DE LA RECHERCHE À L'INDUSTRIE

Special SEE Session:

The MuElec extension for microdosimetry in silicon

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Geant4 Space Users Workshop, Barcelona - 03/05/2013

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OUTLINE

Context and motivation

Brief description of the theory

Implementation in Geant4: The MuElec extension

Some validation/verification results

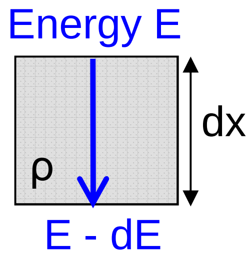
Proton track simulation in Geant4

Conclusion and Perspectives

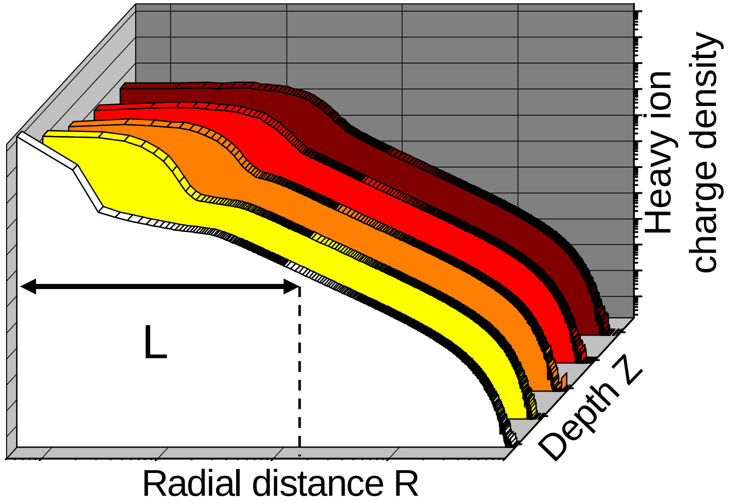
CONTEXT: Need to take into account radial dimension of the ion track

- Test for SEE sensitivity: measure of the SEE cross section vs. LET
- LET = Linear Energy Transfer $LET = -\frac{1}{\rho}\frac{dE}{dx}$

⇒ **Assume same LET = same effect.**



- Vary with depth Z, penetration into matter
  ⇒ Energy deposition = f(Z).
- But also radial dimension R of ion track
  ⇒ Energy deposition = f(Z,R).
- Decreasing size of components L
  ⇒ L < 0.25 µm ⇒ L ~ R or L < R



⇒ **Heavy-ion induced SEE simulation in advanced devices requires the accurate description of radial ionization profiles.**

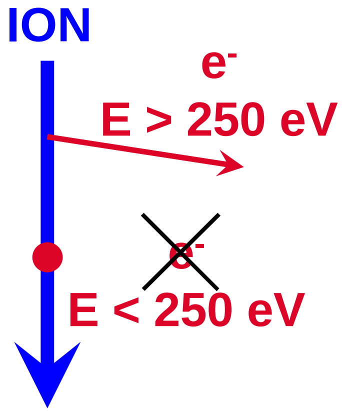
CONTEXT AND MOTIVATION

- Heavy-ion induced SEE simulation in advanced devices requires the accurate description of radial ionization profiles.

- Geant4 = adequate tool to simulate ion tracks
  - Succesfully used in combination with TCAD [1] or SEE prediction tool [2]
  - Down to the 32 nm node.

- Inherent limits in Geant4 ionization models (Livermore):
  - Recommended secondary production threshold at 250 eV
  - Limits the accuracy of ion track below 10 nm in radius

⇒ **Need for more accurate Geant4 ionization models !**



- Since 2010, development of the **"MuElec"** (µ-electronics) extension in Geant4 for microdosimetry in silicon

⇒ **Part of Geant4 since release 9.6 beta (June 2012).**

[1] Raine *et al.*, IEEE TNS, vol. 57, 2010.
[2] Raine *et al.*, IEEE TNS, vol. 58, 2011.

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BRIEF DESCRIPTION OF THE THEORY

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- Calculation of **ionizing cross-section** for the **generation of electrons by incident electrons, protons and heavy ions:**
  - Based on the Complex Dielectric Function Theory (CDFT).
  - Using the procedure described by Akkerman *et al.* [1].

- **CDFT basic quantity: Energy Loss Function**

$$\mathrm{ELF}(\hbar\omega,\vec{q}) = \mathrm{Im}\left[\frac{-1}{\varepsilon(\omega,\vec{q})}\right]$$

  - Differential Cross Section:

$$\frac{d\sigma}{d(\hbar\omega)}(E,\hbar\omega) = \frac{1}{\pi N a_0 E}\int_{q_-}^{q_+} \boxed{\mathrm{ELF}(\hbar\omega,\vec{q})}\frac{dq}{q}$$

Different $q_\pm$ depending on incident particle: e^- or proton/heavy ion

  - Total Cross Section:

$$\sigma(E) = \int_0^{\frac{E+E_b}{2}} \frac{d\sigma}{d(\hbar\omega)} d(\hbar\omega)$$

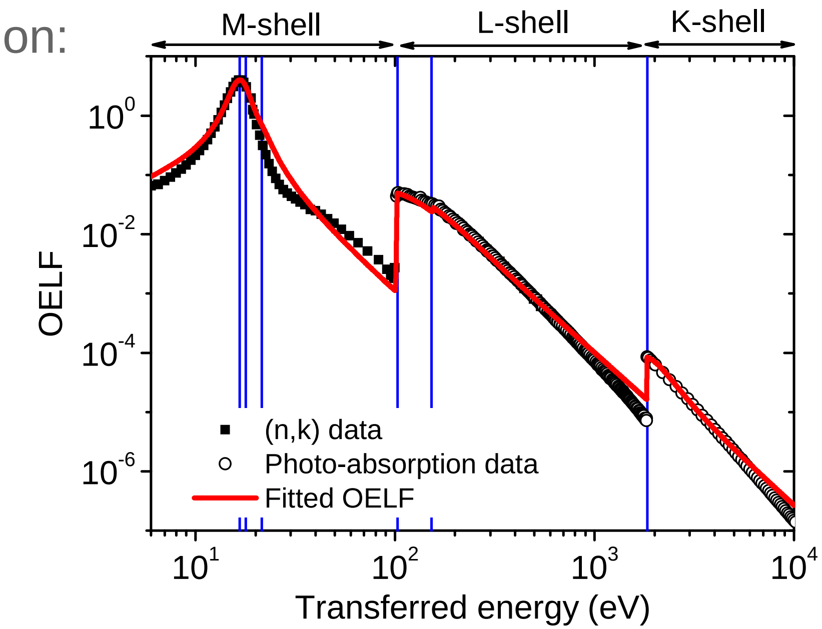
  - Stopping power:

$$S(E) = N\int_0^{E/2} \hbar\omega \frac{d\sigma}{d(\hbar\omega)} d(\hbar\omega)$$

[1] Akkerman *et al.*, NIM B, vol. 227, 2005.

BRIEF DESCRIPTION OF THE THEORY

- Determination of the Energy Loss Function:
  - Optical ELF (OELF): ELF at q = 0.
  - Determined from optical exp. data
  - Fitted with a sum of Drude functions
  - Extension at q ≠ 0: $E_j(q) = E_j + \frac{\hbar^2 q^2}{2m_e}$



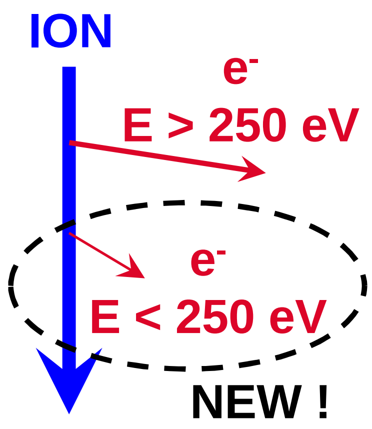
- 6 cross-sections, allowing to distinguish 6 different ionizing interactions:
  - Plasmon excitation,
  - Ejection of an electron from the 5 Si electronic shells:

    M1 (3s), M2 (3p), L1 (2s), L2 (2p) and K (1s) shells.

BRIEF DESCRIPTION OF THE THEORY

- All calculation details in:
  - A. Valentin, *et al.*, *"Geant4 physics processes for microdosimetry simulation: very low energy electromagnetic models for electrons in silicon"*, NIM B, vol. 288, pp. 66 - 73, 2012.
  - A. Valentin, *et al.*, *"Geant4 physics processes for microdosimetry simulation: very low energy electromagnetic models for protons and heavy ions in silicon"*, NIM B, vol. 287, pp. 124 - 129, 2012.

- **No secondary production threshold** energy.
- **Discrete approach on the entire energy range**: explicit simulation of all interactions on a step-by-step basis.



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IMPLEMENTATION IN GEANT4: THE MUELEC EXTENSION

DESCRIPTION OF THE MUELEC EXTENSION

- **Based on the existing Geant4-DNA framework (see previous presentation)**, which uses the same initial theory (CDFT) in liquid water.

- **MuElec extension:**
  - In $G4INSTALL/source/processes/**electromagnetic/lowenergy**
  - 4 classes (2 processes, one model each)

Process	Interaction	Particle	Energy range
G4MuElecInelastic	Ionization	e^-	16.7 eV - 100 MeV
		Proton Heavy ion	50 keV/amu - 1 GeV/amu
G4MuElecElastic	Elastic scattering	e^-	16.7 eV - 100 MeV

  - 2 additional classes: G4MuElecCrossSectionDataSet
    G4MuElecSiStructure

  - Tabulated total and differential cross sections in data files G4EMLOW6.32

[1] Akkerman *et al.*, NIM B, vol. 227, 2005.

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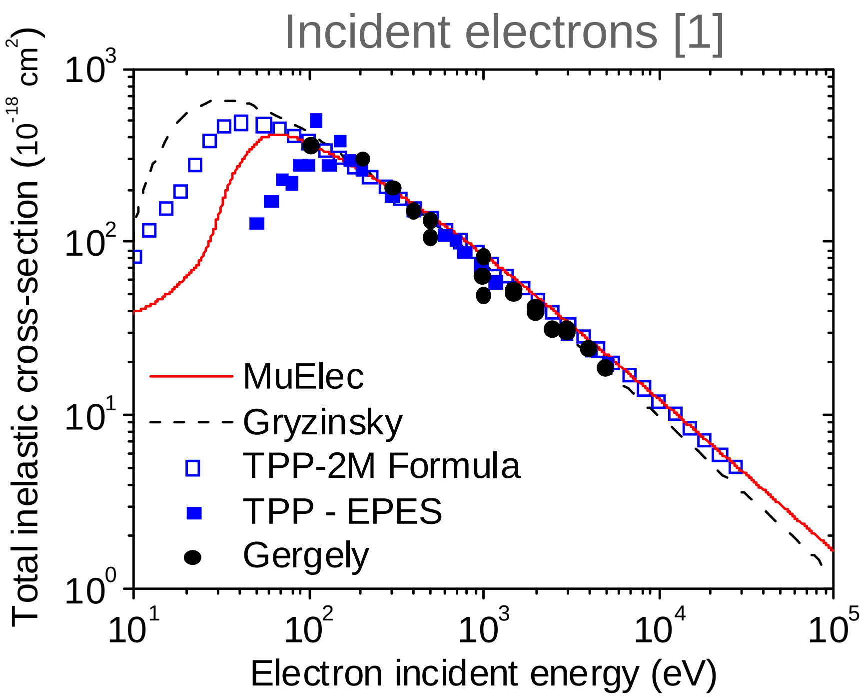
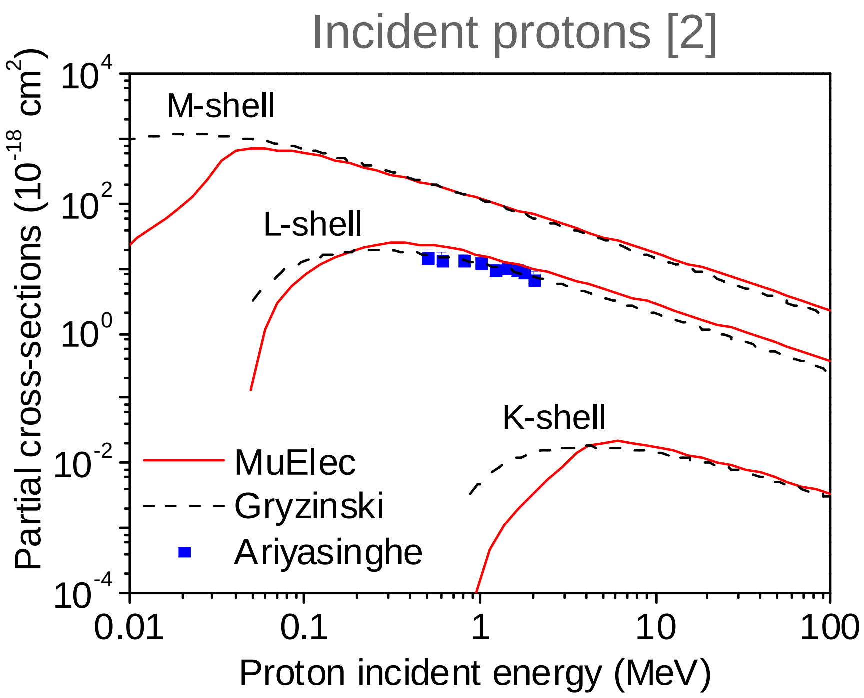
SOME VALIDATION RESULTS

SOME VALIDATION / VERIFICATION RESULTS

- Inelastic cross-section





⇒ Satisfying agreement with data from literature **> 50 eV**

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For more detailed discussion and validations: [1] A. Valentin, *et al.*, NIM B, vol. 288, pp. 66 - 73, 2012.
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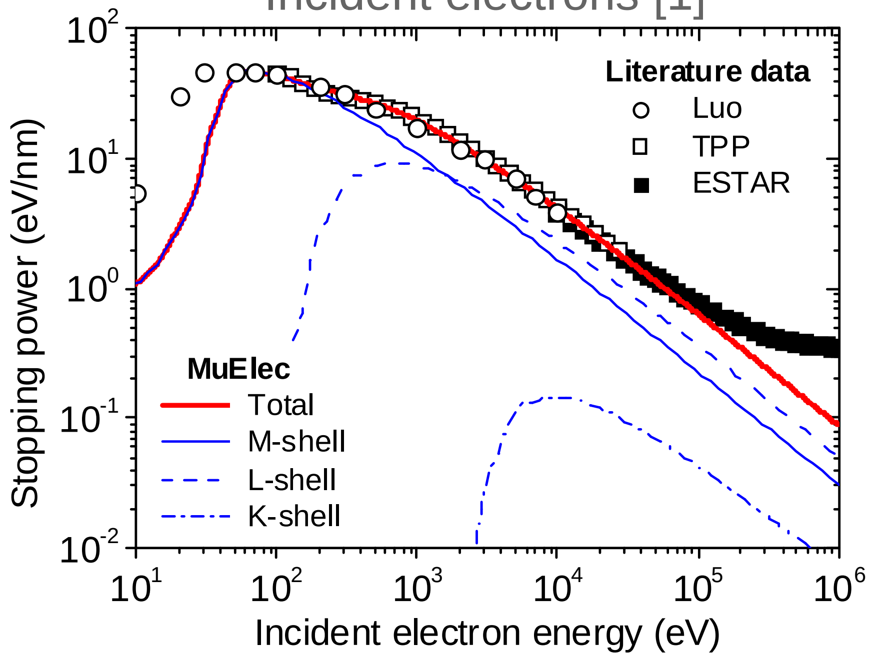
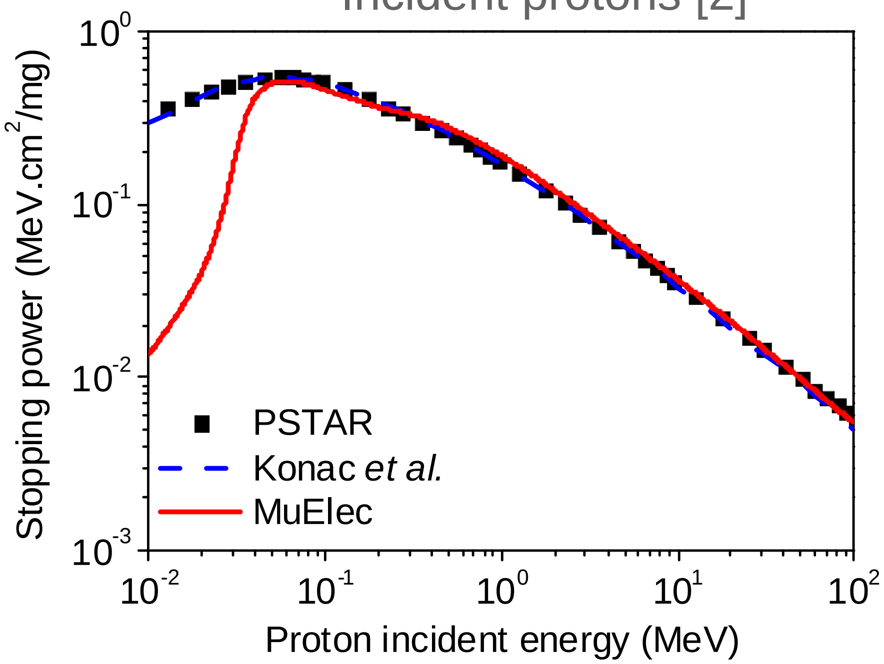
SOME VALIDATION / VERIFICATION RESULTS

- Stopping power

Incident electrons [1]



Incident protons [2]



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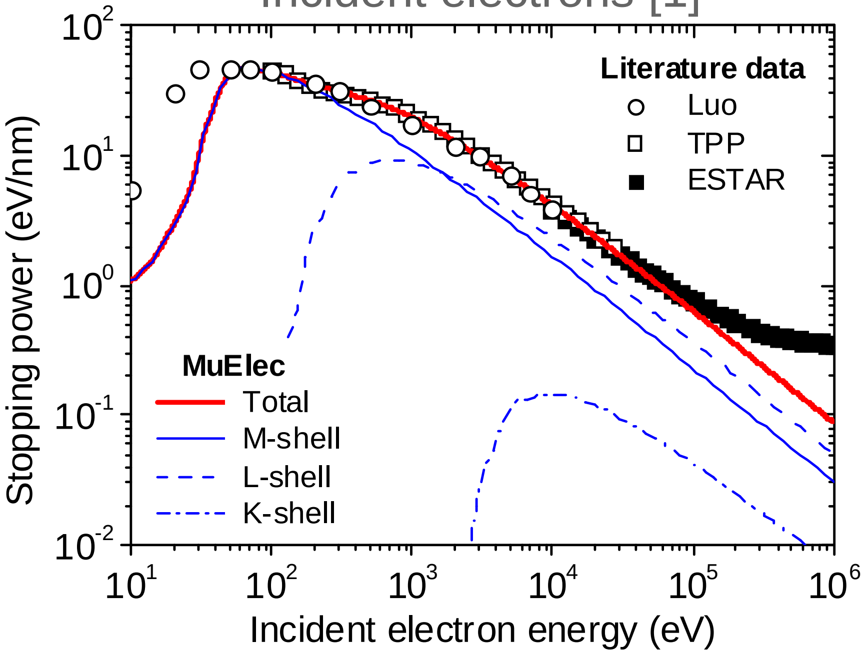

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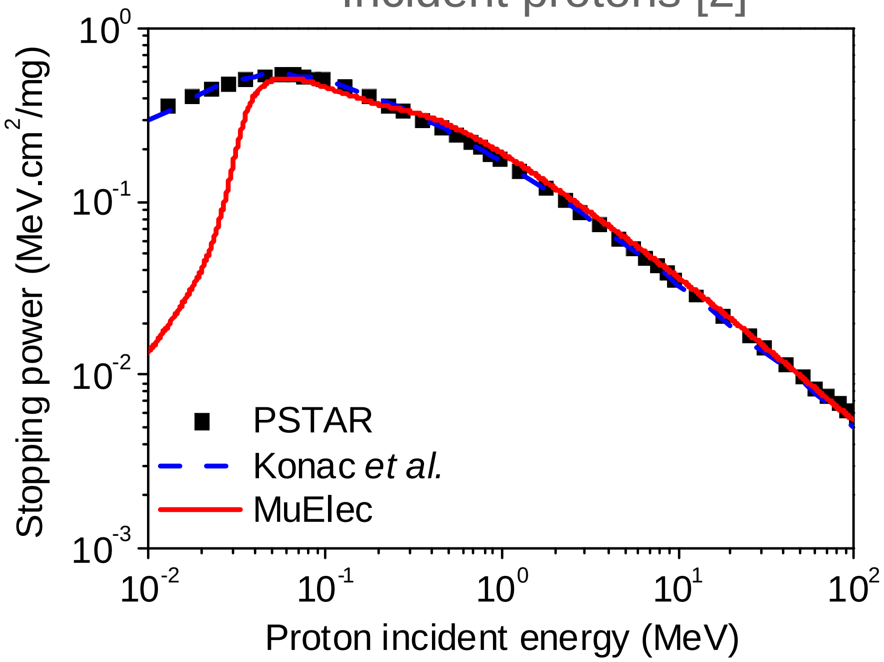

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⇒ Satisfying agreement with data from literature > 50 keV **< 23 MeV**

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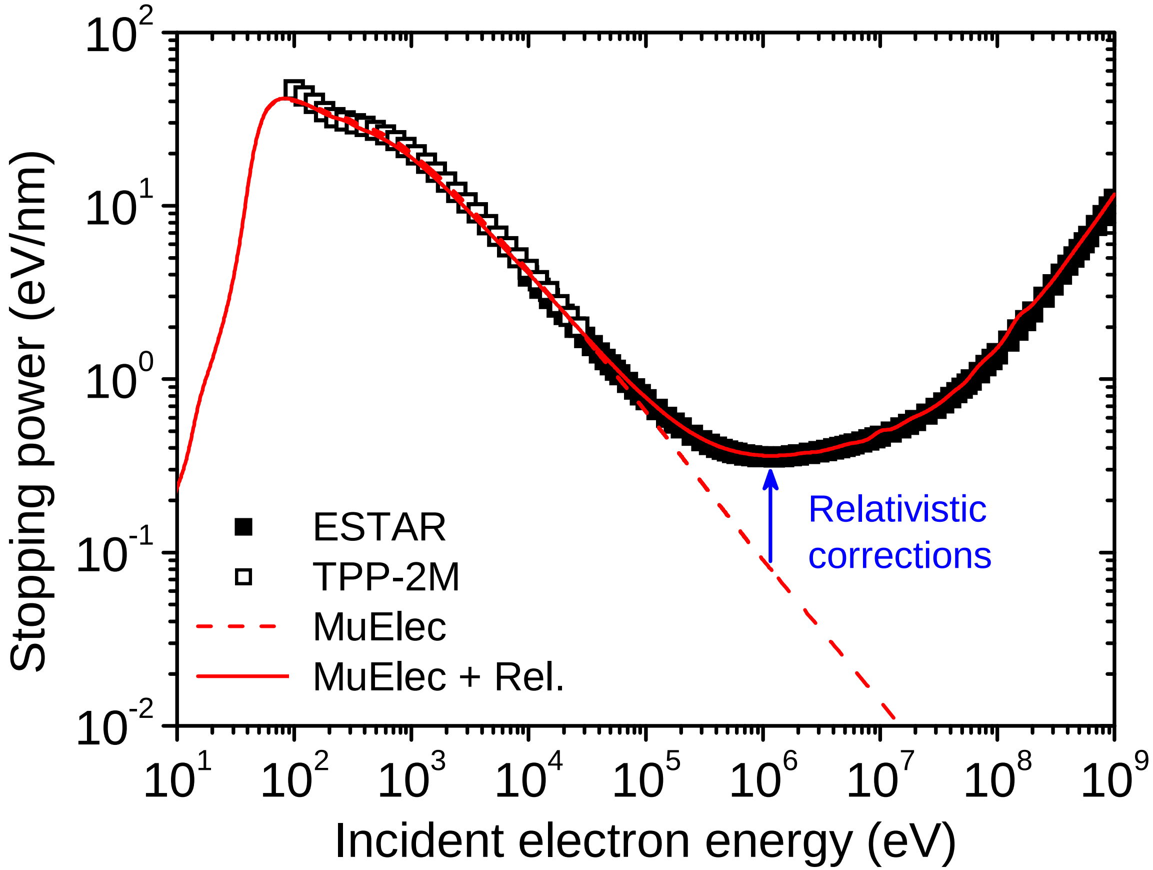
[2] A. Valentin, *et al.*, NIM B, vol. 287, pp. 124 - 129, 2012.

SOME VALIDATION / VERIFICATION RESULTS

- Including relativistic corrections:
  - Up to 1 GeV/amu for protons and heavy ions
  - Up to 100 MeV for electrons



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PROTON TRACK SIMULATION IN GEANT4

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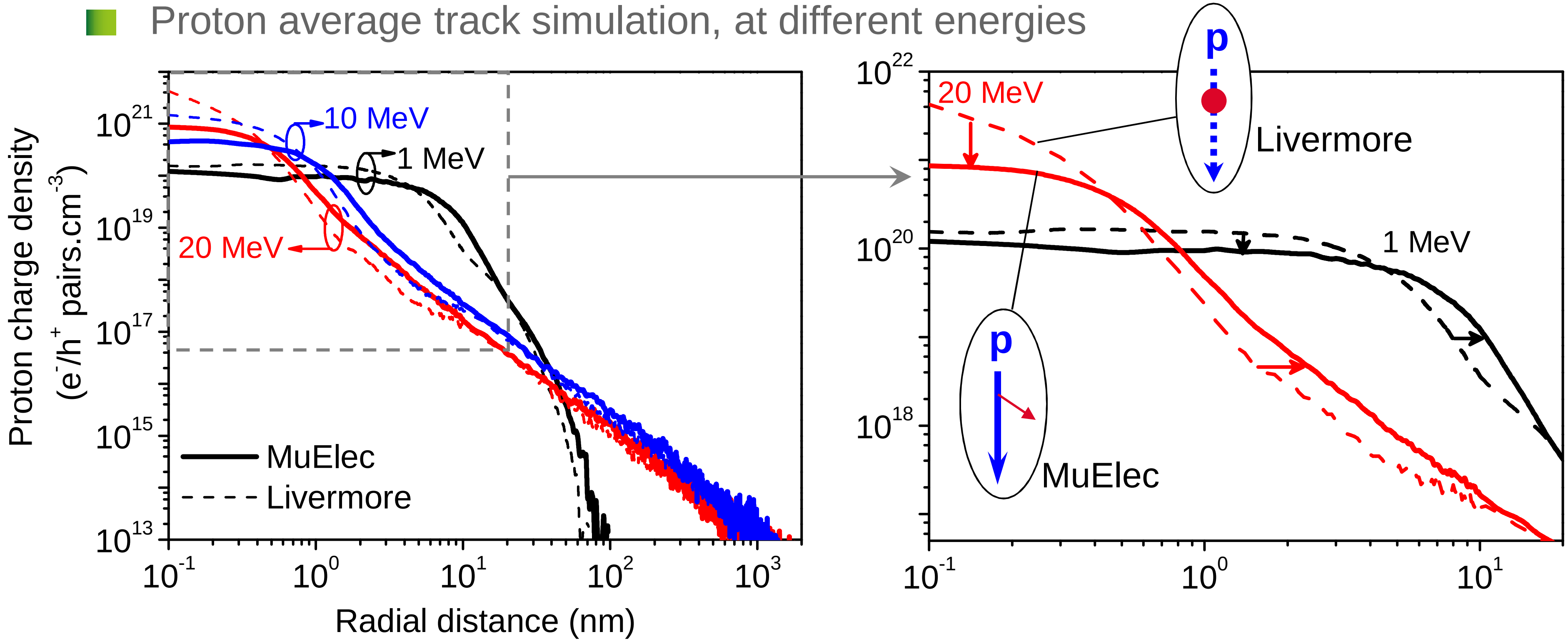
- **Comparison** between the **MuElec extension** and existing Geant4 models (**G4EmLivermorePhysics** physics list).
- Proton average track simulation, at different energies



- As expected, main differences between models in the first 10 nm.

PROTON AND ION TRACK SIMULATION IN GEANT4

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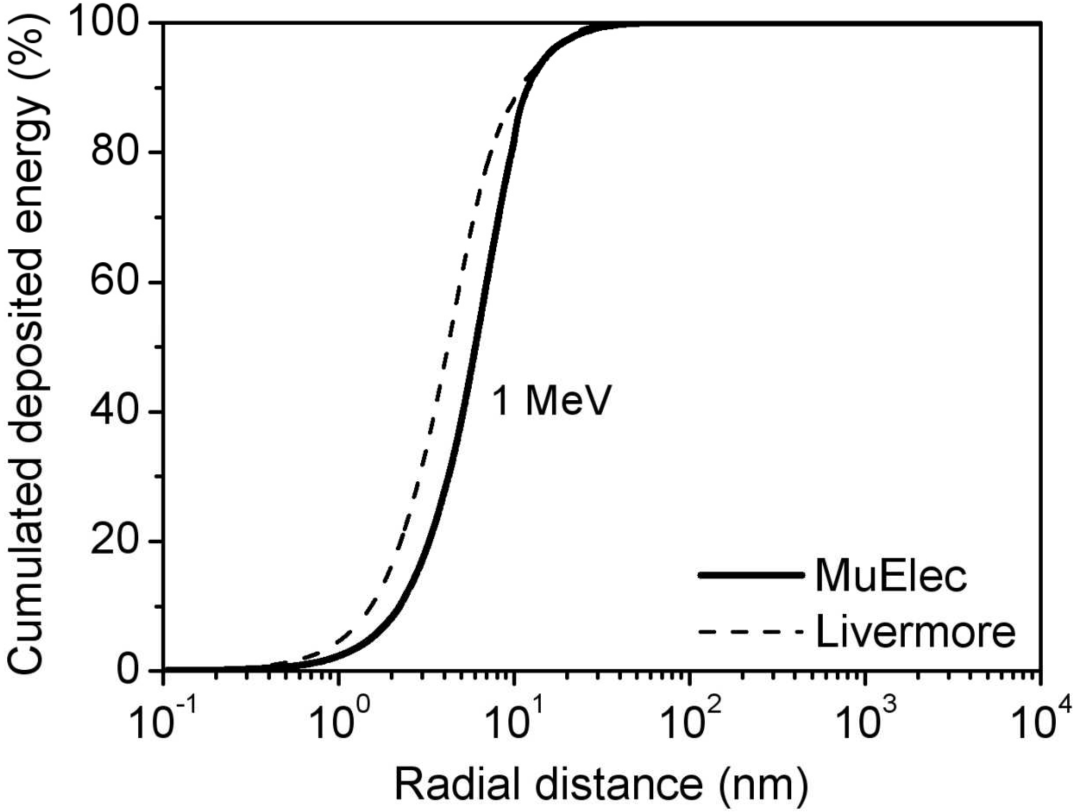
- Cumulated deposited energy:



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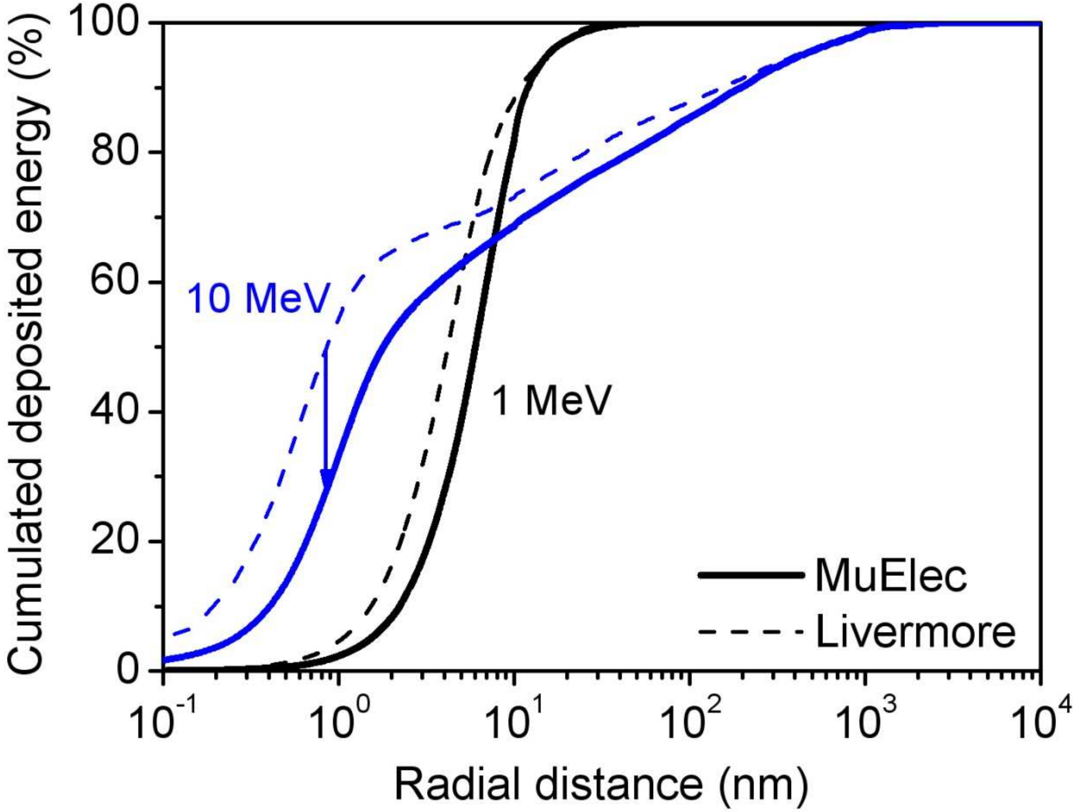

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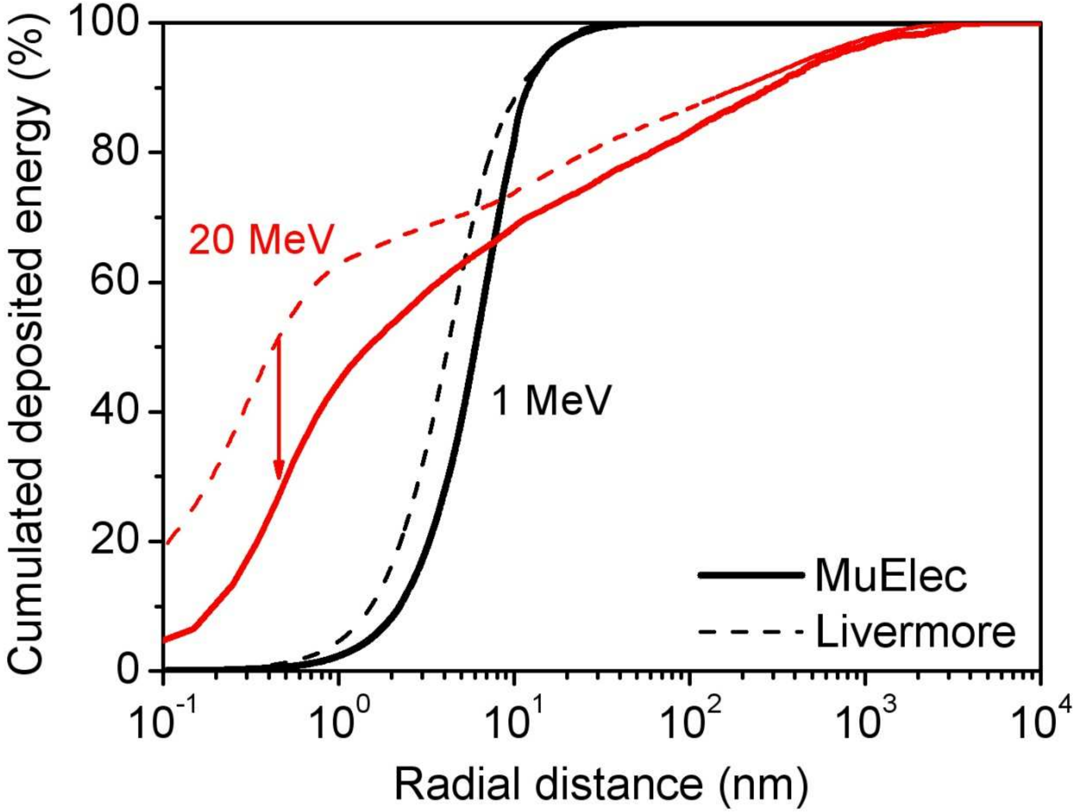

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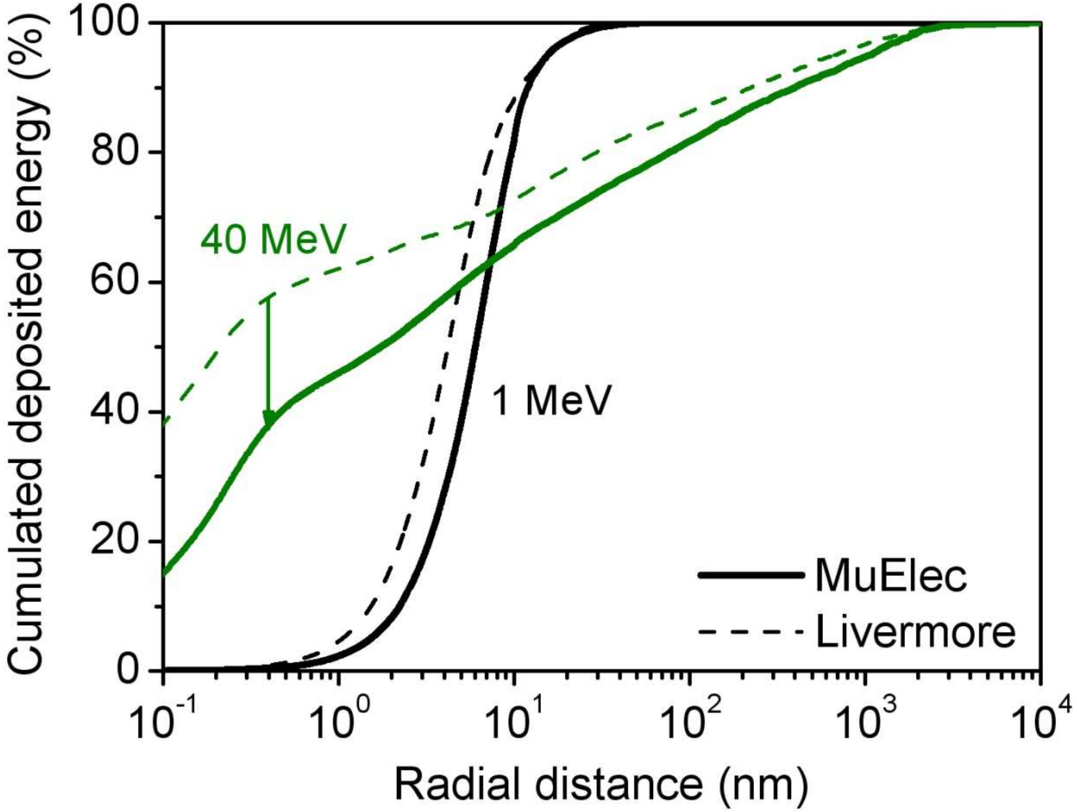

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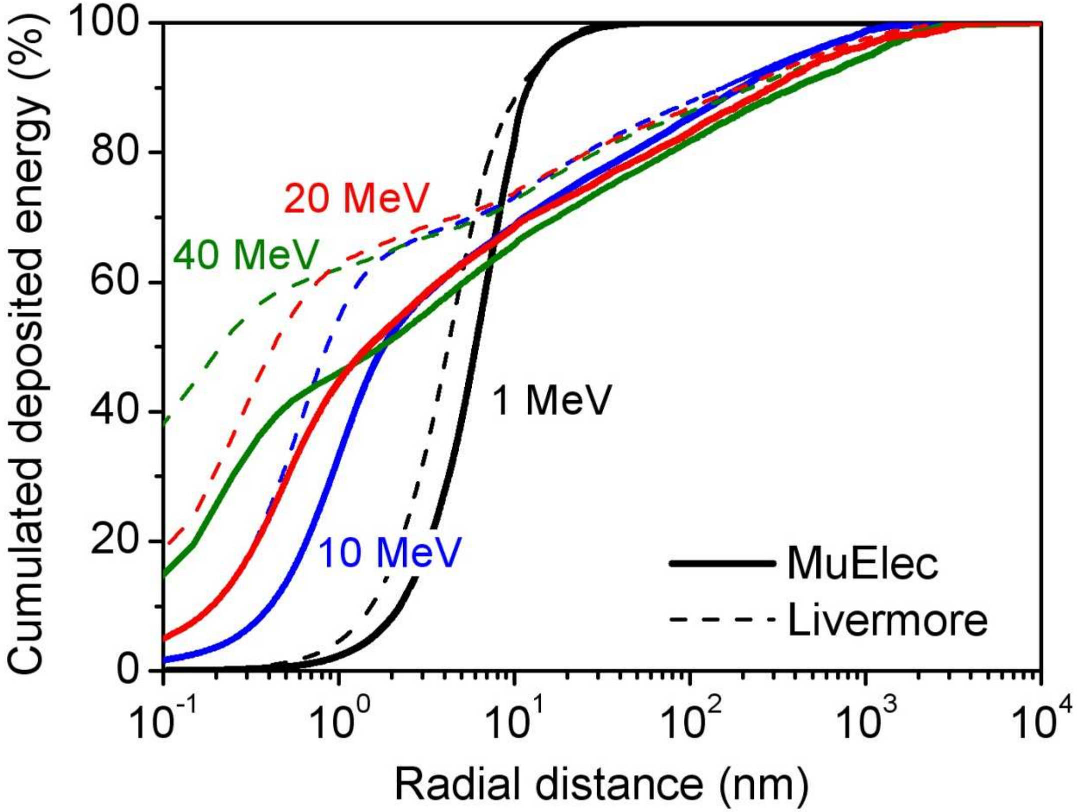


- **Increasing difference with increasing energy, located in the first 2-3 nm.**

⇒ **First application results presented at NSREC (July 2012).**

CONCLUSION AND PERSPECTIVES

CONCLUSION

- New Geant4 ionization models: **“MuElec”** extension.
- Explicit **generation of very low energy electrons**, down to 16.7 eV.

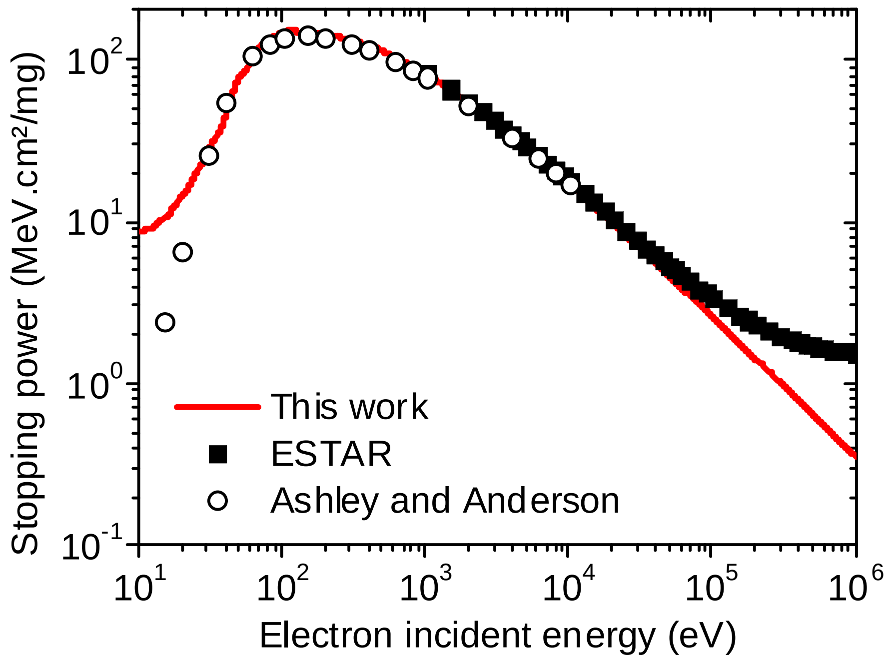
- Validated in comparison with data from literature:
  - e^-: 50 eV - 100 MeV
  - Proton/heavy ions: 50 keV/amu - 1 GeV/amu

- Two published articles describing theory, Geant4 implementation, validation/verification results
- One application article in IEEE TNS, Dec. 2012.

- MuElec web page: Accessible from the web page of the LowE EM WG
  https://twiki.cern.ch/twiki/bin/view/Geant4/LoweMuElec

PERSPECTIVES: Extension to other materials

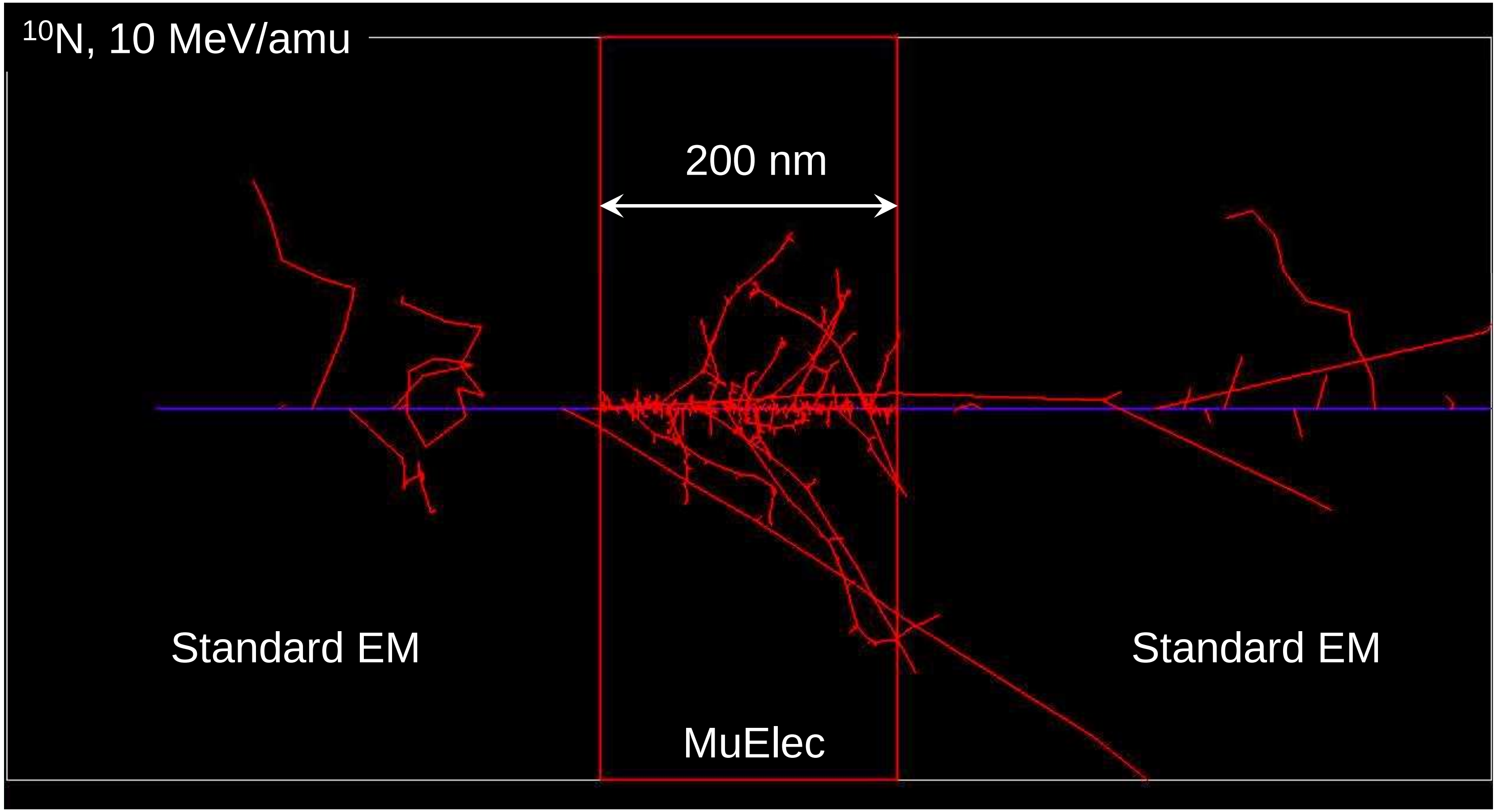
- SiO_2 in progress
  - Preliminary calculations performed



  - Need for additional validation
  - To be implemented in Geant4
- In contact with other teams to develop MuElec for additional materials: dielectrics (ONERA), gold (MGH)

PERSPECTIVES

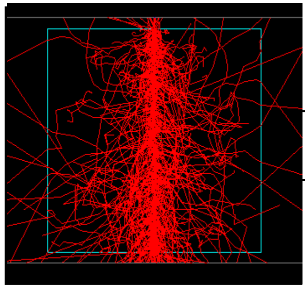
- Release of a user example and a dedicated physics constructor to show how to combine Standard EM or Low Energy EM processes with MuElec Physics processes (similar to **microdosimetry** example)



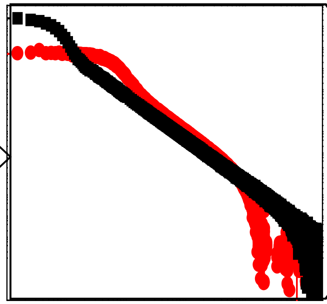
TCAD SIMULATION

- **MuElec and G4EmLivermorePhysics tracks in TCAD simulations**

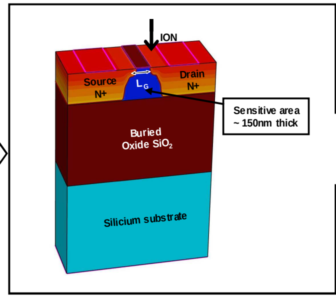
Geant4 Simulation (Monte Carlo)



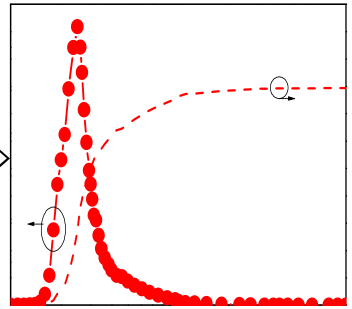
Track structure



Synopsys Simulation



Response of the transistor (isolated device)



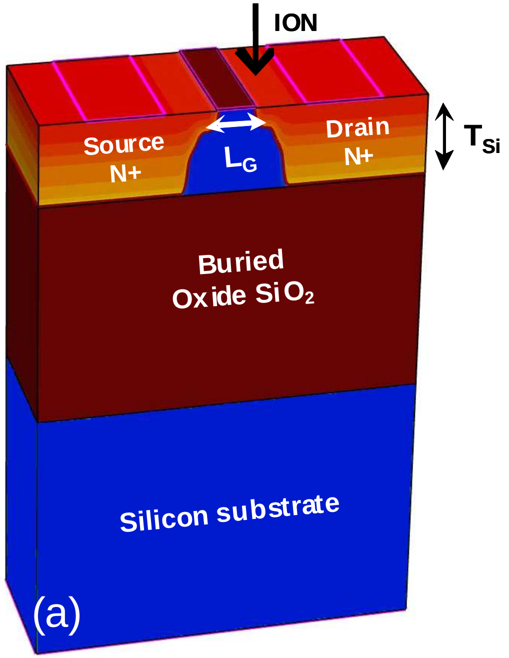
Particule-matter interaction

TCAD Simulation

- ^{78}Kr ions, different energies: 5, 10, 15 and 23 MeV/amu + 40 MeV/amu
- Different transistor structures

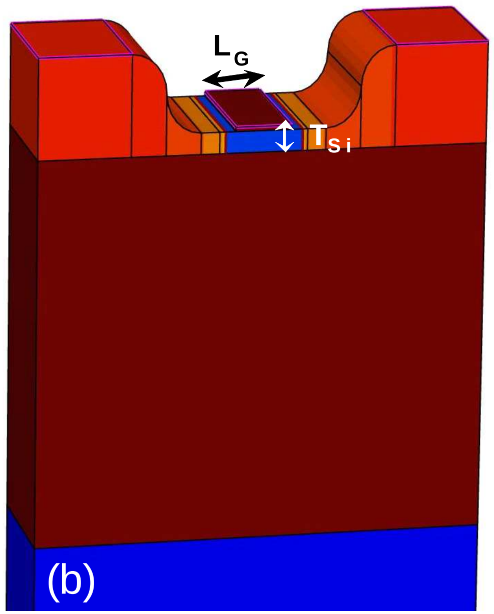
TCAD SIMULATION

70 nm PDSOI



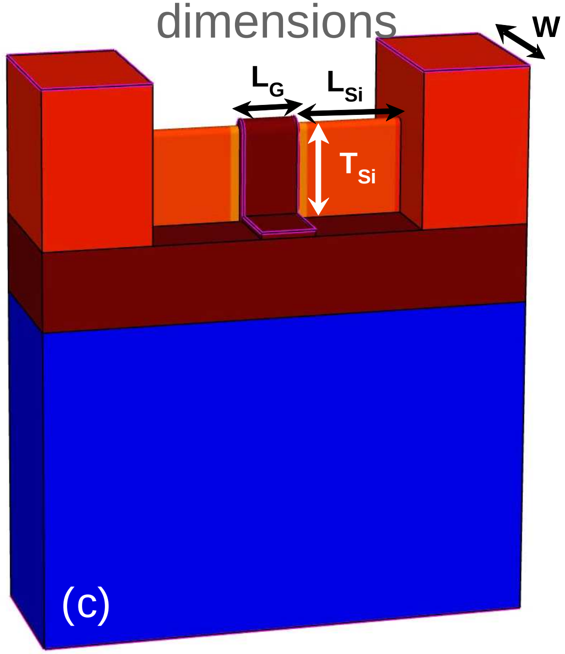
L_G = 70 nm
T_{Si} = 150 nm

24 nm FDSOI



L_G = 24 nm
T_{Si} = 8 nm

SOI FinFETs with varying dimensions



L_G = 20 nm
LSi = 100; 40 nm
WSi = 10; 5 nm
TSi = 50; 30; 12 nm

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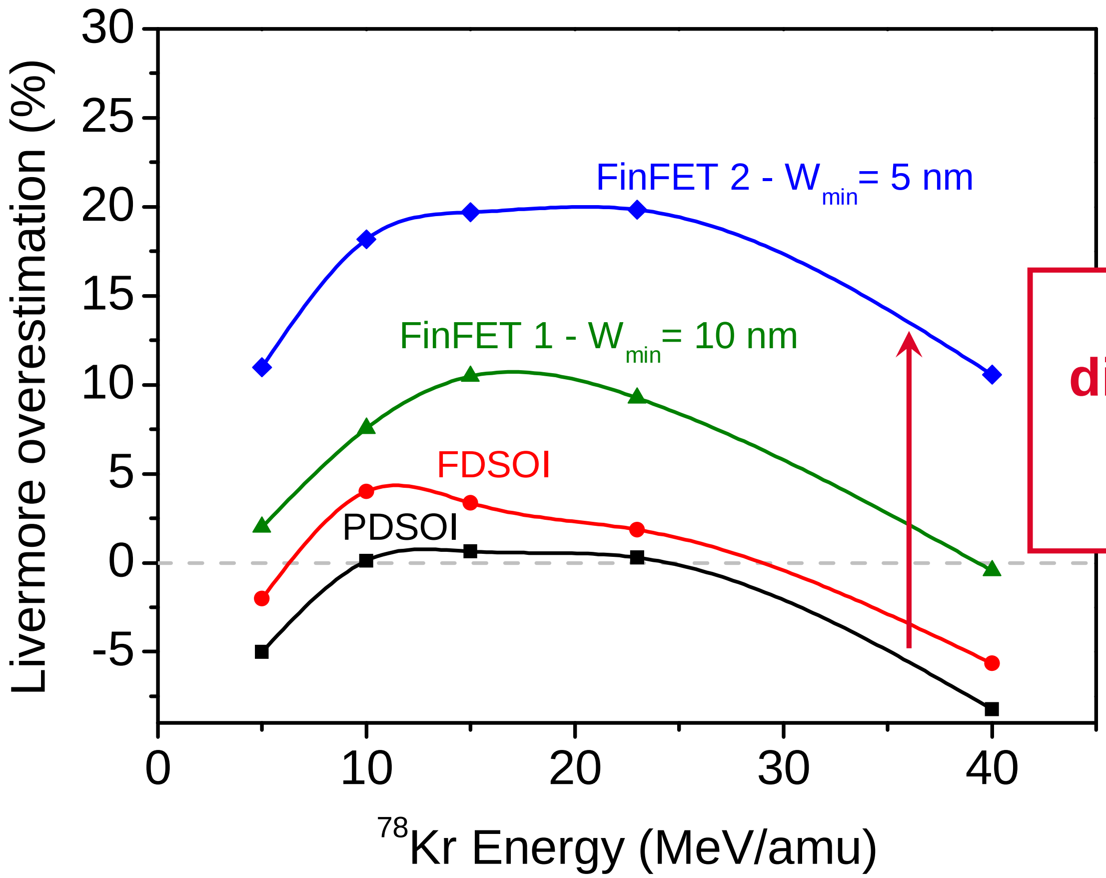
- MuElec and G4EmLivermorePhysics tracks in TCAD simulations
- Results as percentage difference between the two approaches:



Increasing difference with technology integration

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