DE LA RECHERCHE À L'INDUSTRIE

The MuElec extension for microdosimetry in silicon

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OUTLINE

Context and motivation

Brief description of the theory

Implementation in Geant4: The MuElec extension

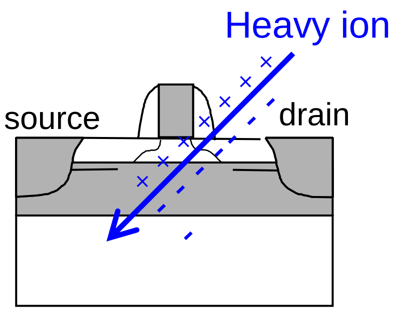
Some validation results

Proton track simulation in Geant4

Conclusion and Perspectives

CONTEXT: Study of electronic components under irradiation

- Passage of a single ion in a transistor's sensitive area:
  - Energy loss by (direct) ionization
  - Generation of electron-hole pairs
  - Transport/collection in semiconductor
  - SEE = Single-Event Effect



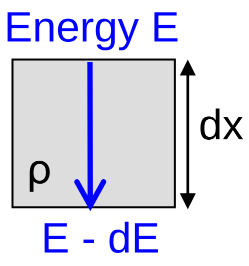
- SEE = Functional anomaly or destructive effect in an electronic component, due to a single particle crossing the device.

- Examples of SEE:
  - Non-destructive effects: Corruption of a single bit in a memory array (SEU).
    Propagation of a transient parasitic signal (SET).
  - Destructive effects: Rupture of the gate oxide (SEGR).
    Burnout of a power device (SEB).
  - Destructive or not: Single-Event Latch-up (SEL).

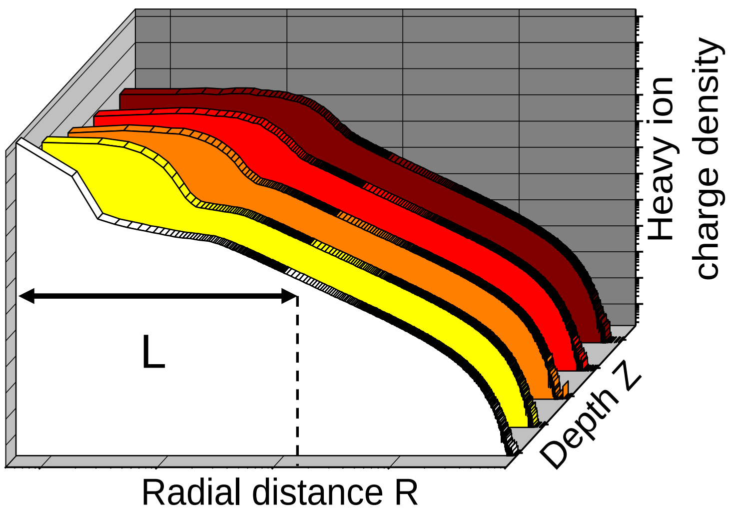
CONTEXT: Need to take into account radial dimension of the ion track

- 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

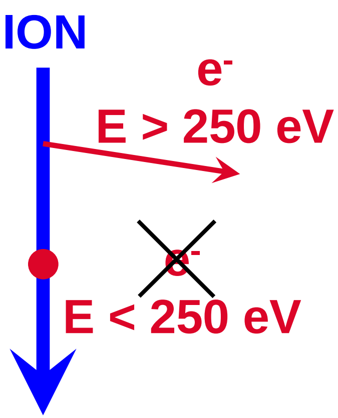


⇒ **Heavy-ion induced SEE simulation in advanced devices requires the accurate description of radial ionization profiles.**

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 last Geant4 release (v9.6 beta, June 2012).**

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

BRIEF DESCRIPTION OF THE THEORY

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BRIEF DESCRIPTION OF THE THEORY

- 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:

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

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

  - Total Cross Section:

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

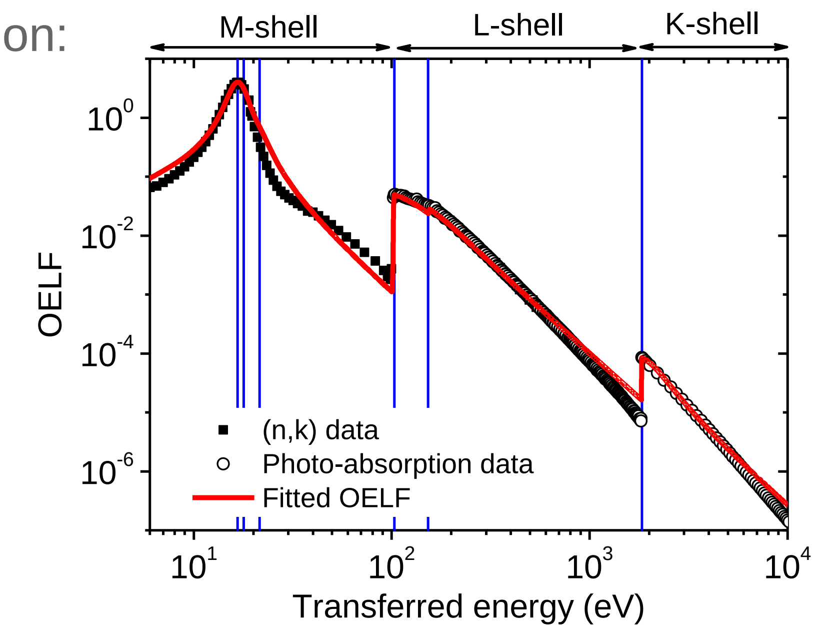
  - Stopping power:

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

[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: $E_j(q) = E_j + \frac{\hbar^2 q^2}{2m_e}$



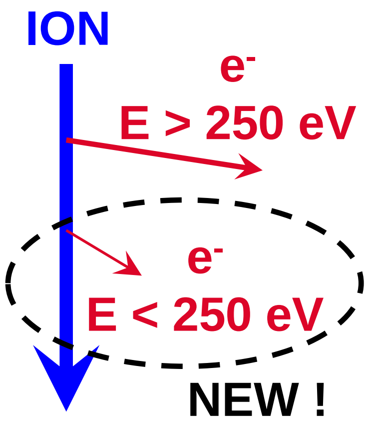
- 6 cross-sections, allowing to distinguish 6 different ionizing interactions:
  - Plasmon excitation,
  - Ejection of an electron from the 5 Si electronic shells:

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

DESCRIPTION OF THE MUELEC EXTENSION

- 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.



IMPLEMENTATION IN GEANT4: THE MUELEC EXTENSION

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

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

Process	Model	Interaction	Particle	Energy range
G4MuElecInelastic	G4MuElecInelasticModel	Ionization	e^-	16.7 eV - 50 keV
			Proton Heavy ion	50 keV/amu - 23 MeV/amu
G4MuElecElastic	G4MuElecElasticModel	Elastic scattering	e^-	16.7 eV - 50 keV

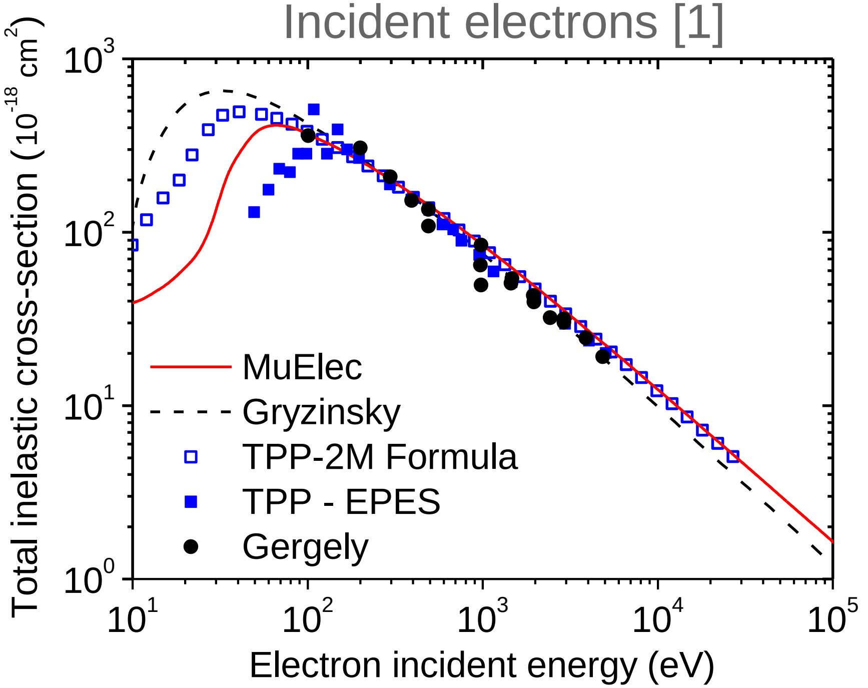
  - 2 additional classes: G4MuElecCrossSectionDataSet
    G4MuElecSiStructure
  - Tabulated total and differential cross sections in **G4EMLOWX.Y**

SOME VALIDATION RESULTS

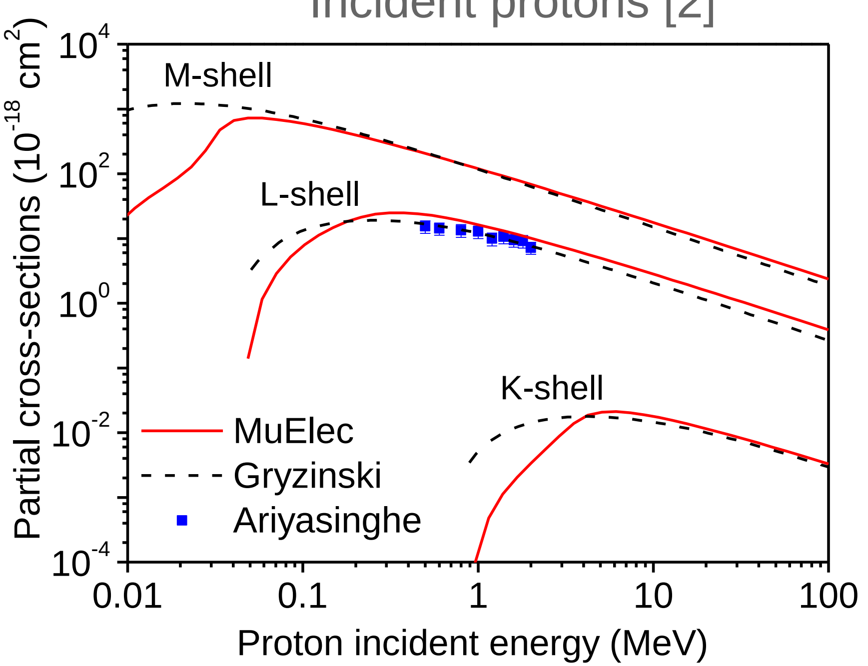
SOME VALIDATION / VERIFICATION RESULTS

- Inelastic cross-section

Incident electrons [1]



Incident protons [2]



⇒ 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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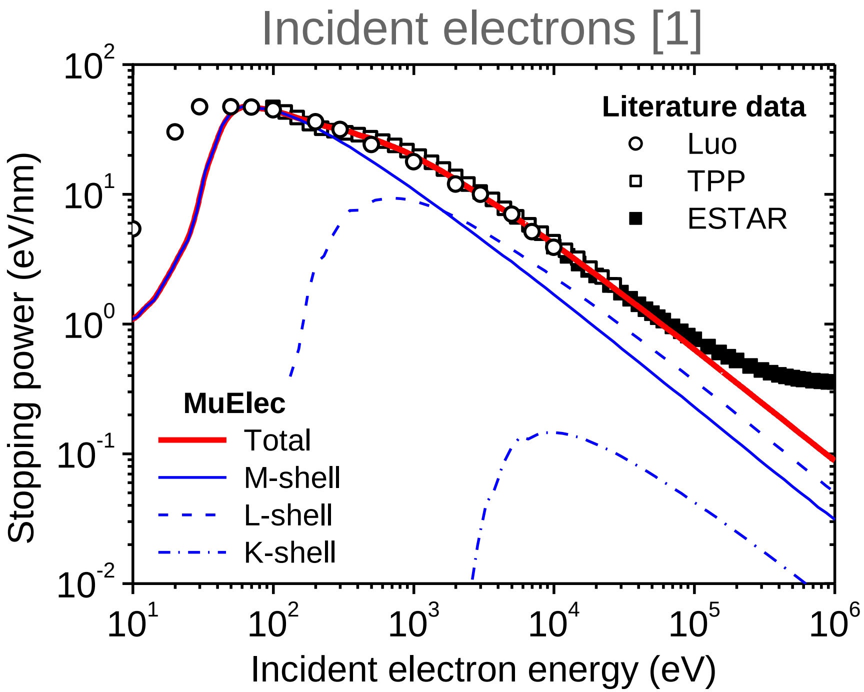
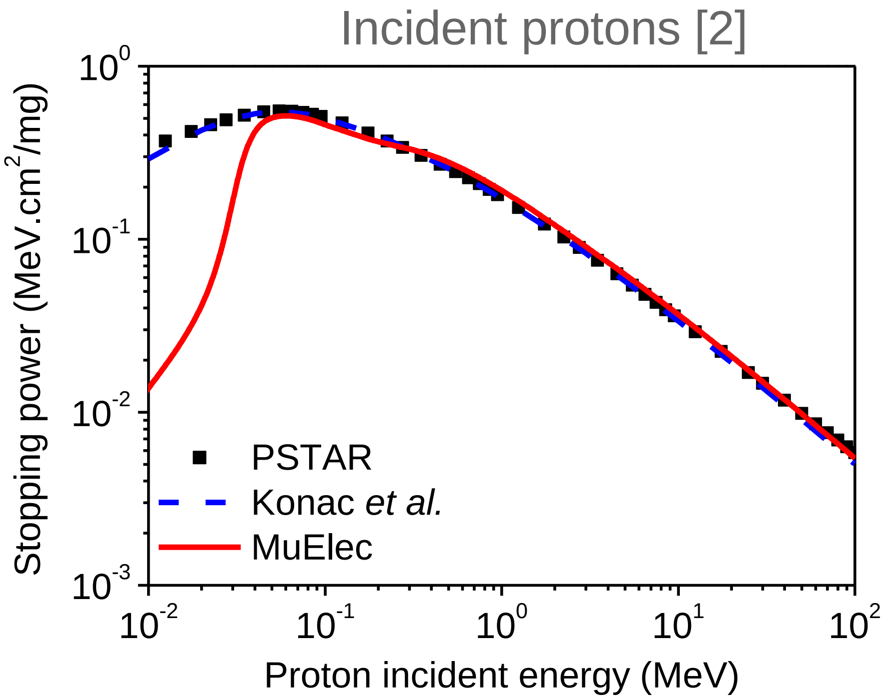
- Stopping power





⇒ Satisfying agreement with data from literature > 50 eV and **< 50 keV**

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Stopping power

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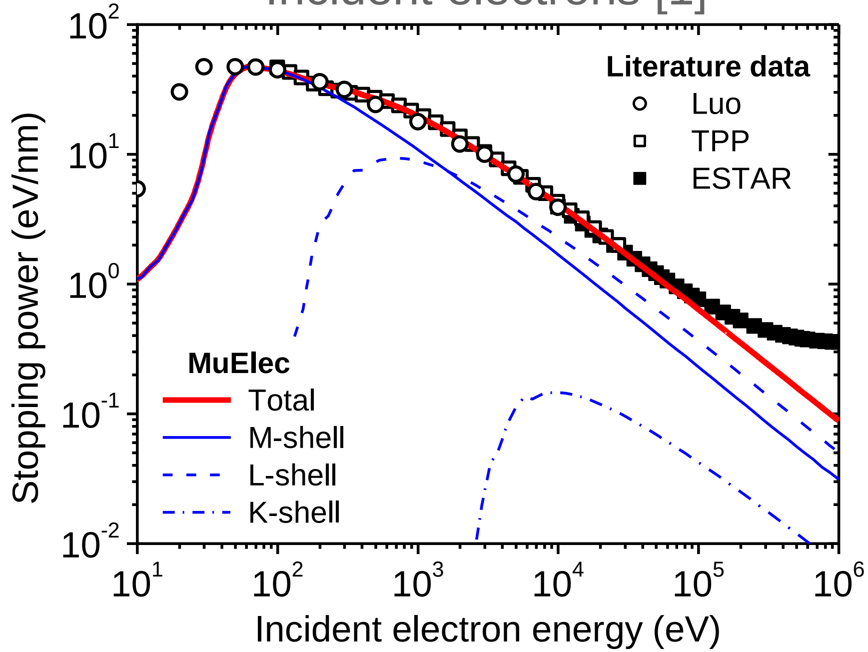

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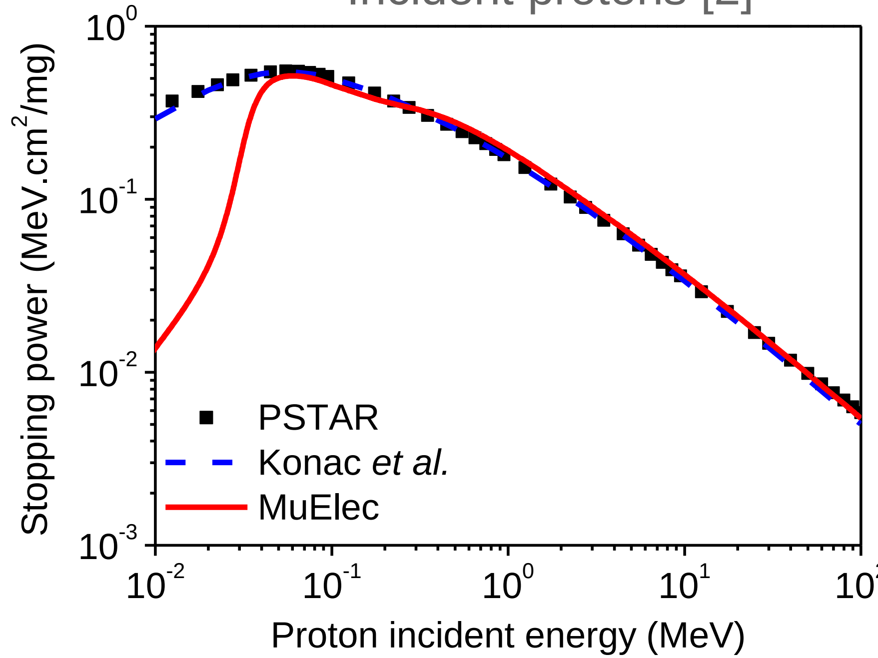

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⇒ Satisfying agreement with data from literature > 50 keV **< 23 MeV**

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PROTON TRACK SIMULATION IN GEANT4

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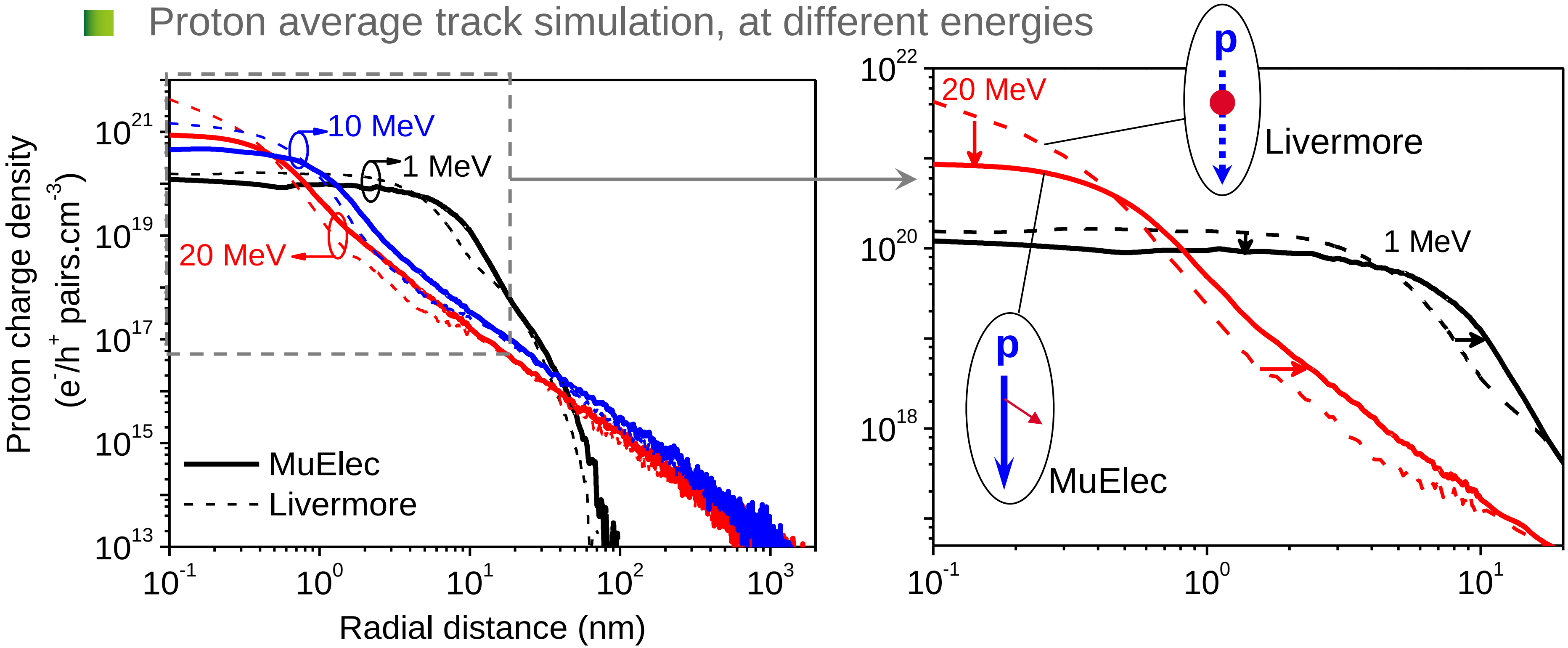
- **Comparison** between the **MuElec extension** and existing Geant4 models (**G4EmLivermorePhysics** physics list).
- Proton average track simulation, at different energies



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

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

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➢ **Conclusion and Perspectives**

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 - 50 keV
  - Proton/heavy ions: 50 keV/amu - 23MeV/amu

- Two published articles describing theory, Geant4 implementation, validation/verification results
- One application article under review in IEEE TNS

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

PERSPECTIVES

- Corrections need to be applied to widen the energy range of application:
  - Electron-electron exchange effects < 50 eV ☹ *(not better)*
  - Relativistic corrections for higher energies ☺ *(up to 1 GeV/amu)*

- Properly taking into account plasmon excitation ???

- Extension to other microelectronics materials: SiO2 in progress

- To be checked: Combination of Standard EM or Low Energy EM processes with MuElec Physics processes

- Development of a dedicated physics constructor
- Development of a user example

- Adaptation to be used in Geant4-MT ?

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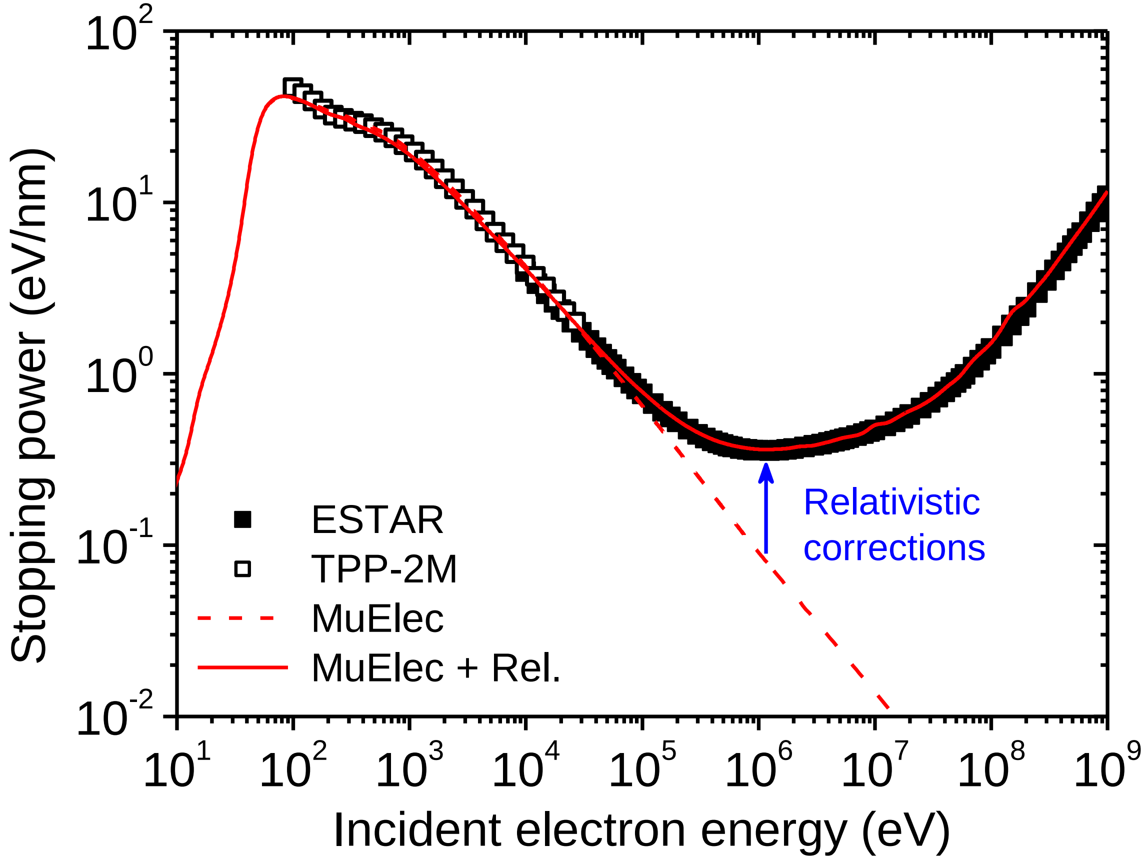

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