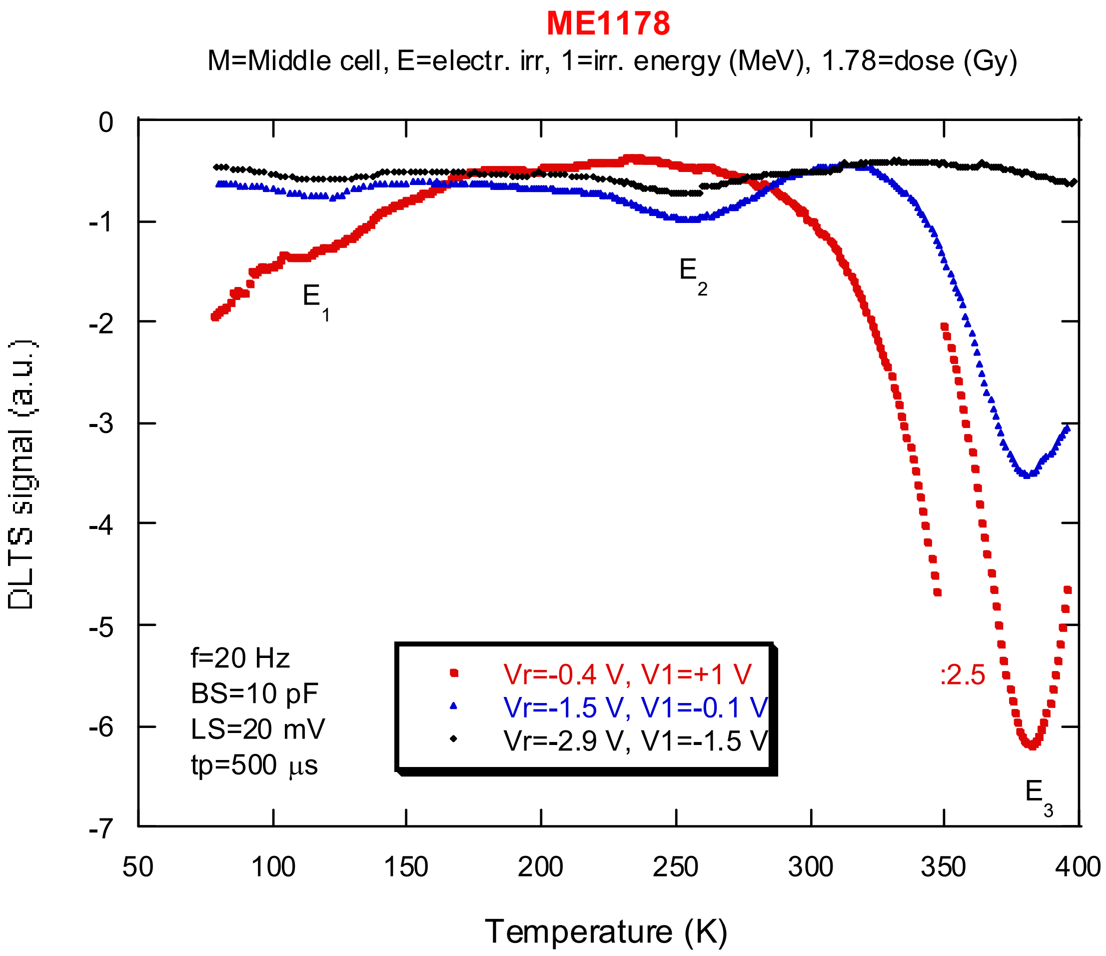
Further remarks

a) It has been observed that the amplitude of E3 peak drastically reduces with the distance from the interface (i.e. it is a property expected for interface states). Since this peak is also present in non-irradiated samples, it has been attributed to interface states.

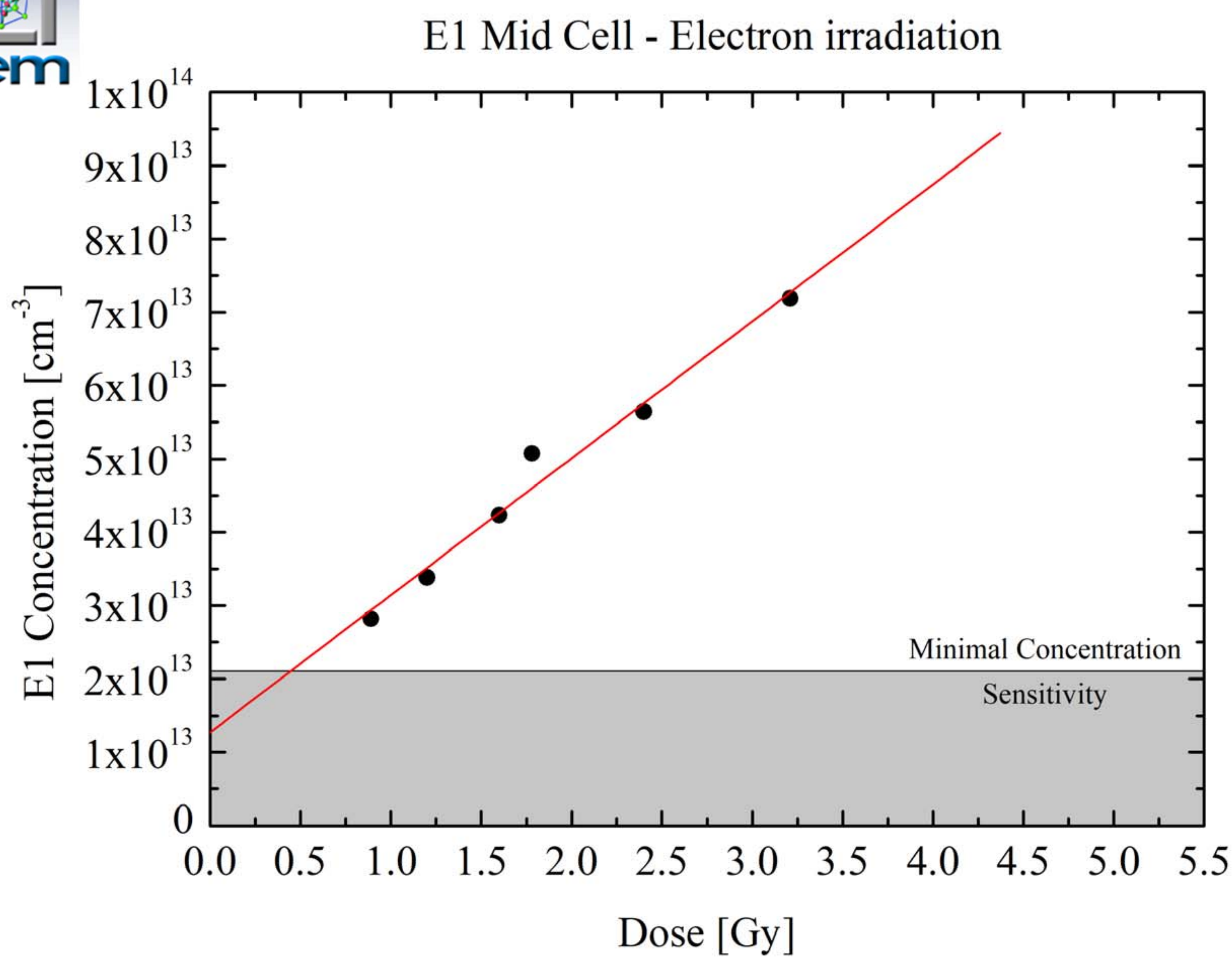
b) The DLTS spectra obtained by application of forward bias pulses do not exhibit positive DLTS peaks, corresponding to minority carrier traps. This could be probably caused by the relatively high doping level in the the GaAs.

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 **E1** peak


E1 Mid Cell - Electron irradiation
E1 Concentration [cm^-3]
Dose [Gy]
Minimal Concentration
Sensitivity
1x10^14
9x10^13
8x10^13
7x10^13
6x10^13
5x10^13
4x10^13
3x10^13
2x10^13
1x10^13
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5

- The additional concentration of E_1 traps is well consistent with a linear dependence on the NIEL Dose due to electron irradiation, i.e., with

NIEL (in units of MeV cm^2 / g) x Particle fluence (in part/cm^2) = NIEL dose

→ thus,

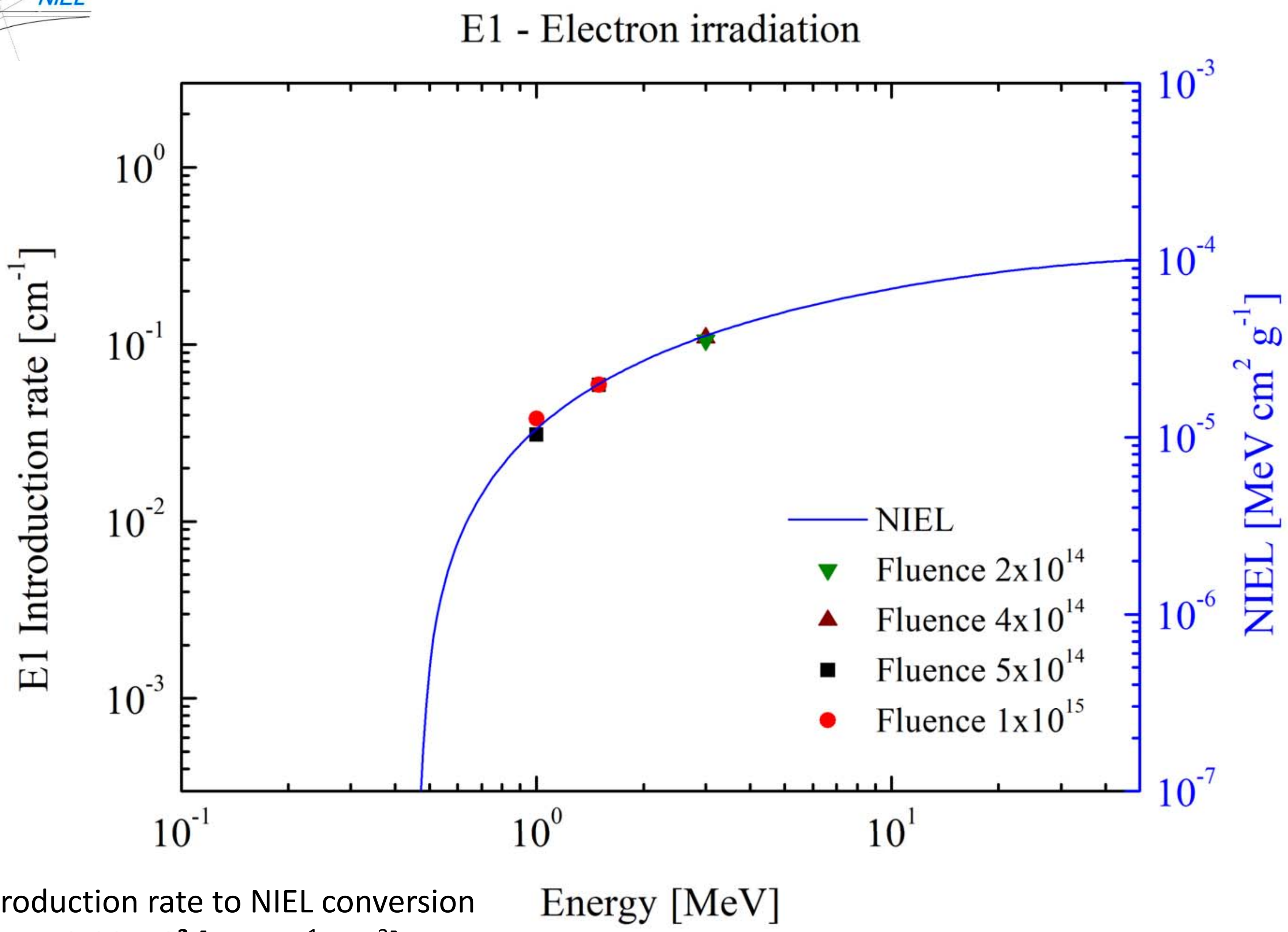
the introduction rate E_1 traps (in units cm^{-1}) at energy *E*

= E_1 trap concentration / particle fluence

is proportional to NIEL (in units of MeV cm^2 / g) at energy *E*

with a proportionality constant given by

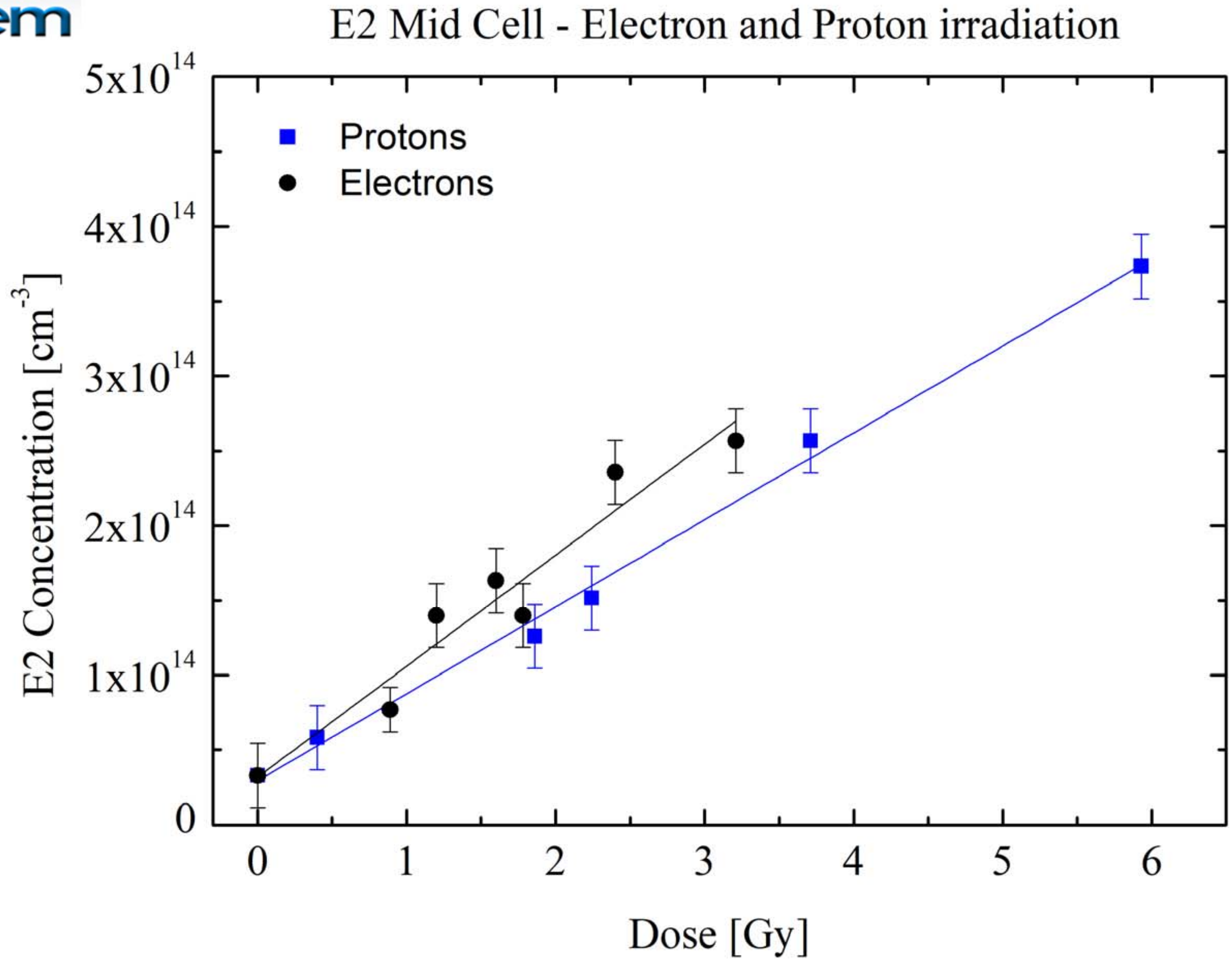
the slope of the E_1 traps vs NIEL Dose

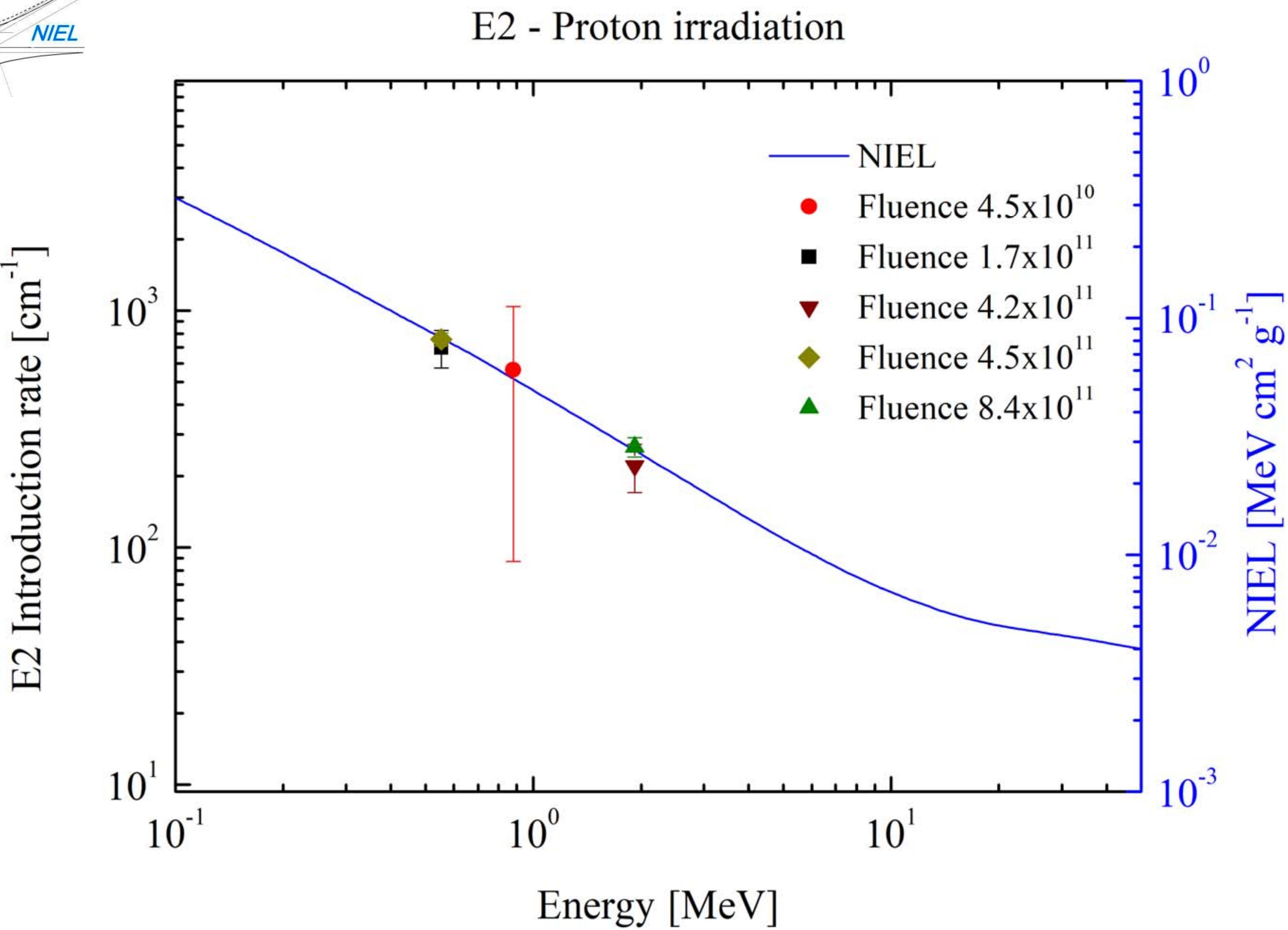


Introduction rate to NIEL conversion factor: **2.99x10^{3}** [g MeV^{-1} cm^{-3}]

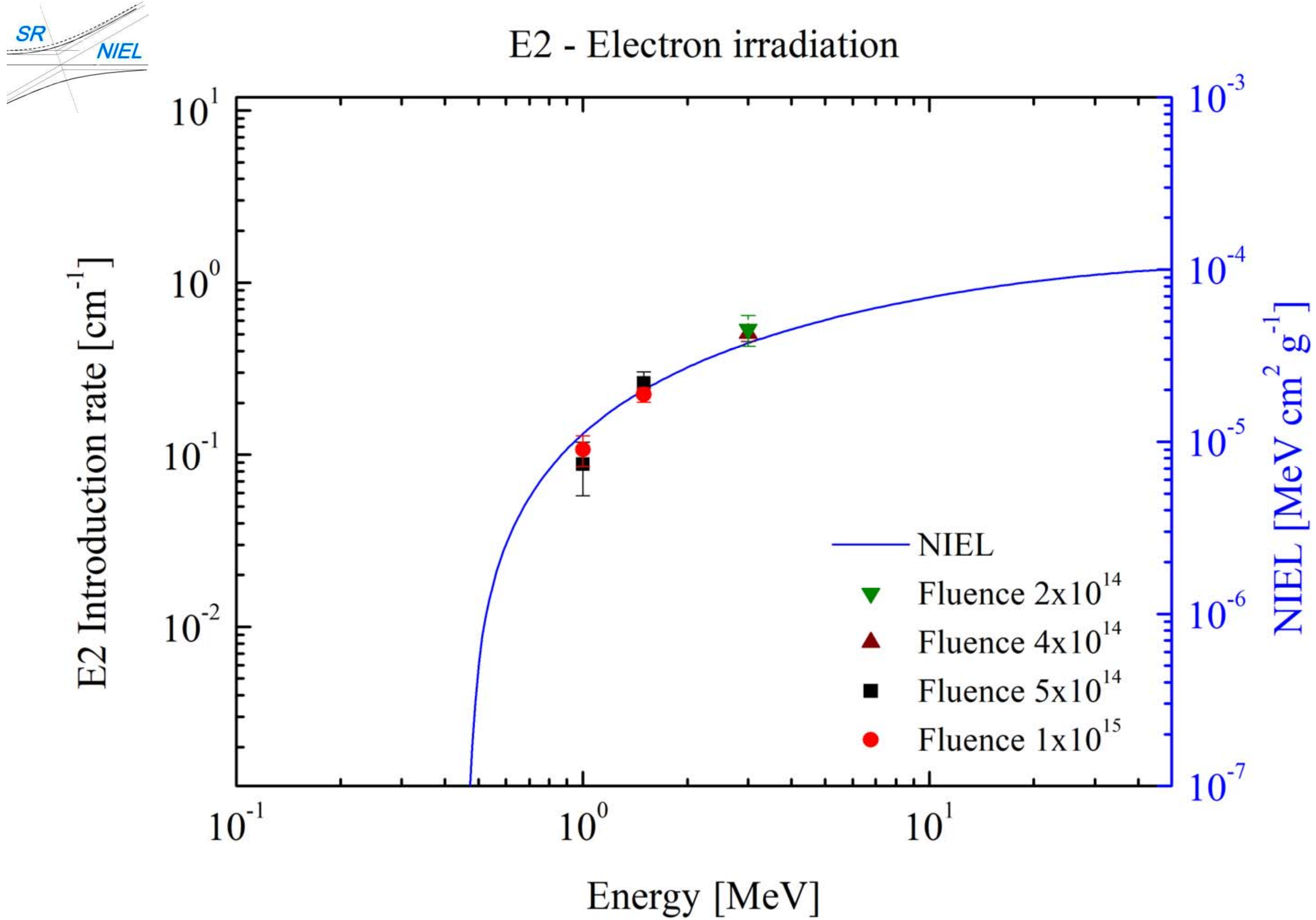
DLTS **E2** peak

Indipendent fit for electrons and protons

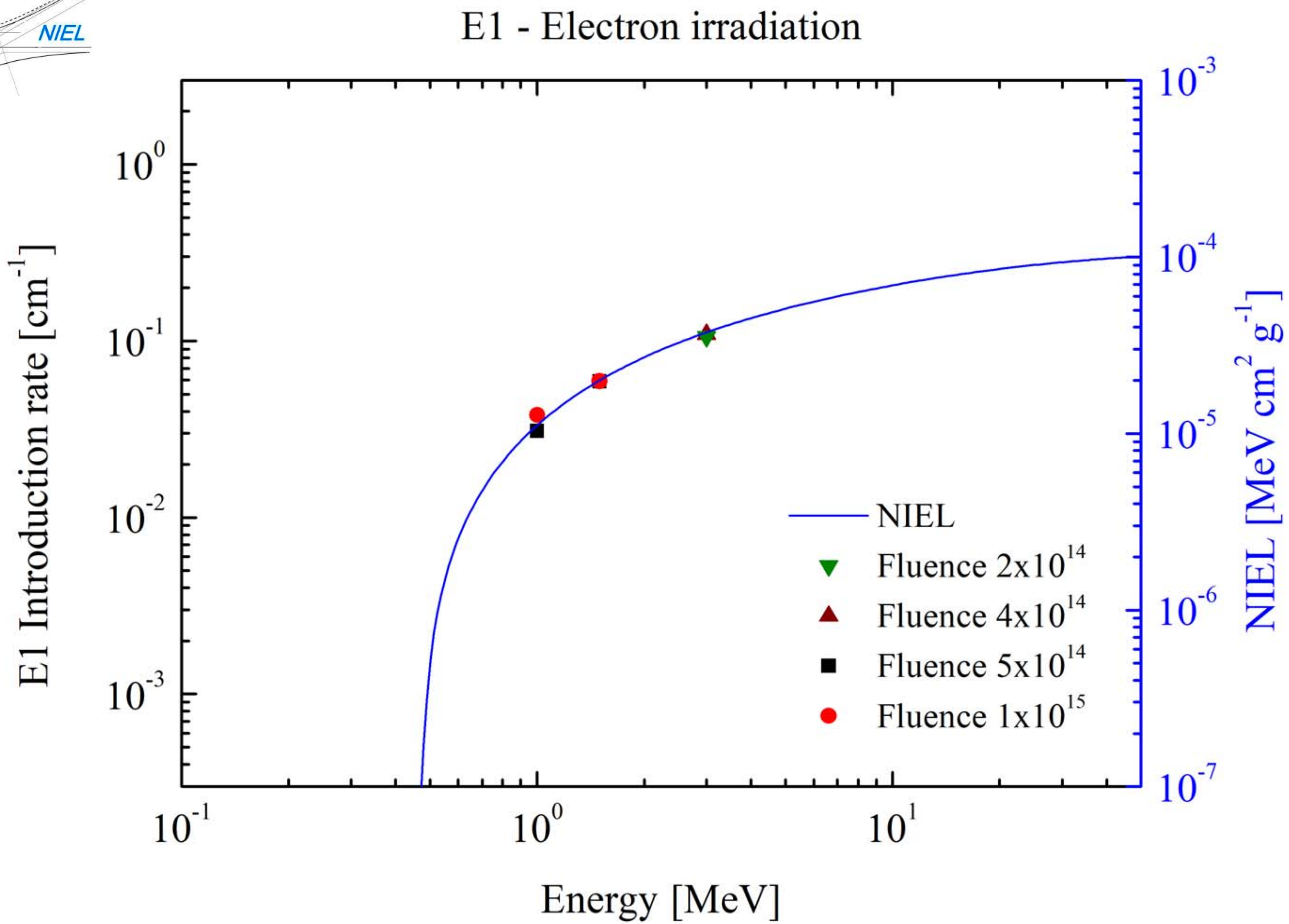

E2 Mid Cell - Electron and Proton irradiation
Protons
Electrons
E2 Concentration [cm-3]
Dose [Gy]
0
1x10^14
2x10^14
3x10^14
4x10^14
5x10^14
0
1
2
3
4
5
6



Introduction rate to NIEL conversion factor: **$9.32x10^3$** [g MeV^{-1} cm^{-3}]

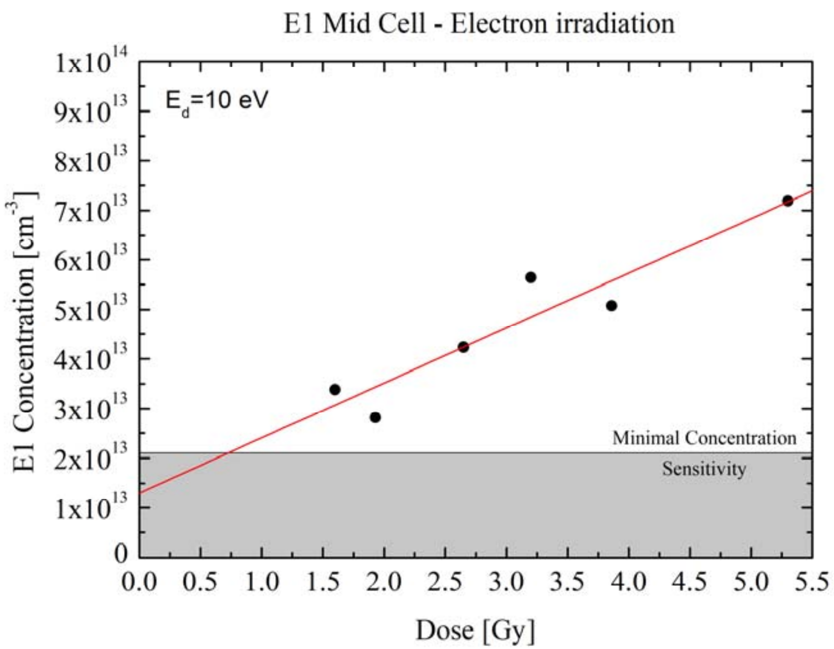


Introduction rate to NIEL conversion factor: **1.19x10^{4}** [g MeV^{-1} cm^{-3}]

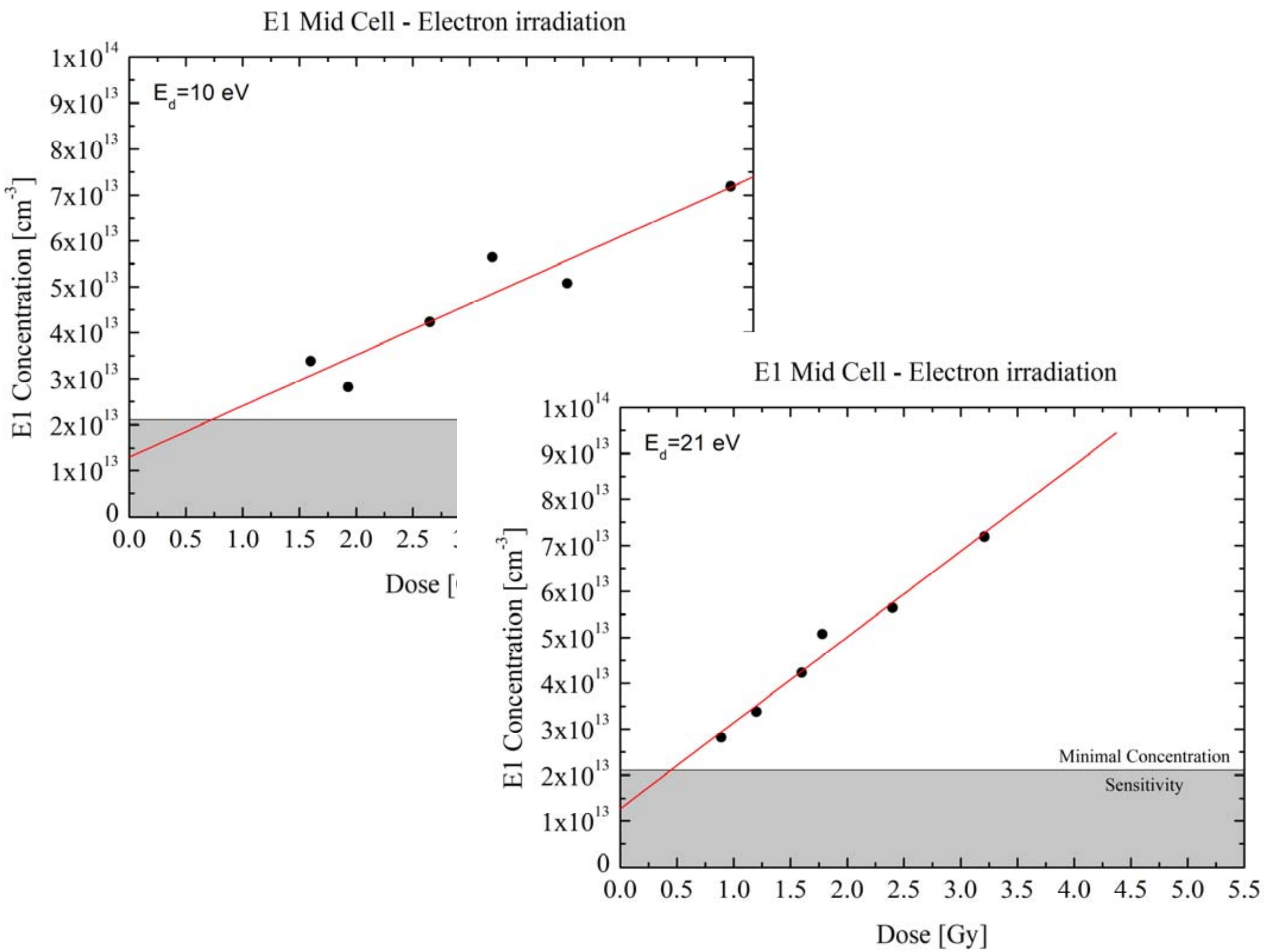


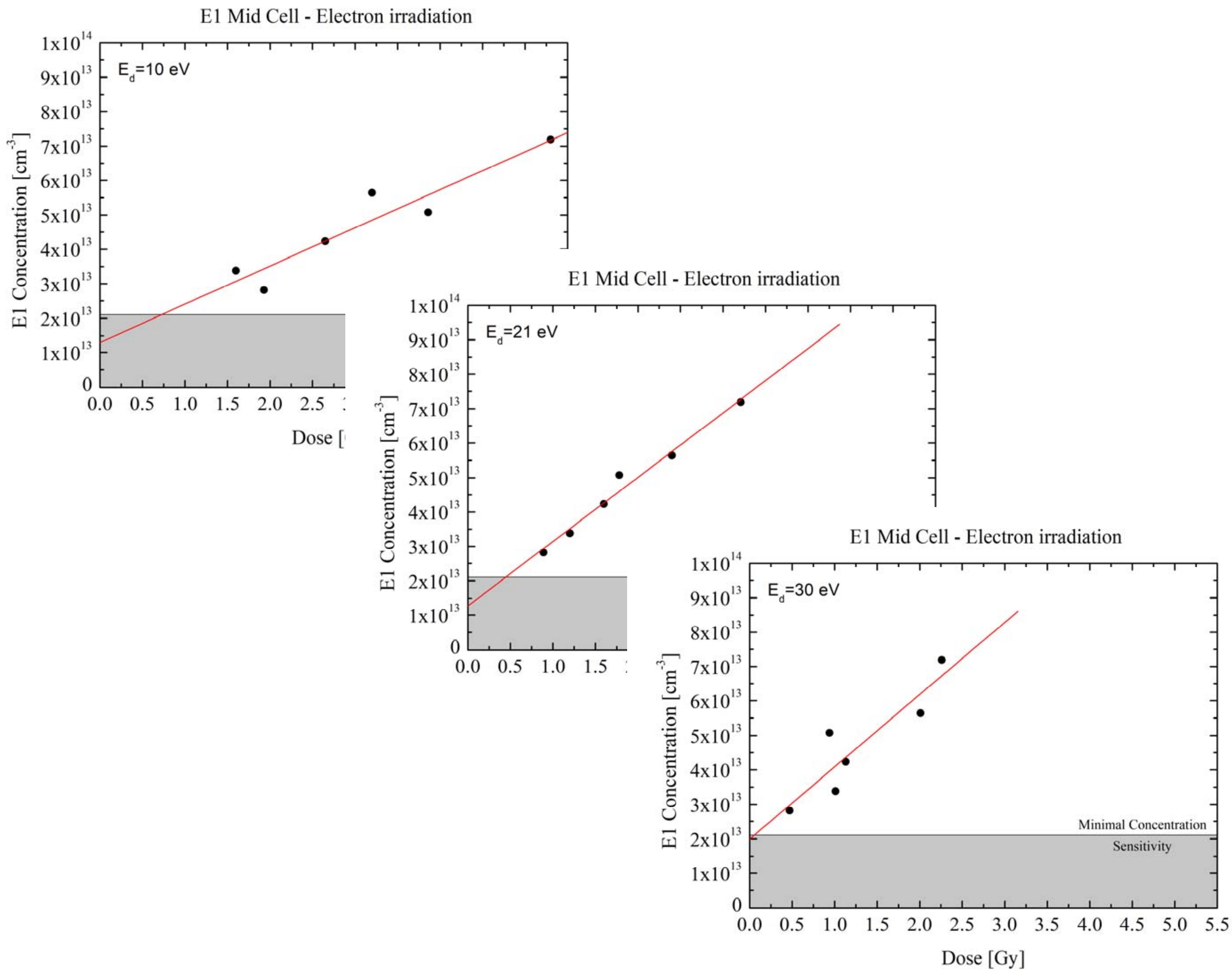
Introduction rate to NIEL conversion factor: **2.99x10^3** [g MeV^{-1} cm^{-3}]

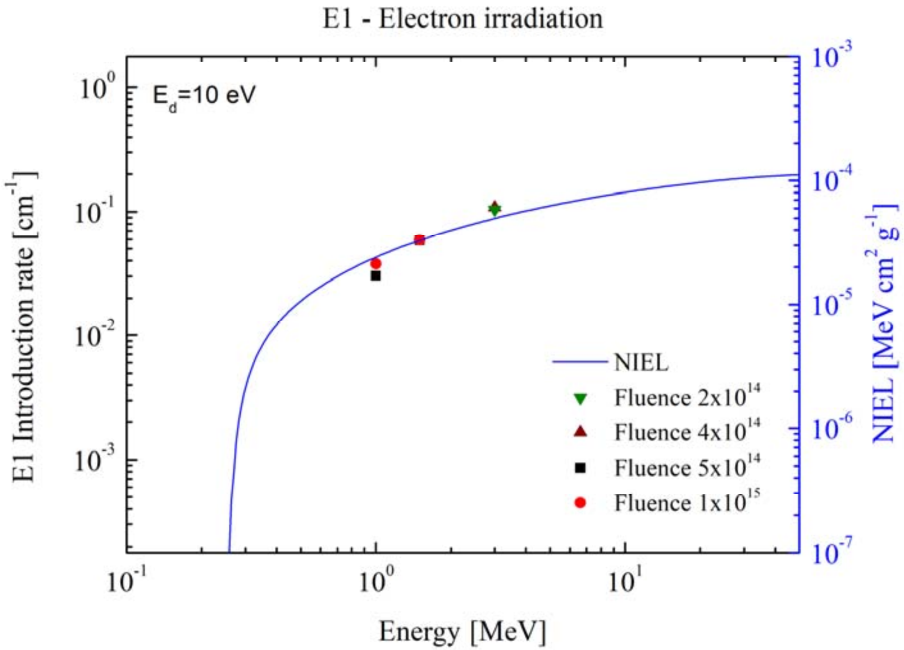
Using E_1 trap concentrations from electron irrradiations for confirming Ed

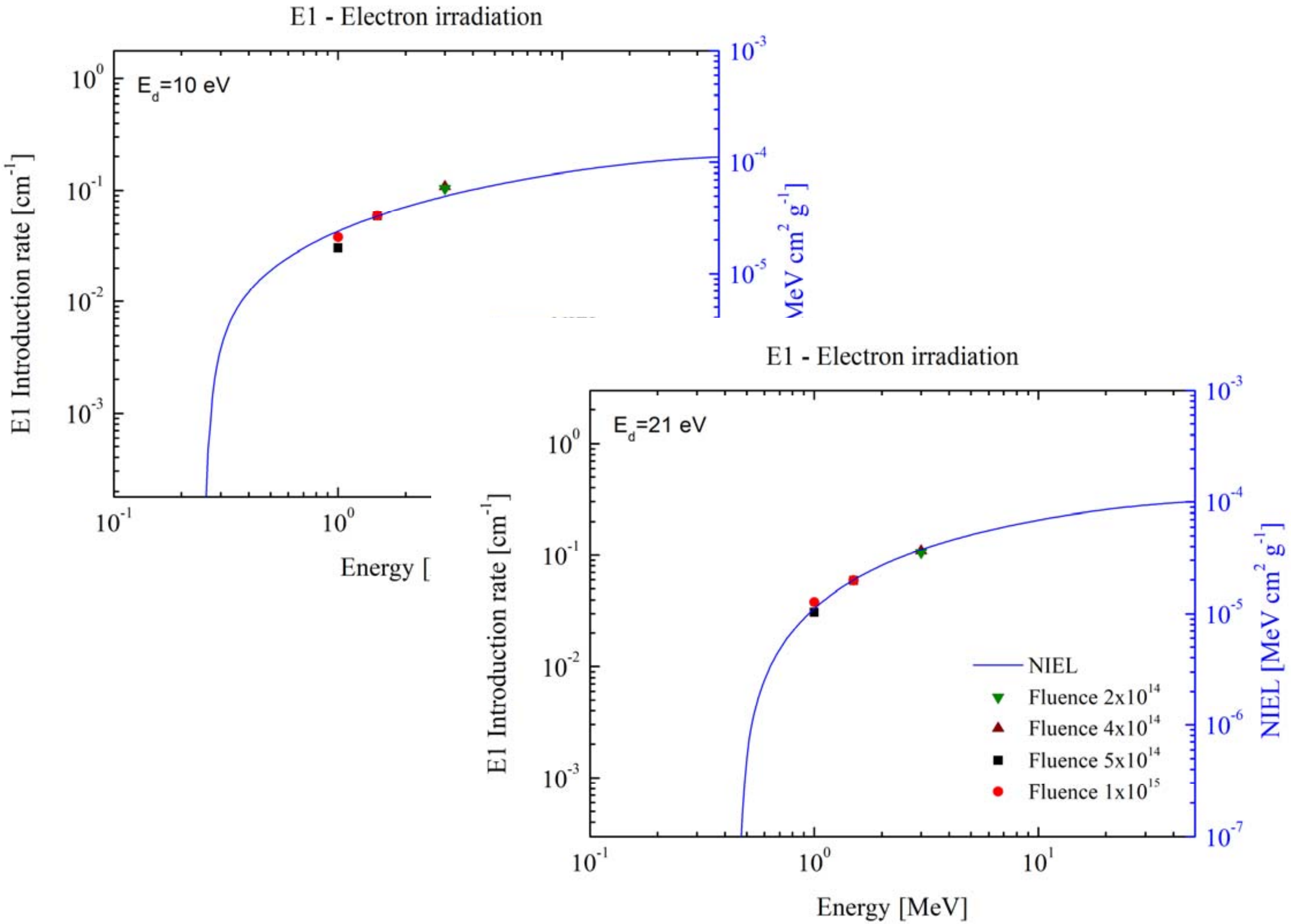


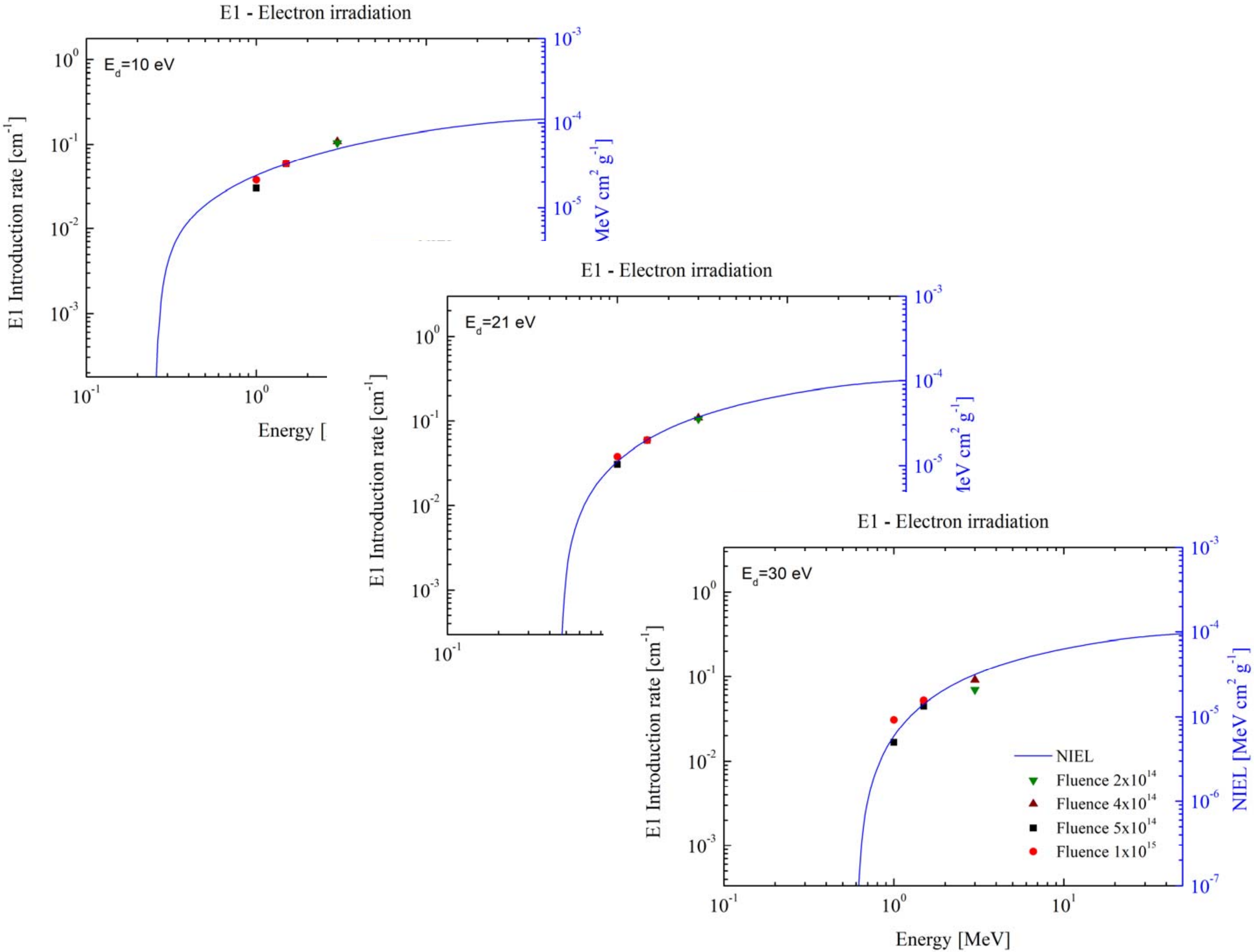
E1 Mid Cell - Electron irradiation
E1 Concentration [cm-3]
Dose [Gy]
Ed=10 eV
Minimal Concentration
Sensitivity
1x10^14
9x10^13
8x10^13
7x10^13
6x10^13
5x10^13
4x10^13
3x10^13
2x10^13
1x10^13
0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5


E1 Mid Cell - Electron irradiation
E$_d$=10 eV
E1 Concentration [cm^{-3}]
Dose [
E1 Mid Cell - Electron irradiation
E$_d$=21 eV
Minimal Concentration
Sensitivity
E1 Concentration [cm^{-3}]
Dose [Gy]


E1 Mid Cell - Electron irradiation
E$_d$=10 eV
E1 Concentration [cm^{-3}]
E1 Mid Cell - Electron irradiation
E$_d$=21 eV
E1 Concentration [cm^{-3}]
E1 Mid Cell - Electron irradiation
E$_d$=30 eV
E1 Concentration [cm^{-3}]
Minimal Concentration
Sensitivity
Dose [Gy]


E1 - Electron irradiation
E_d=10 eV
E1 Introduction rate [cm^{-1}]
NIEL [MeV cm^2 g^{-1}]
Energy [MeV]
NIEL
Fluence 2x10^{14}
Fluence 4x10^{14}
Fluence 5x10^{14}
Fluence 1x10^{15}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{1}


E1 - Electron irradiation
E_d=10 eV
E1 Introduction rate [cm^-1]
Energy [
E1 - Electron irradiation
E_d=21 eV
E1 Introduction rate [cm^-1]
NIEL [MeV cm^2 g^-1]
Energy [MeV]
NIEL
Fluence 2x10^14
Fluence 4x10^14
Fluence 5x10^14
Fluence 1x10^15



E1 - Electron irradiation
E_d=10 eV
E1 Introduction rate [cm^-1]
Energy [
E1 - Electron irradiation
E_d=21 eV
E1 Introduction rate [cm^-1]
E1 - Electron irradiation
E_d=30 eV
E1 Introduction rate [cm^-1]
NIEL [MeV cm^2 g^-1]
Energy [MeV]
NIEL
Fluence 2x10^14
Fluence 4x10^14
Fluence 5x10^14
Fluence 1x10^15

Three accepted posters at :

1) IEEE NSREC (2017)
Displacement Damage dose and DLTS Analyses on Triple and Single Junction solar cells irradiated with electrons and protons, Carsten Baur, Roberta Campesato, Mariacristina Casale, Massimo Gervasi, Enos Gombia, Erminio Greco, Aldo Kingma, P.G. Rancoita, Davide Rozza, Mauro Tacconi.
2) IEEE PVSEC (2017)
NIEL DOSE Analysis on Triple Junction cells 30% efficient and related single junctions, Roberta Campesato, Erminio Greco, Mariacristina Casale, Massimo Gervasi, P.G. Rancoita, Davide Rozza, Mauro Tacconi, Enos Gombia, Aldo Kingma, Carsten Baur.
3) IEEE PVSEC (2018)
Radiation Resistance of Low Cost High Efficiency Triple Junction solar cells, Roberta Campesato, Erminio Greco, Mariacristina Casale, Massimo Gervasi, P.G. Rancoita, Davide Rozza, Mauro Tacconi, Enos Gombia, Aldo Kingma, Carsten Baur.

One oral presentation at:

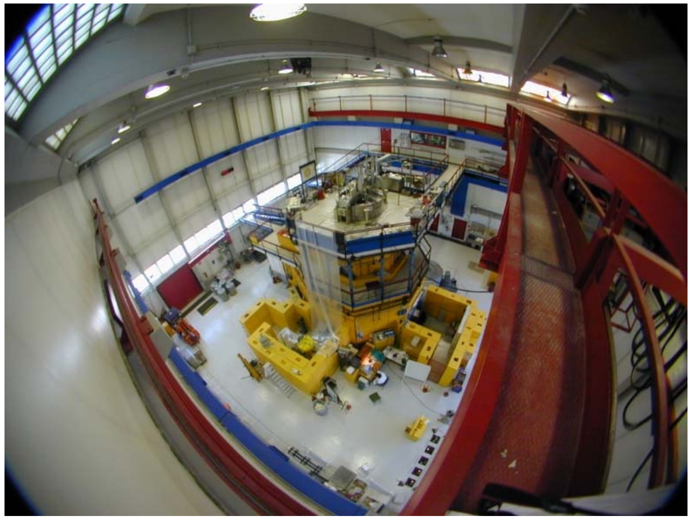
4) 35th EUPVSEC (2018)
Effects of Irradiation on Triple and Single Junction InGaP/GaAs/Ge Solar Cells, Roberta Campesato, Erminio Greco, Mariacristina Casale, Massimo Gervasi, P.G. Rancoita, Davide Rozza, Mauro Tacconi, Enos Gombia, Aldo Kingma, Carsten Baur.

Neutron irradiations

An additional experimental activity was undertaken (within ASIF framework) from beginning 2018 dedicated to neutron irradiation using TRIGA reactor at ENEA-Casaccia.

The irradiation required one week (starting on April 19) at the TRIGA reactor and was aimed at:

1) Determination of the neutron spectral fluence
2) Irradiation of CESI solar cells and diodes (the same used for electrons and protons)
3) Only very preliminary results are available since a few days



Measurement of neutron flux spectrum

Istituto Nazionale di Fisica Nucleare
sez. di Milano Bicocca

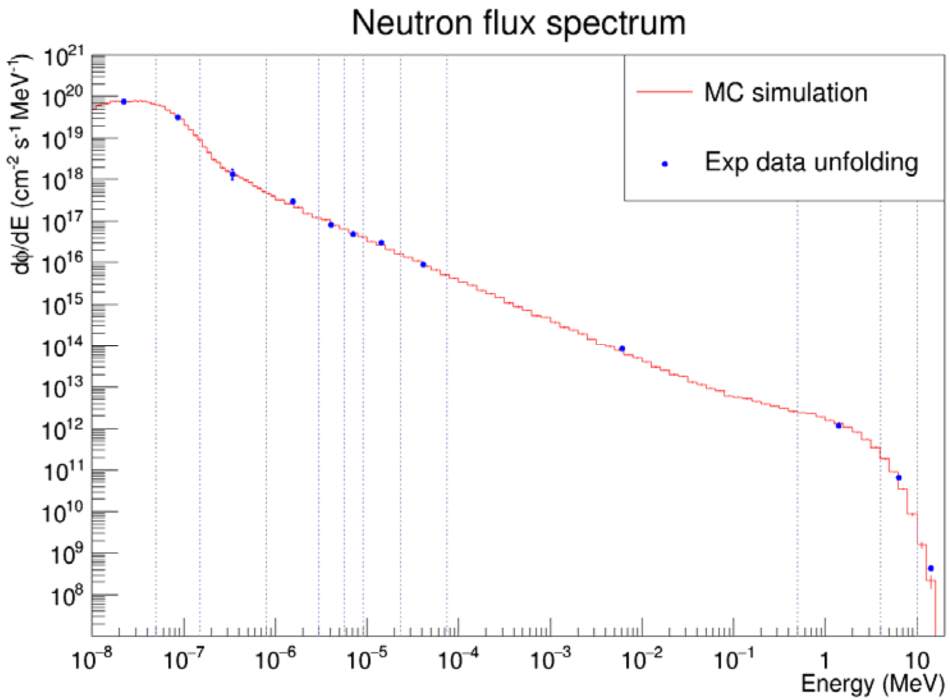
Methodology developed and tested at **TRIGA Mark II reactor in Pavia**:

- neutron activation of samples made of various elements;
- γ-spectroscopy of activated samples to measure the activation rates (**R_i**) of many reactions;
- unfolding of neutron flux spectrum using experimental data of activation rates and corresponding cross sections.

Results of measurements in the central channel of TRIGA Pavia

Uncertainties:

- ~2% for total flux intensity;
- ≤10% in specific energy bins of neutron spectrum



Measurements at TRIGA Enea Casaccia

- Same methodology developed for TRIGA PV, with some **improvements** due to **high accuracy** requirements on flux spectrum measurements.
- Analysis expected to be completed by end of June.
- Solar cells and diodes irradiated together with monitor samples to get few percent accuracy on neutron fluence.

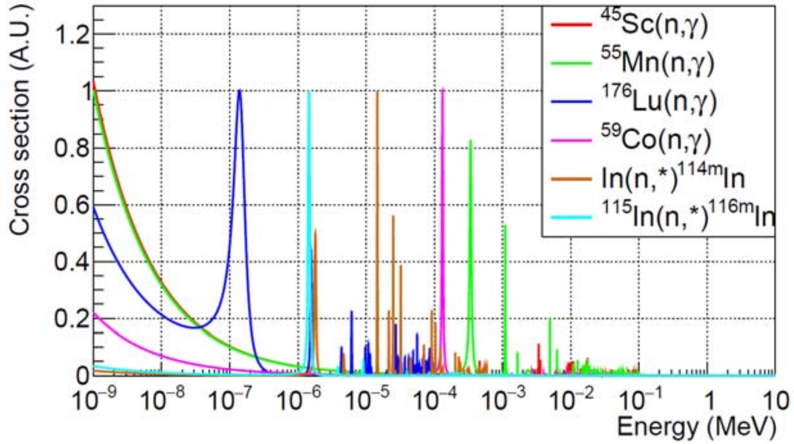
D. Chiesa, E. Previtali, and M. Sisti. Bayesian statistics applied to neutron activation data for reactor flux spectrum analysis. Annals of Nuclear Energy, vol. 70, pp. 157 – 168, 2014. DOI: 10.1016/j.anucene.2014.02.012

Methodology for neutron flux measurement

Istituto Nazionale di Fisica Nucleare
sez. di Milano Bicocca

- **Irradiation** of samples containing different elements, to measure the neutron **activation rate** (R) of many reactions characterized by different cross sections.

$$R = \mathcal{N} \int \phi(E)\sigma(E)\mathrm{d}E$$



- Neutron flux spectrum *Φ(E)* is unfolded combining the activation rate and the cross section data of various reactions which are induced with different proportions by neutrons with different energies.

- The activation rate is determined by measuring the **activity** of neutron-activated isotopes.

Activity after irradiation: $A(t) = R\left(1 - e^{-\lambda t_{irr}}\right)e^{-\lambda t}$

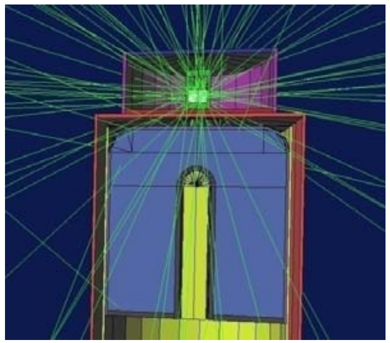
λ = decay constant
t_{irr} = irradiation time

- Activity is measured through **γ-spectroscopy with HPGe detectors** as follows:

Fit of peaks in experimental spectra to get the **counting rate (*C*)** of each γ-line.	MC simulation of γ-spectroscopy measurements to get the **efficiency (ε)** for each γ-line.

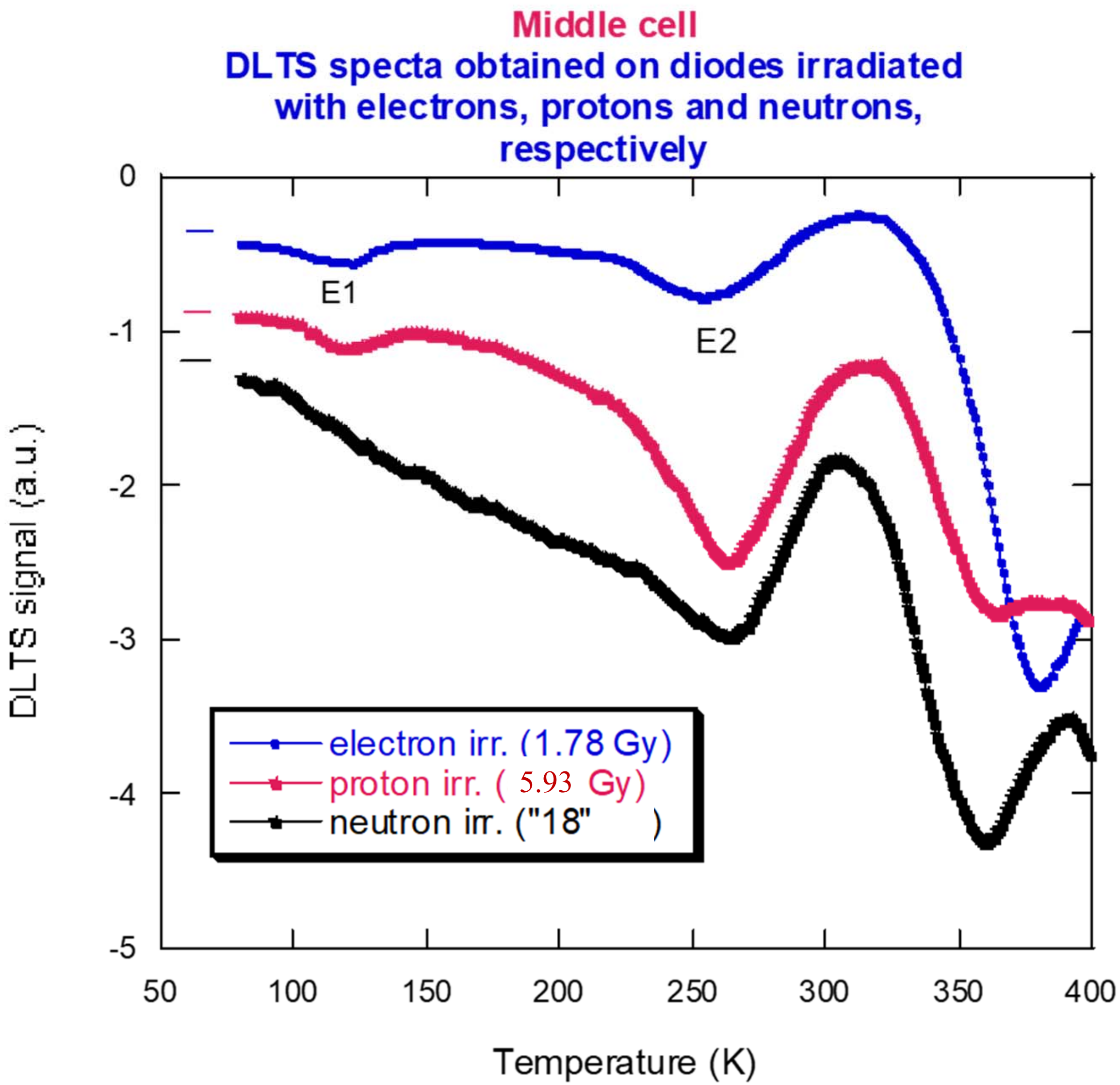
Absolute activity evaluation: ***A = C / ε***

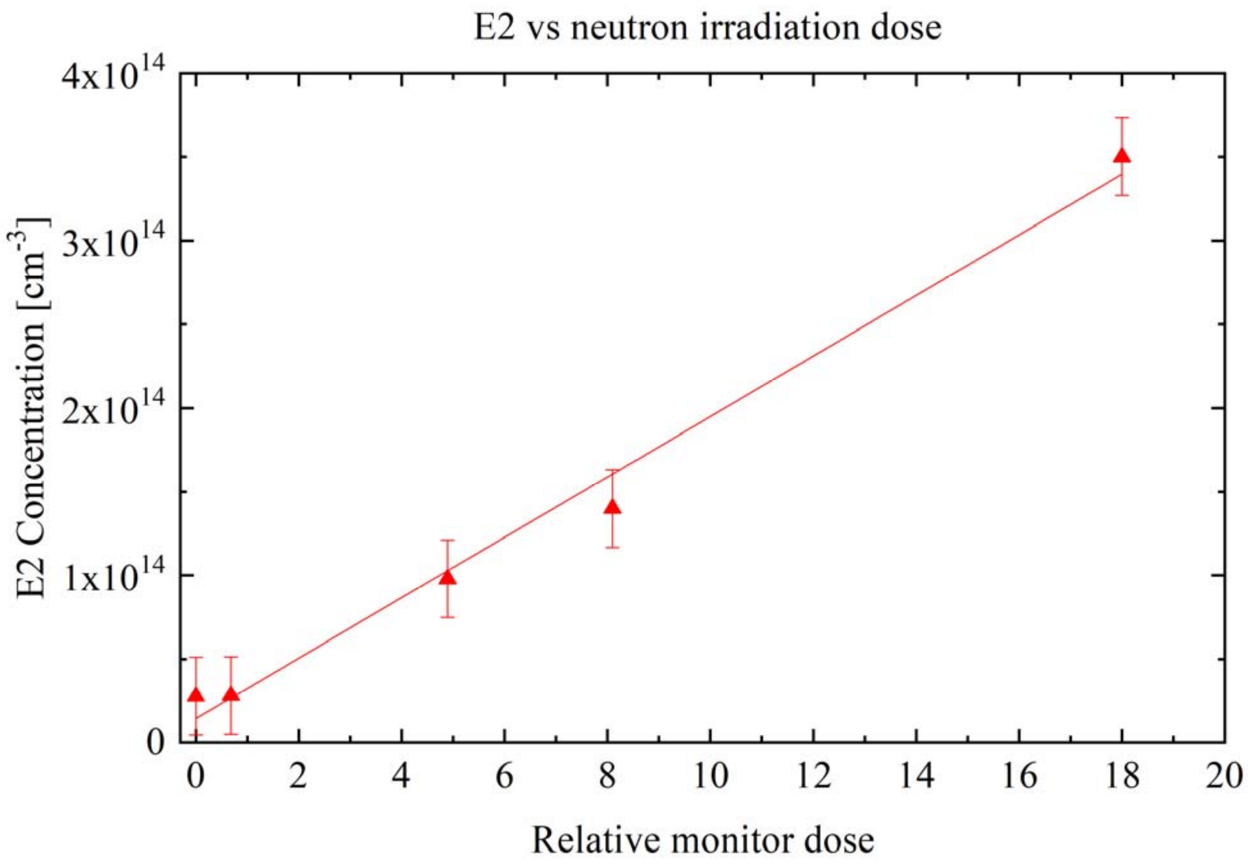
Requires



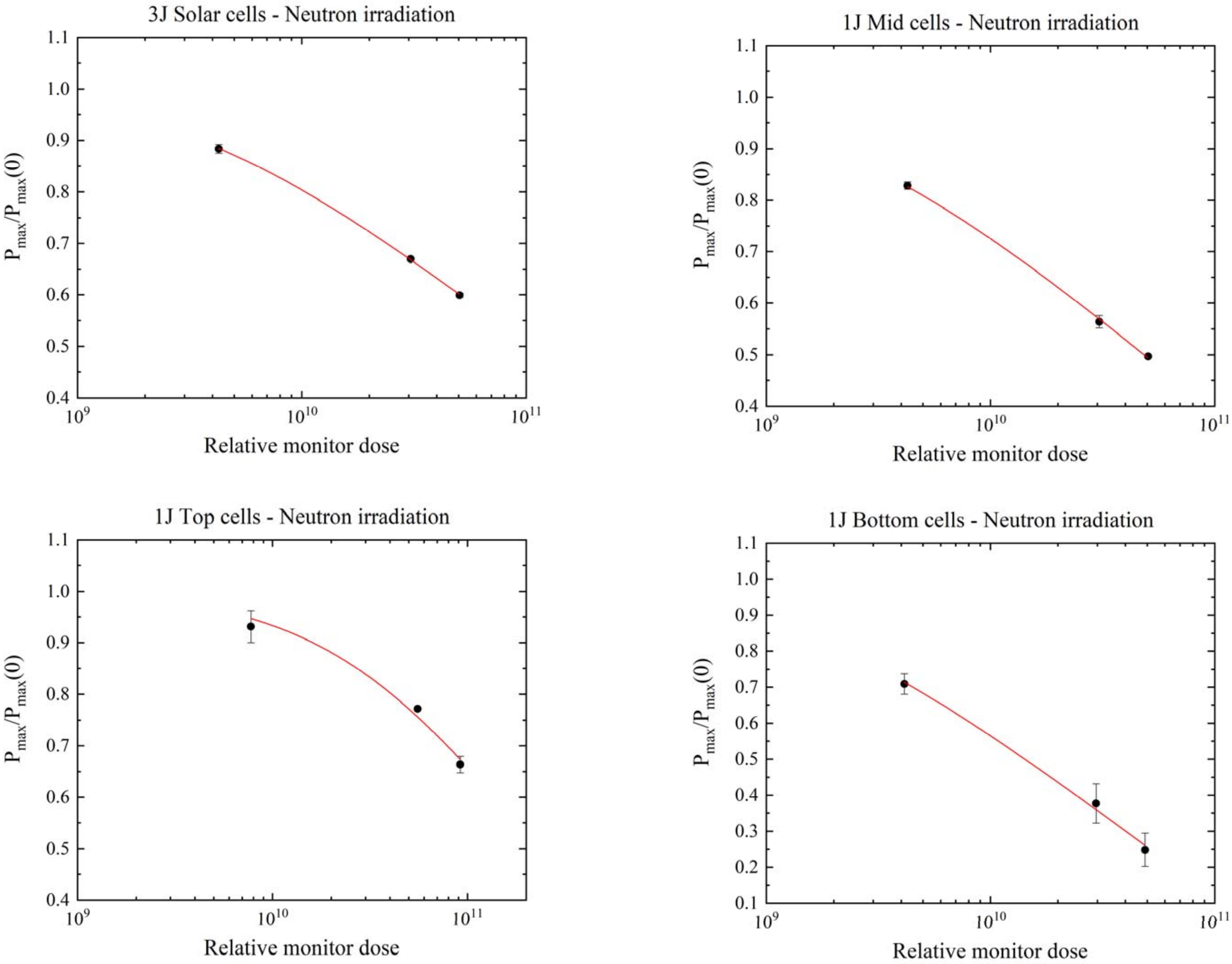
Characterization of efficiency with calibrated γ-sources to optimize and validate the MC (GEANT4) simulation model of HPGe detector.

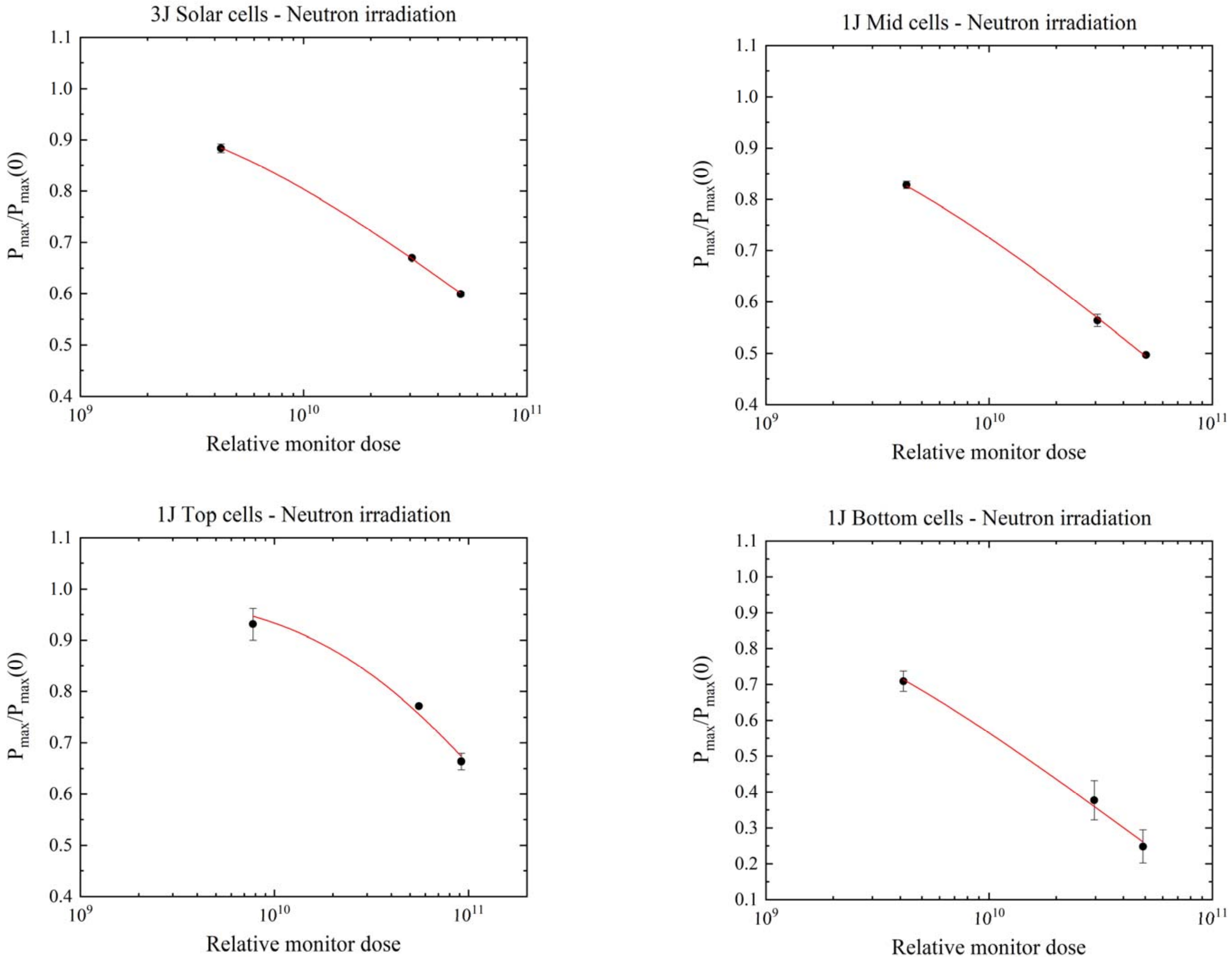
E2 obtained from neutron irradiated GaAs diodes

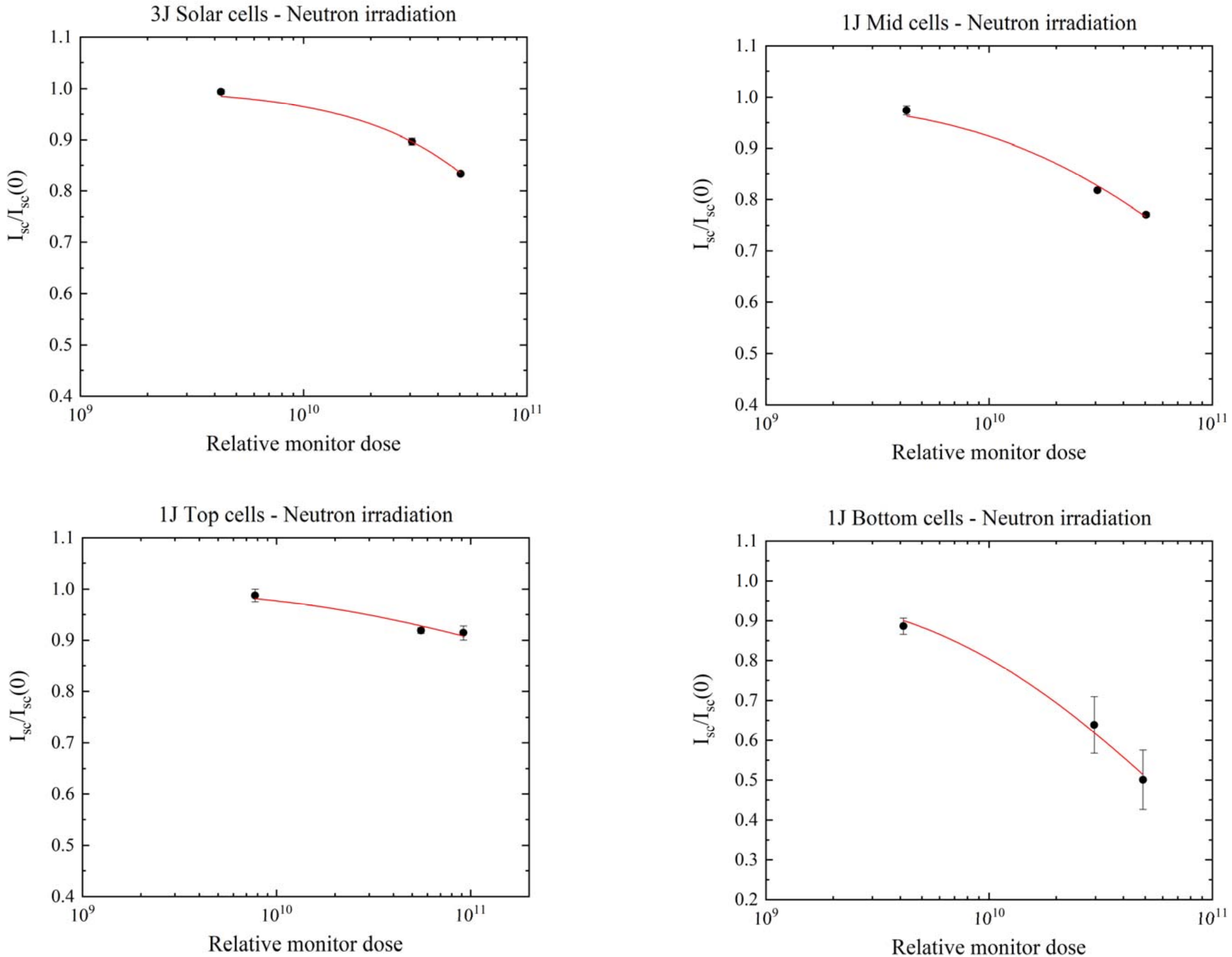

Middle cell
DLTS specta obtained on diodes irradiated
with electrons, protons and neutrons,
respectively
DLTS signal (a.u.)
Temperature (K)
E1
E2
electron irr. (1.78 Gy)
proton irr. (5.93 Gy)
neutron irr. ("18")
0
-1
-2
-3
-4
-5
50
100
150
200
250
300
350
400

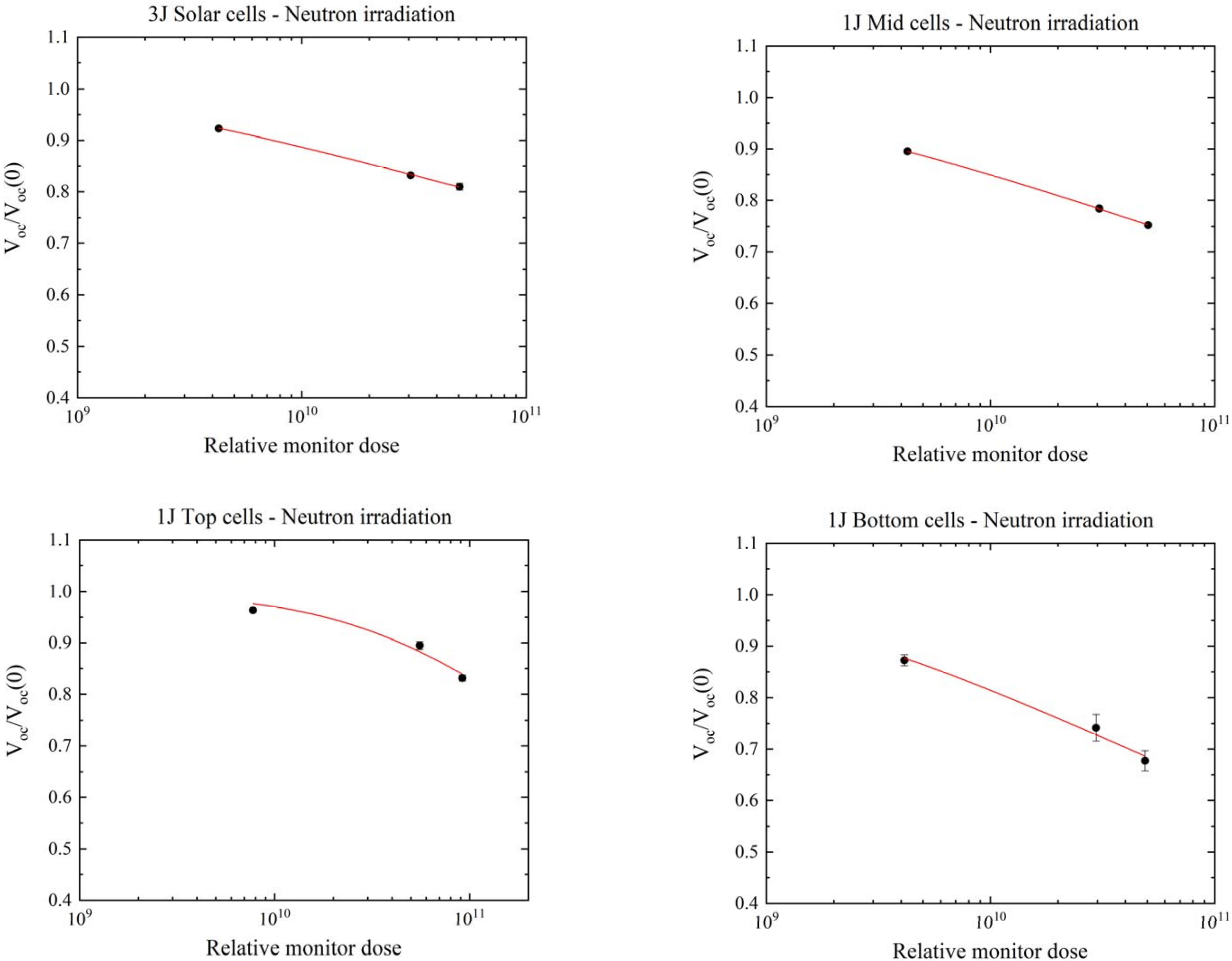


E2 vs neutron irradiation dose
E2 Concentration [cm-3]
4x10^14
3x10^14
2x10^14
1x10^14
0
0
2
4
6
8
10
12
14
16
18
20
Relative monitor dose


3J Solar cells - Neutron irradiation
1J Mid cells - Neutron irradiation
1J Top cells - Neutron irradiation
1J Bottom cells - Neutron irradiation
$P_{max}/P_{max}(0)$
Relative monitor dose
10^9
10^{10}
10^{11}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1


3J Solar cells - Neutron irradiation
1J Mid cells - Neutron irradiation
1J Top cells - Neutron irradiation
1J Bottom cells - Neutron irradiation
$P_{max}/P_{max}(0)$
Relative monitor dose
10^9
10^{10}
10^{11}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1


3J Solar cells - Neutron irradiation
1J Mid cells - Neutron irradiation
1J Top cells - Neutron irradiation
1J Bottom cells - Neutron irradiation
$I_{sc}/I_{sc}(0)$
Relative monitor dose
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
10^9
10^{10}
10^{11}


3J Solar cells - Neutron irradiation
1J Mid cells - Neutron irradiation
1J Top cells - Neutron irradiation
1J Bottom cells - Neutron irradiation
$V_{oc}/V_{oc}(0)$
Relative monitor dose
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
10^9
10^{10}
10^{11}

Remarks (summary)

- 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 found for Ga and As is 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.
- E_2 level has a trap concentration only slightly larger for electron irradiations with respect to those with protons at the same NIEL dose; while E_1 is substantially larger.
- E_1 and E_2 introduction rates as a function of incoming particle energy exhibit a good agreement with those expected by means of sr-niel

➡ These set of measurements of P/Pmax, Isc, Voc and introduction rates of levels are experimentally supporting the validity of sr-niel treatment for obtaining NIEL doses.

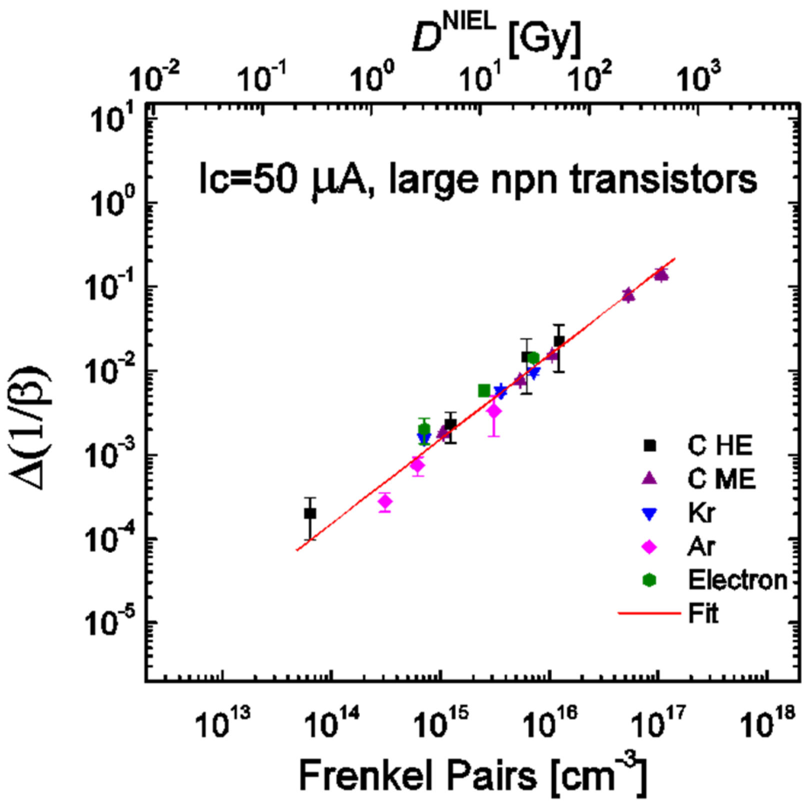
Current/future work

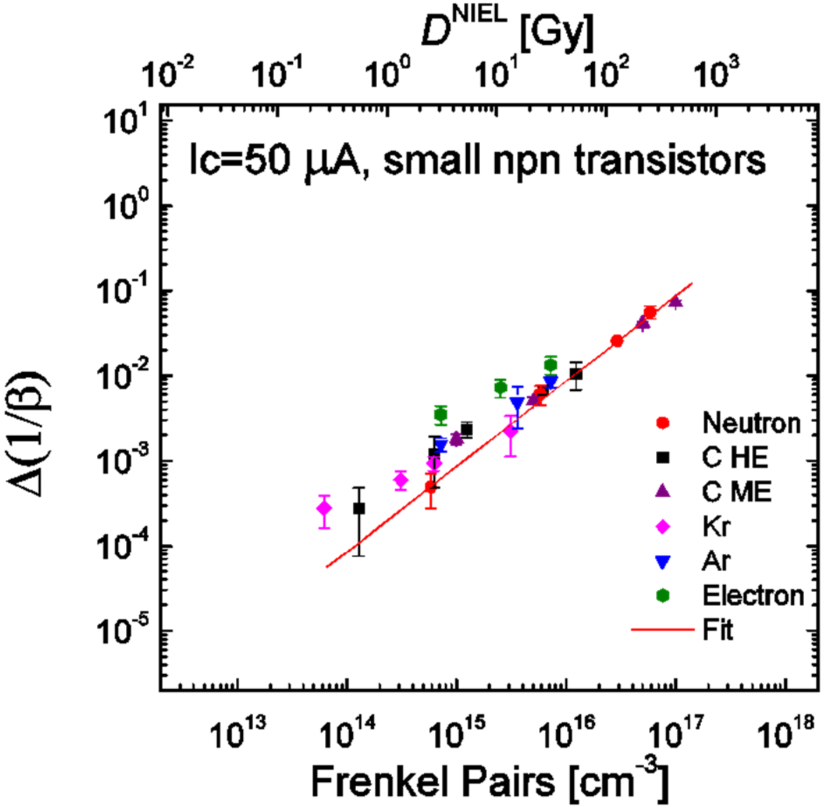
- Irradiations of solar cells and diodes with neutrons can be useful for a better understanding of introduction rates of trapping levels, in addition to what already achieved with protons and electrons.

- Measurements of irradiated diodes with lower doping concentrations can result in understanding of trapping levels below the bottom of the conduction band.

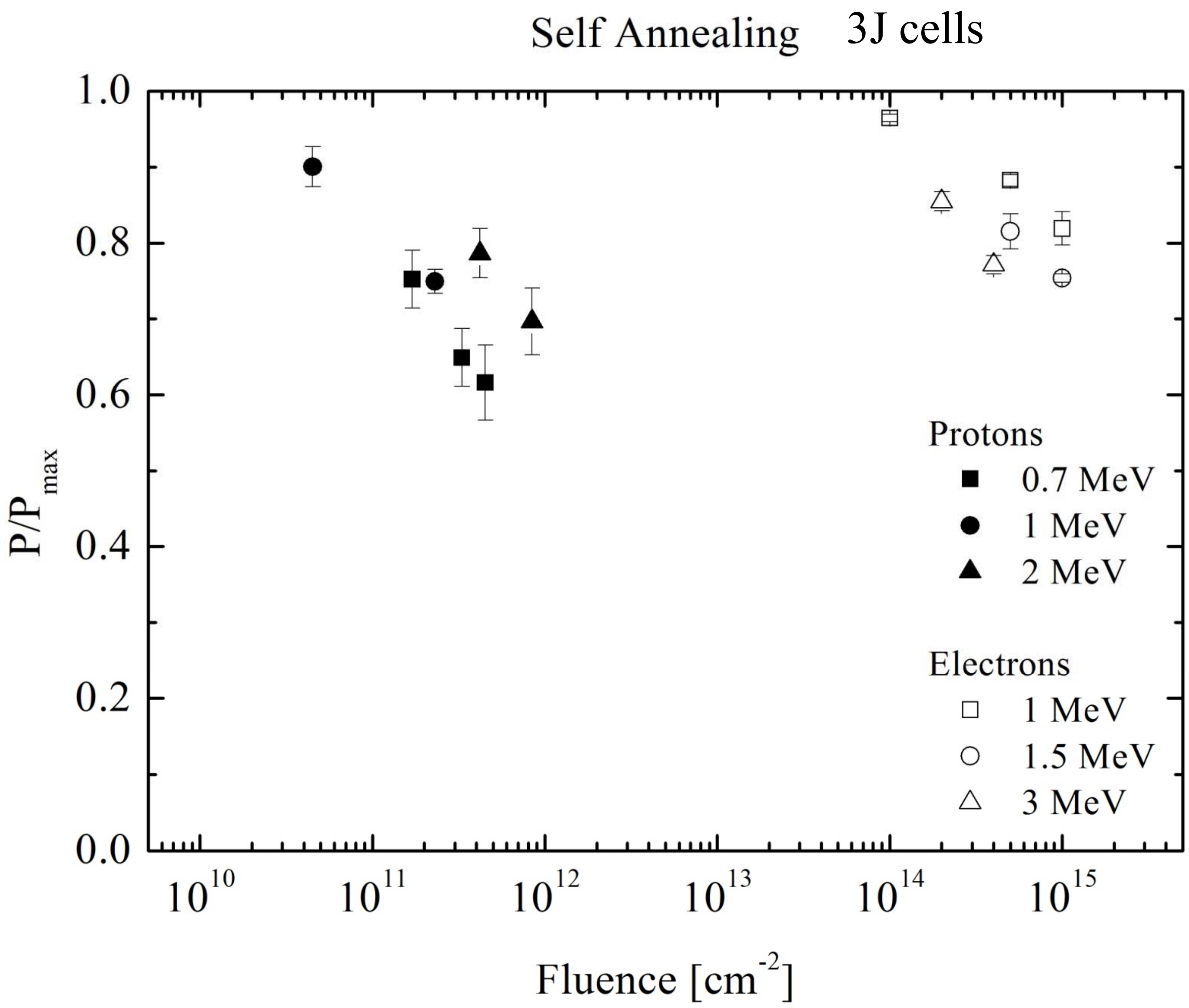
Back up

Bipolar Transistors STMicroelectronics

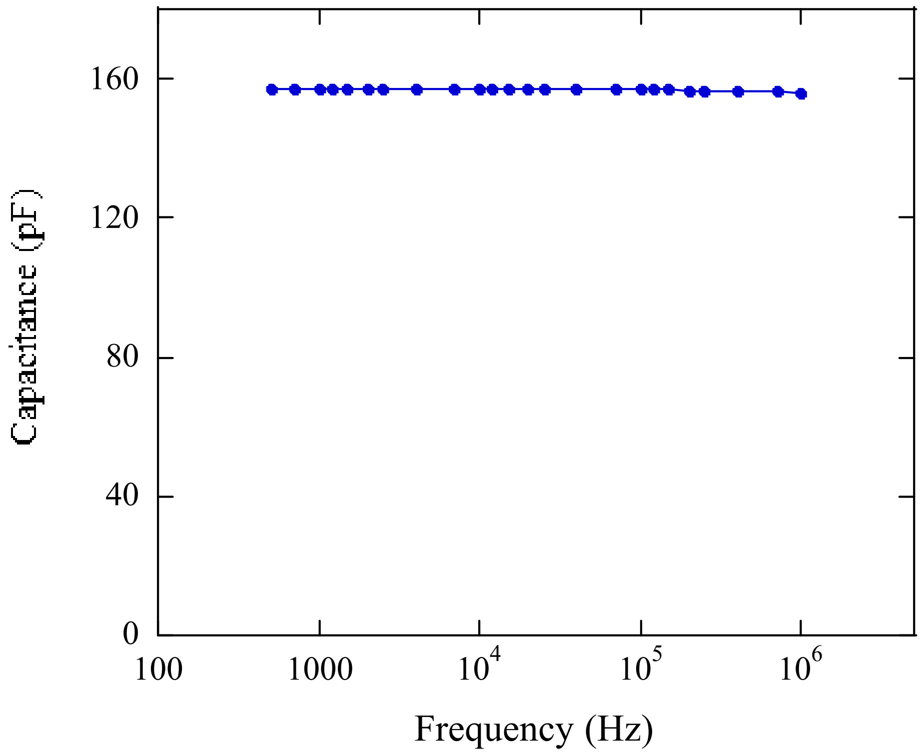




Consolandi et al., Nucl. Instr. and Meth. B 252 (2006), 276-284; doi:10.1016/j.nimb.2006.08.018



Self Annealing 3J cells
P/P$_{max}$
Fluence [cm^{-2}]
Protons
0.7 MeV
1 MeV
2 MeV
Electrons
1 MeV
1.5 MeV
3 MeV

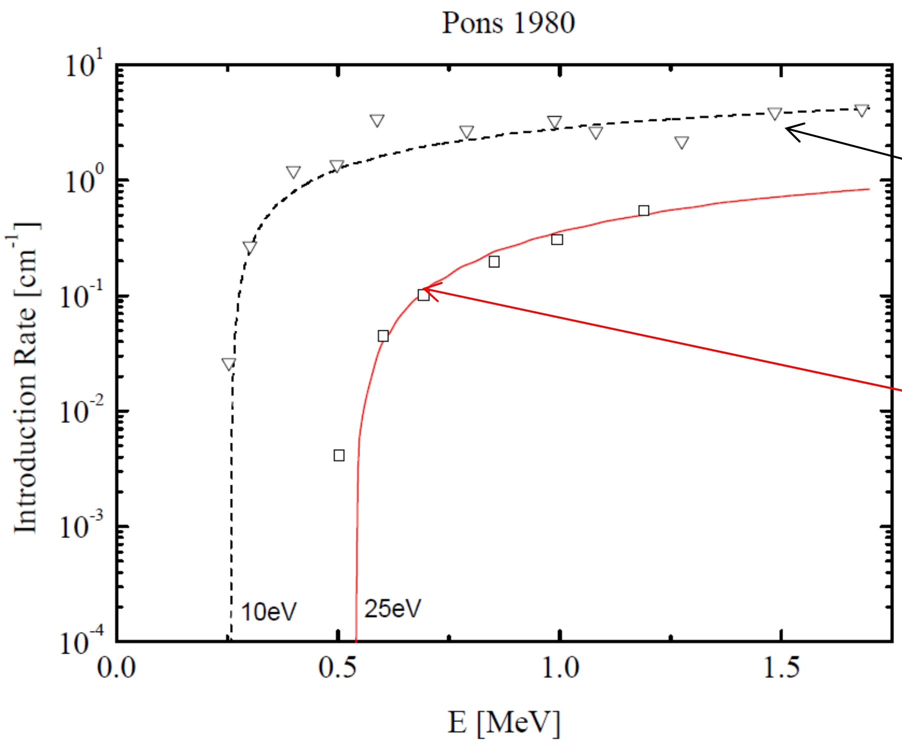


Capacitance vs frequency of a mesa structure obtained on the middle cell.

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).

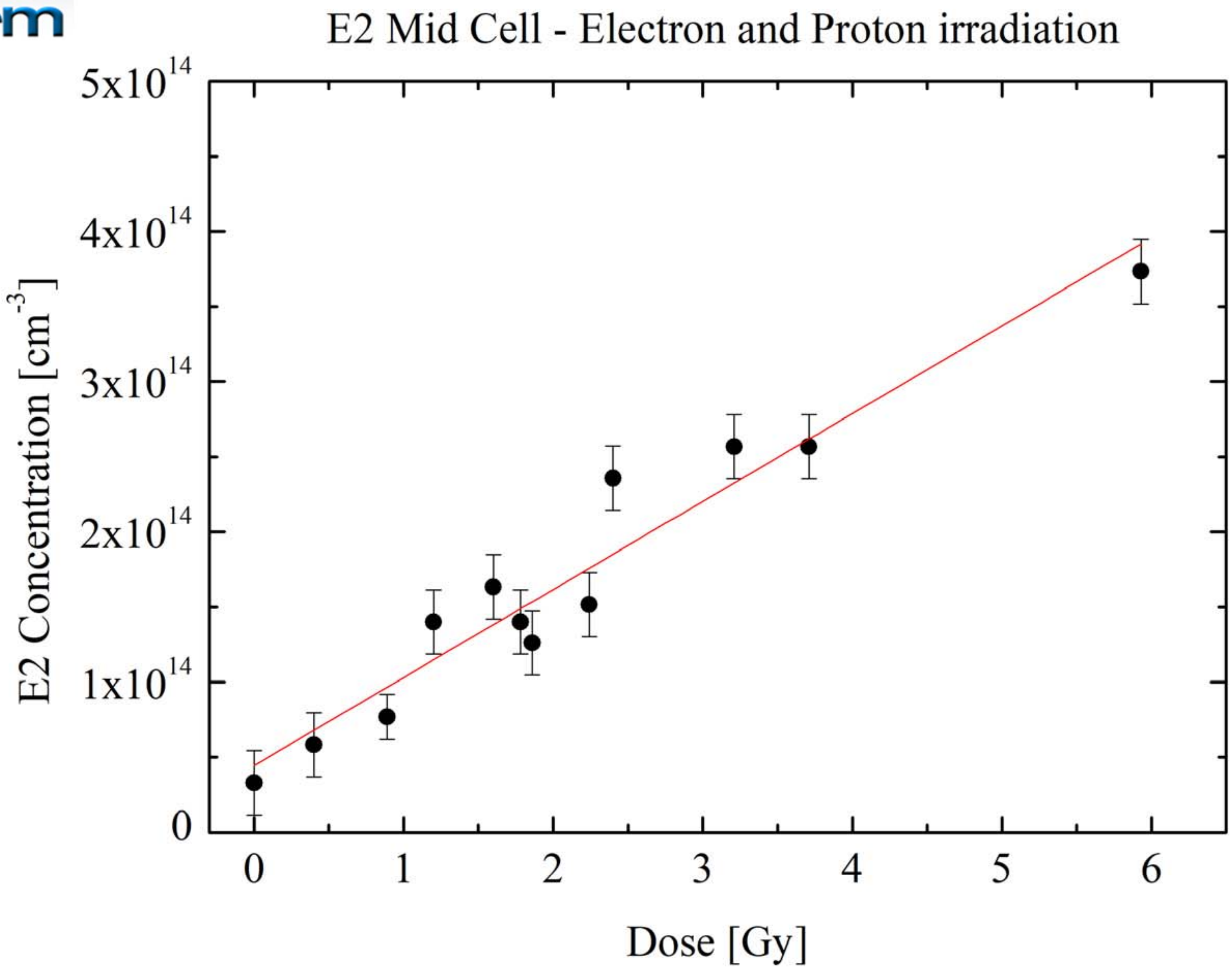
after II stages annealing: 25 eV

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

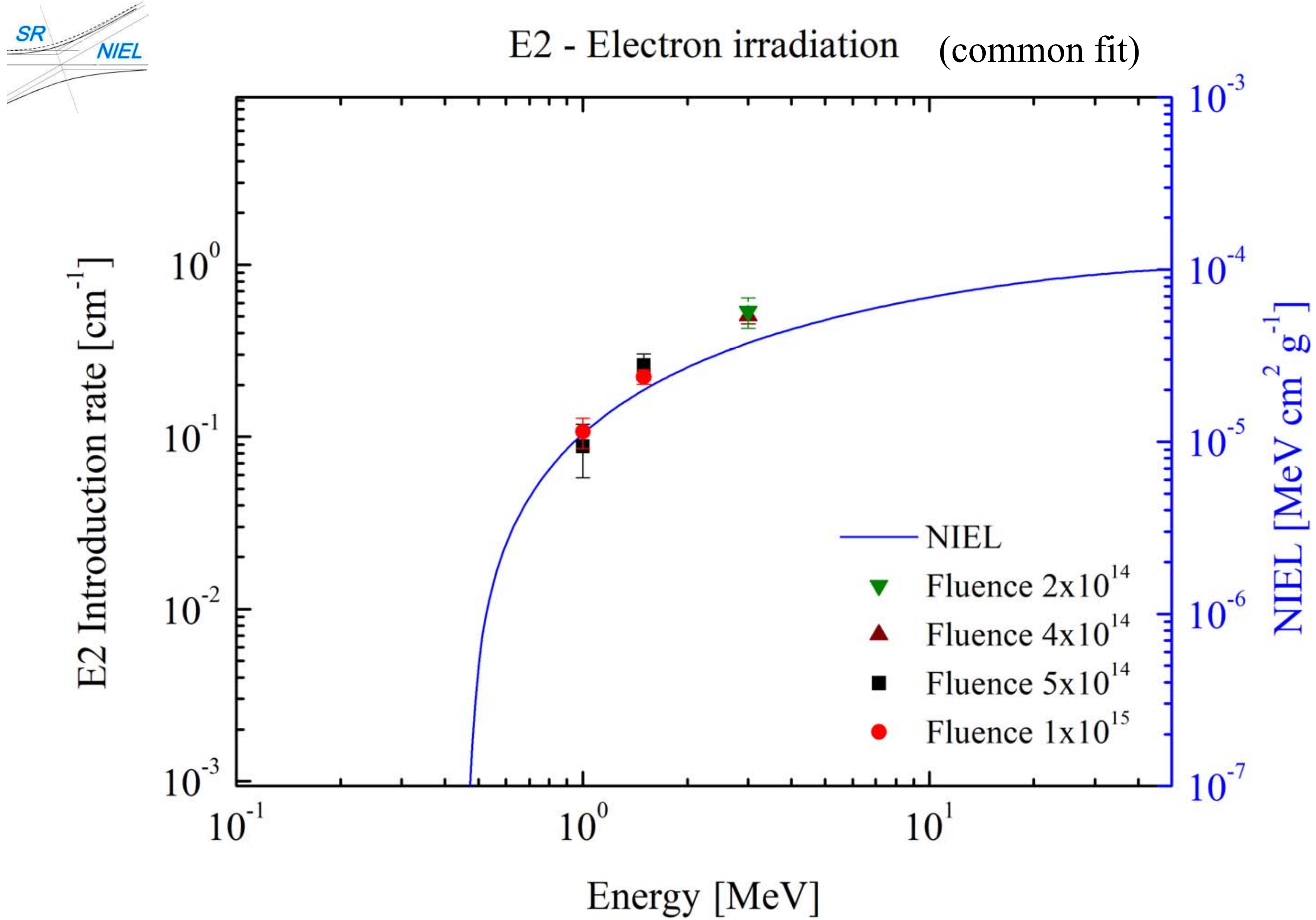
the (self-) annealing effect is **expected to cause a shift of the damage energy threshold to a value larger than 10 eV**. In that paper, the authors correctly remarked about a possible disappearing of divacancies.

(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)

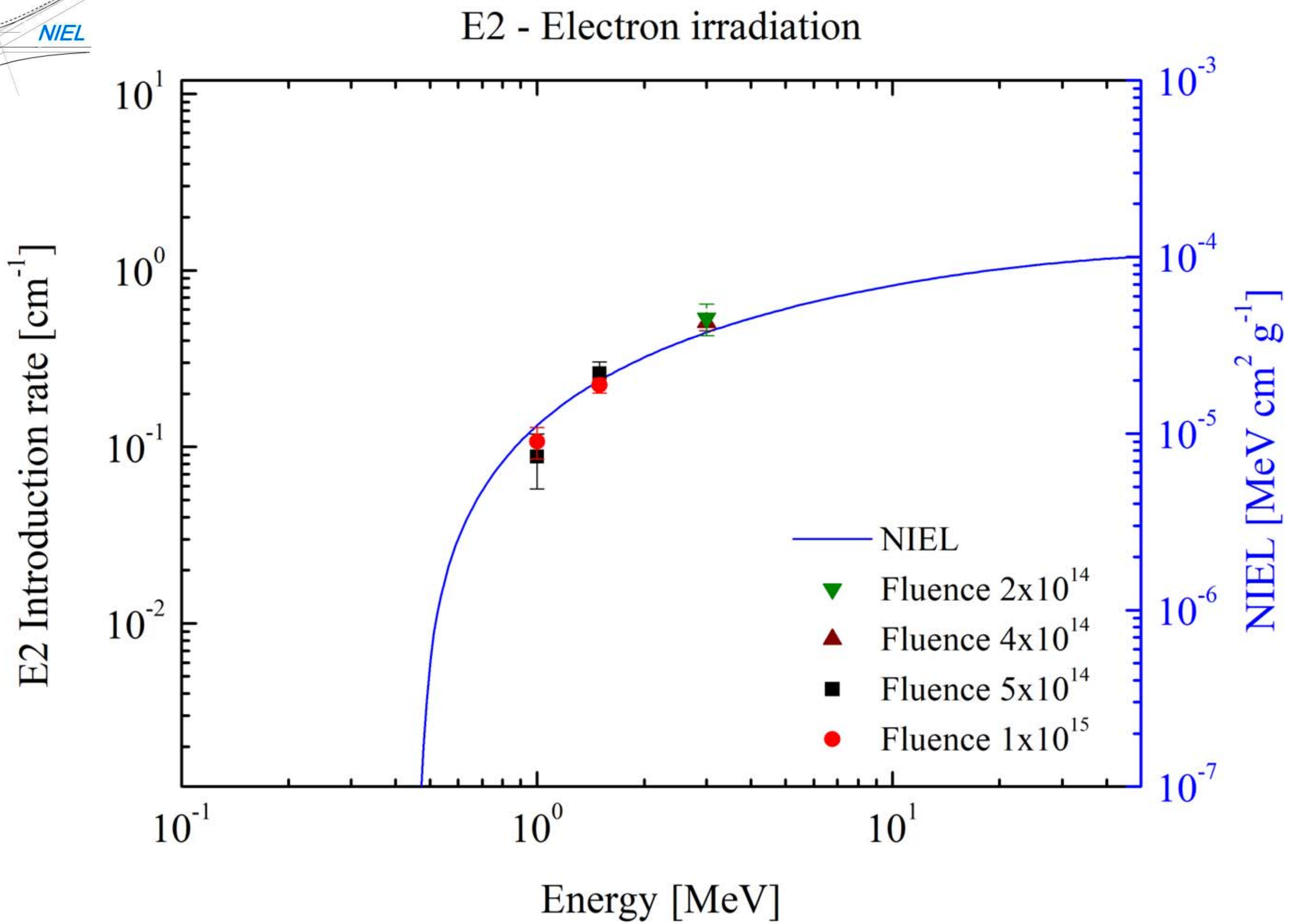
DLTS **E2** peak
Common fit for electrons and protons



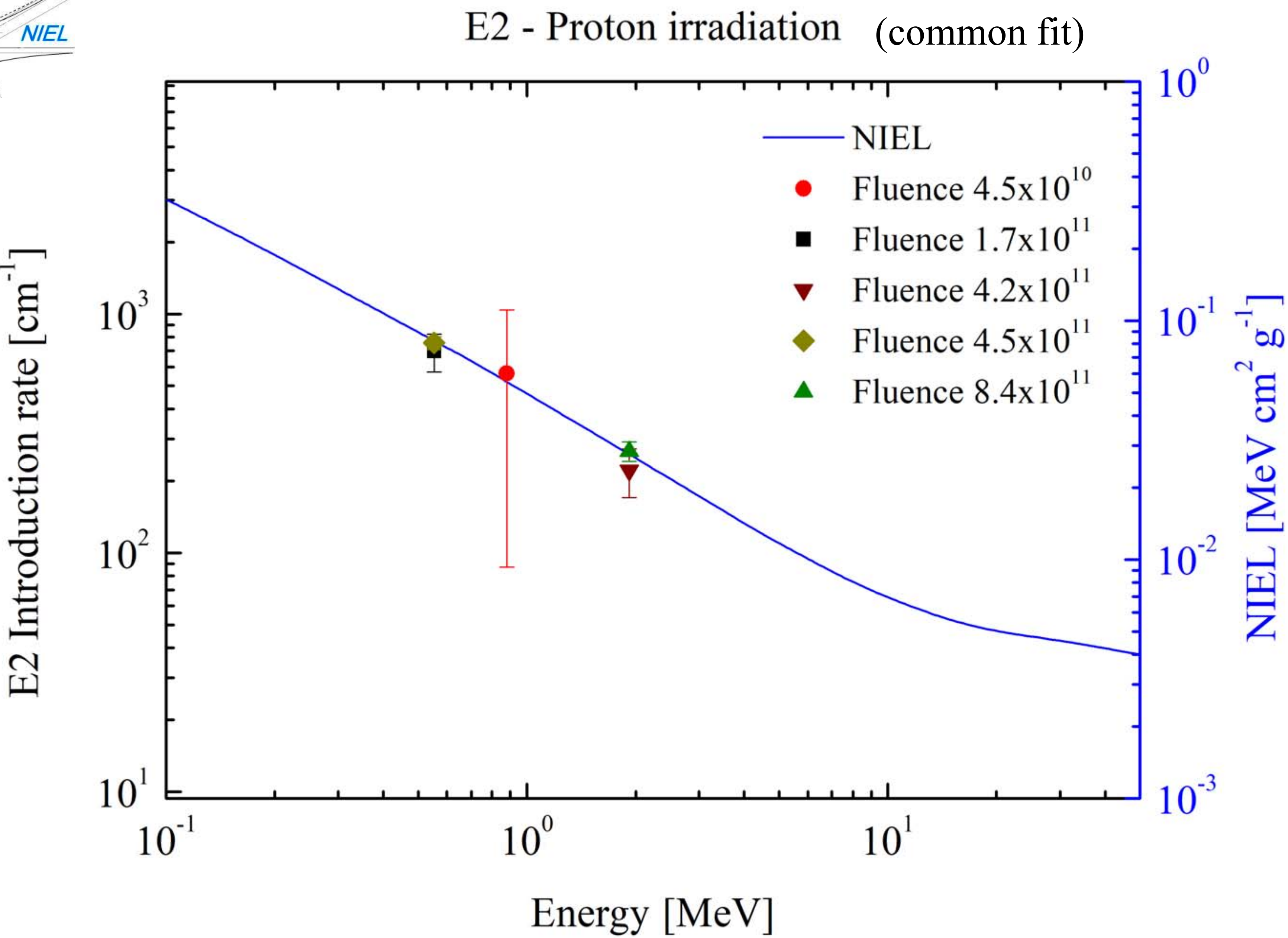
E2 Mid Cell - Electron and Proton irradiation
E2 Concentration [cm^{-3}]
Dose [Gy]
0
1x10^{14}
2x10^{14}
3x10^{14}
4x10^{14}
5x10^{14}
0
1
2
3
4
5
6



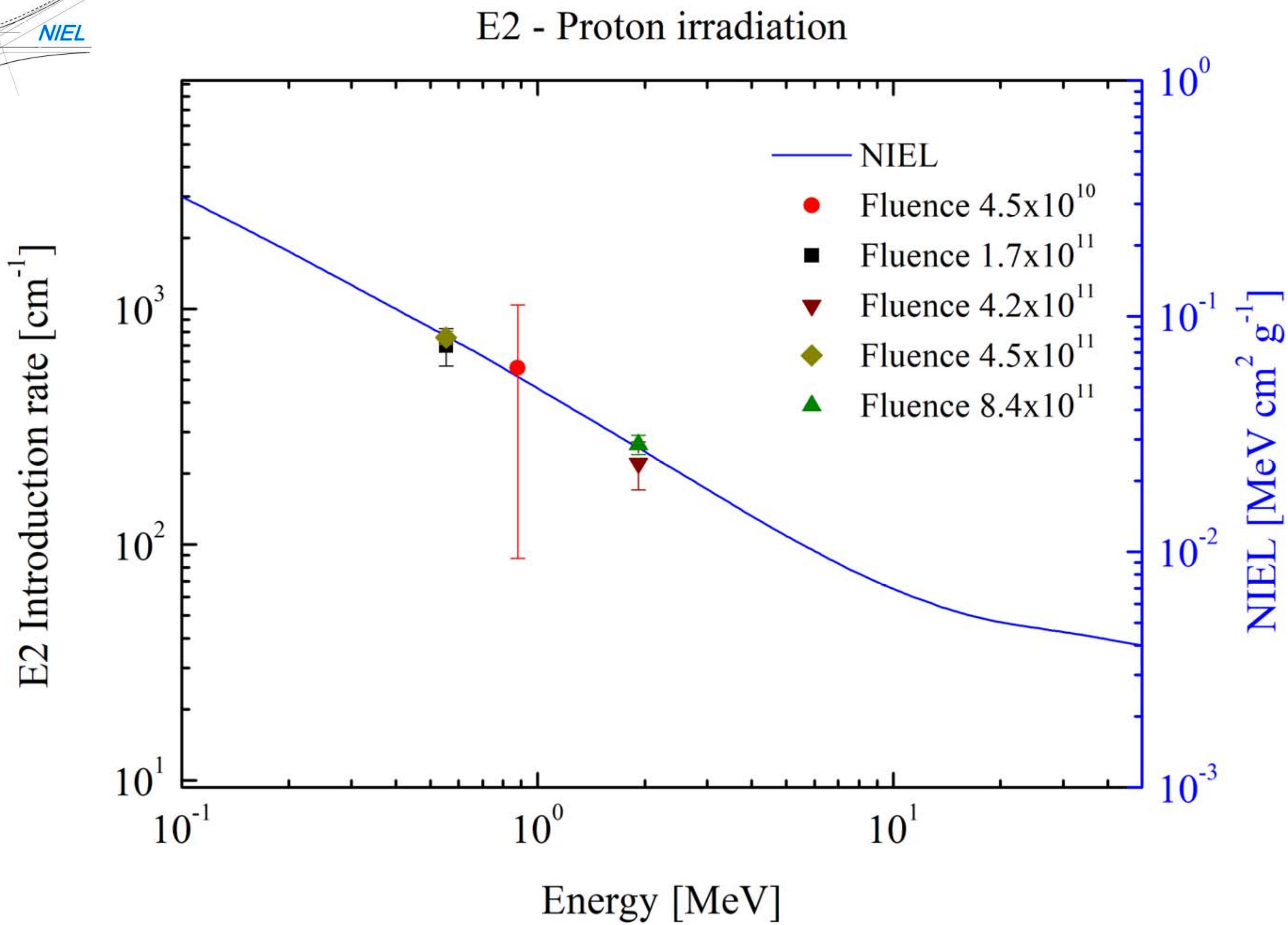
Introduction rate to NIEL conversion factor: **9.37x10³** [g MeV⁻¹ cm⁻³]



Introduction rate to NIEL conversion factor: **1.19×10^4** [g MeV^{-1} cm^{-3}]



Introduction rate to NIEL conversion factor: **9.37×10^3** [g MeV^{-1} cm^{-3}]



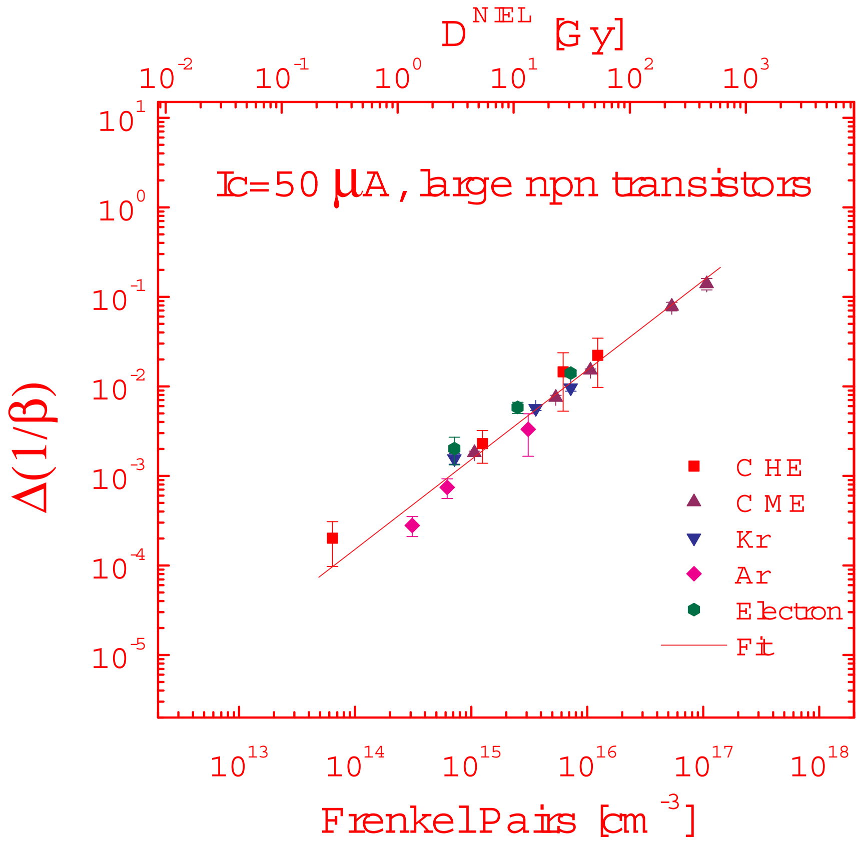
Introduction rate to NIEL conversion factor: **9.32x10³** [g MeV⁻¹ cm⁻³]

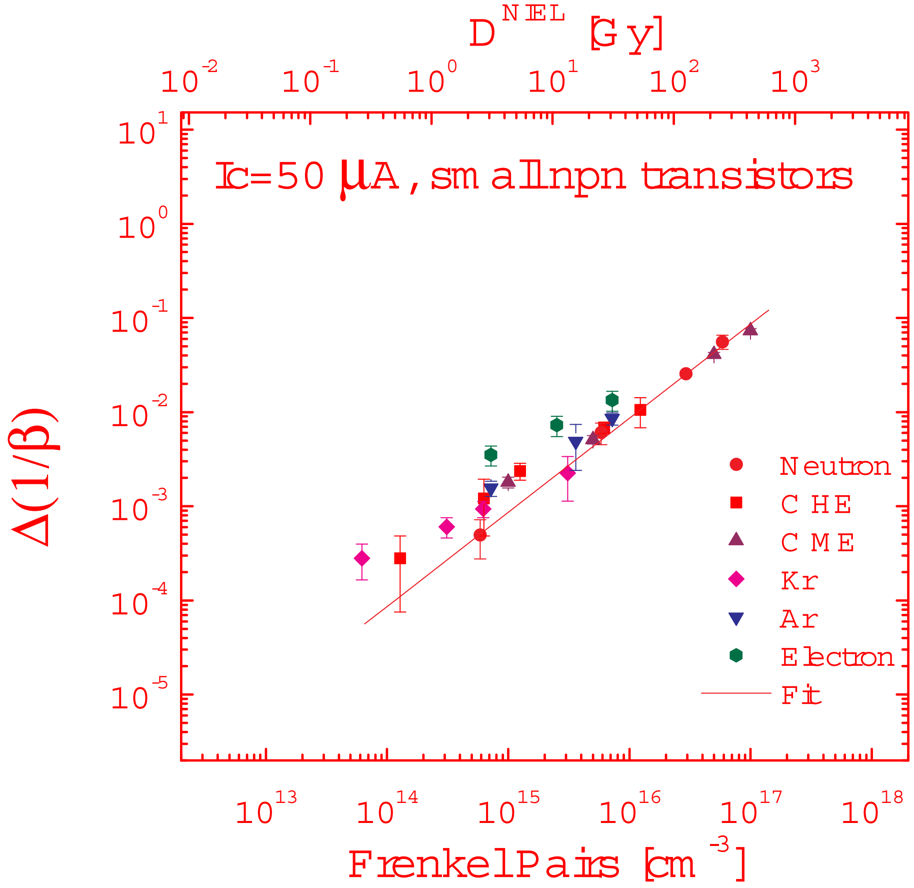
Further remarks

a) It has been observed that the amplitude of E3 peak drastically reduces with the distance from the interface (i.e. it a property expected for interface states). Since this peak is also present in non-irradiated samples, it has been attributed to interface states.

b) The DLTS spectra obtained by application of forward bias pulses, i.e. by injection of minority carriers in the depletion layers, do not exhibit positive DLTS peaks commonly associated to minority carrier traps. This could be attributed to the difficulty of changing the occupancy state of minority carrier traps in the GaAs base due to the relatively high doping level of the p-type base.

Bipolar Transistors STMicroelectronics





Bipolar Transistors STMicroelectronics