Correlations of direct ionization effects from low-E protons to energetic heavy ions

17-19 May, 2021
RADSAGA Final Conference and Industrial event

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RADiation and Reliability Challenges for Electronics used in Space, Aviation, Ground and Accelerators (RADSAGA) is a project funded by the European Commission under the Horizon2020 Framework Program under the Grant Agreement 721624. RADSAGA began in Mars 2017 and will run for 5 years.

Presentation outline

- General Objective
- Stopping Force Model
- Proton Direct Ionization Cross Section Model
- Proton Direct Ionization Test Guidelines

General Objective

- From GA:
  - "To study direct ionisation effects caused by low - energy protons as w ell as energetic heavy ions.... for space systems low -E proton sensitivity is a major reliability concern since their flux is large at low Earth orbits. Also at ground level, low-E singly charged particles such as protons or muons could have a significant impact on the SEU rate...."
- To build simple models to estimate (LEP-induced) SEUs and consecutively expedite the SER estimations for modern technologies

Stopping Force Model

- Combination of two (or three) models of electronic stopping force
  - Covering the low (Firsov or LSS), intermediate (Bohr), and high (Bethe) energies/velocities
- Modification and parametrisation of the stopping number equation from Bloch
  - Allows for smooth transition from *low* to *high* velocities with a single equation
  - Empirical parameterization
- Fitting the parameters to experimental data
  - Data provided by the Nuclear Data Service of the International Atomic Energy Agency (database originally collected and maintained by prof. Helmut Paul)

Stopping Force Model

Electronic stopping force (or Linear Energy Transfer)

$$-\left.\frac{dE}{dx}\right|_e = N \cdot S,$$

Where N = *target atomic density*, and *stopping cross-section* is

$$S = 4\pi Z_1^2 Z_2 \left(\frac{v_0}{v}\right)^2 2\mathrm{R}a_0^2 L$$

Stopping number

Stopping Force Model

Bloch's model (from textbooks) gives the stopping number as

$$L_{Bloch} = \ln\left(\underbrace{C\frac{m_e v^3}{Z_1 I v_0}\frac{1}{\sqrt{1+\left(\frac{Cv}{2Z_1 v_0}\right)^2}}}_{\chi_{Bloch}}\right)$$

At low (or intermediate) velocities

$$L_{Bloch} \approx \ln\left(C\frac{m_e v^3}{Z_1 I v_0}\right) \equiv L_{Bohr}$$

At high velocities

$$L_{Bloch} \approx \ln\left(\frac{2m_e v^3}{I}\right) \equiv L_{Bethe}$$

BUT DOES NOT WORK FOR $v \rightarrow 0$

Stopping Force Model

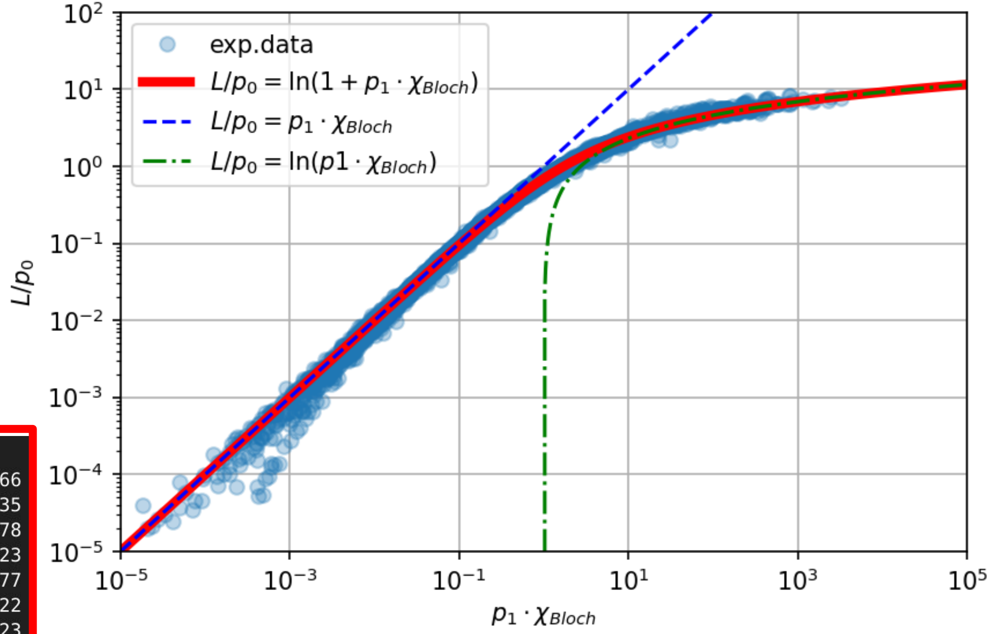
Low velocity issue solved by

$$L_{model} = p_0 \cdot \ln\left(1 + p_1 \chi_{Bloch}\right)$$

Just need to fit to the data

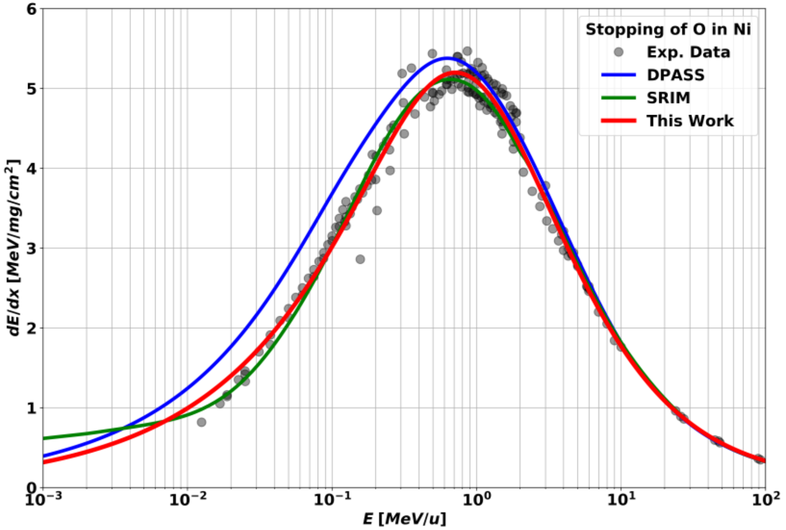
Proj	Trgt	Z1	Z2	p0	p1
He	Cu	2	29	1.23018	0.45466
F	Ti	9	22	0.92597	0.55335
Si	C	14	6	1.19375	0.27578
O	Ag	8	47	0.82555	0.87323
F	Ag	9	47	0.94510	0.74877
C	Ta	6	73	0.86102	0.83822
N	Si	7	14	0.83954	0.62323
Al	Al	13	13	1.17878	0.19577

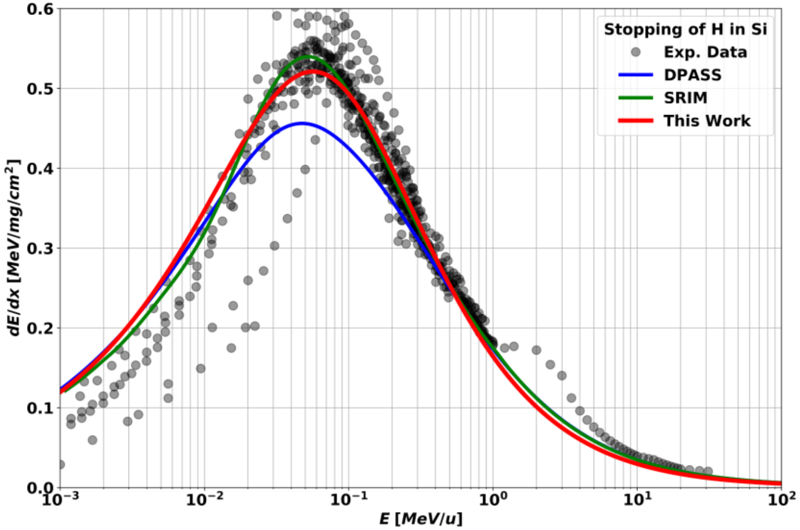
Universal plot



Stopping Force Model

Accuracy of the model comparable to other established stopping force models





Stopping Force Model

Comparison between different models for *H, He, O, Ar, Kr,* and *Xe* projectiles in *C, Al, Si,* and *Ni* targets (model vs. experimental data)

	Low (<0.1 MeV/u)	Intermediate (0.1-10 MeV/u)	High (>10 MeV/u)	Full
N_{data}	1859	3163	190	5212
This Work	-8.26 ± 28.47	2.08 ± 8.84	11.63 ± 20.80	-1.26 ± 19.56
SRIM	-10.23 ± 37.44	1.70 ± 8.25	8.51 ± 18.48	-2.32 ± 24.28
DPASS	-19.21 ± 39.15	2.94 ± 12.97	6.60 ± 19.60	-4.83 ± 27.89

[SRIM]: Semi-empirical estimates developed by Ziegler *et al.* (http://www.srim.org/)
[DPASS]: *Ab initio* calculations developed by P. Sigmund *et al.* (https://www.sdu.dk/en/dpass)

Stopping Force Model

- Pros:
  - Simple equations and only a few parameters
  - Easy to implement anywhere (compared to e.g. SRIM)
  - Open source
  - Public Python package in progress

- Cons:
  - Currently parameters (p_0,p_1) from lookup tables and interpolation
  - Uncertainties for projectile-target combinations outside current experimental (Z_1, Z_2) space

Proton Direct Ionization Cross Section Model

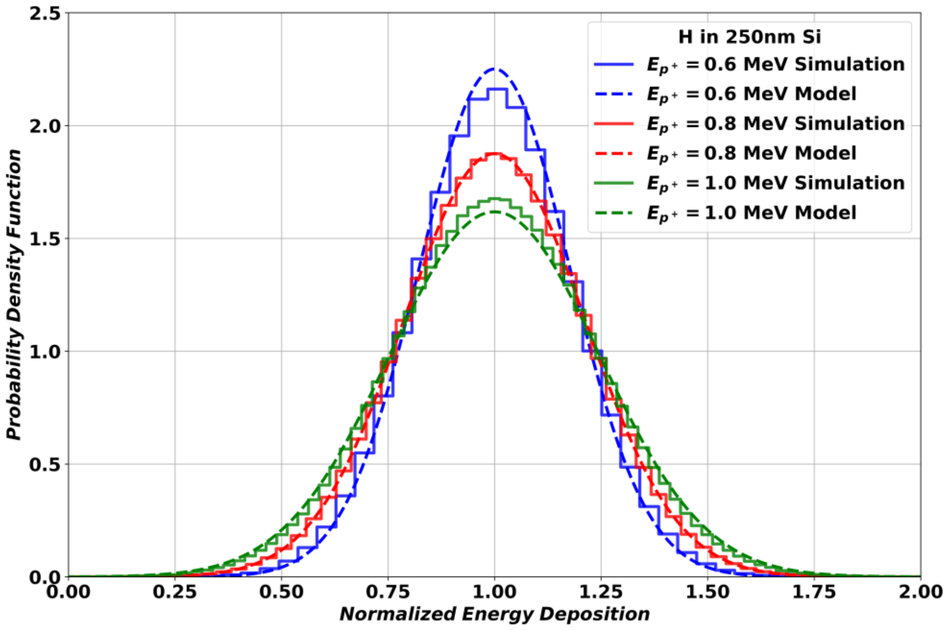
- Combination of the stopping force model with straggling model [1]

- Estimation of ***mean*** and ***variance*** of energy deposition inside sensitive volume (SV) after BEOL
  - With *critical charge* (*Qcrit*) it provides estimates for SEU cross-section
    ...or more importantly by flipping the procedure…
  - From experimental SEU data, one can estimate:
    SV size, ***BEOL thickness***, and ***Qcrit***

[1] A. Javanainen et al. "Semi-Empirical Model for SEGR Prediction", IEEE TNS, vol. 60, pp. 2660 Aug. 2013

Proton Direct Ionization Cross Section Model

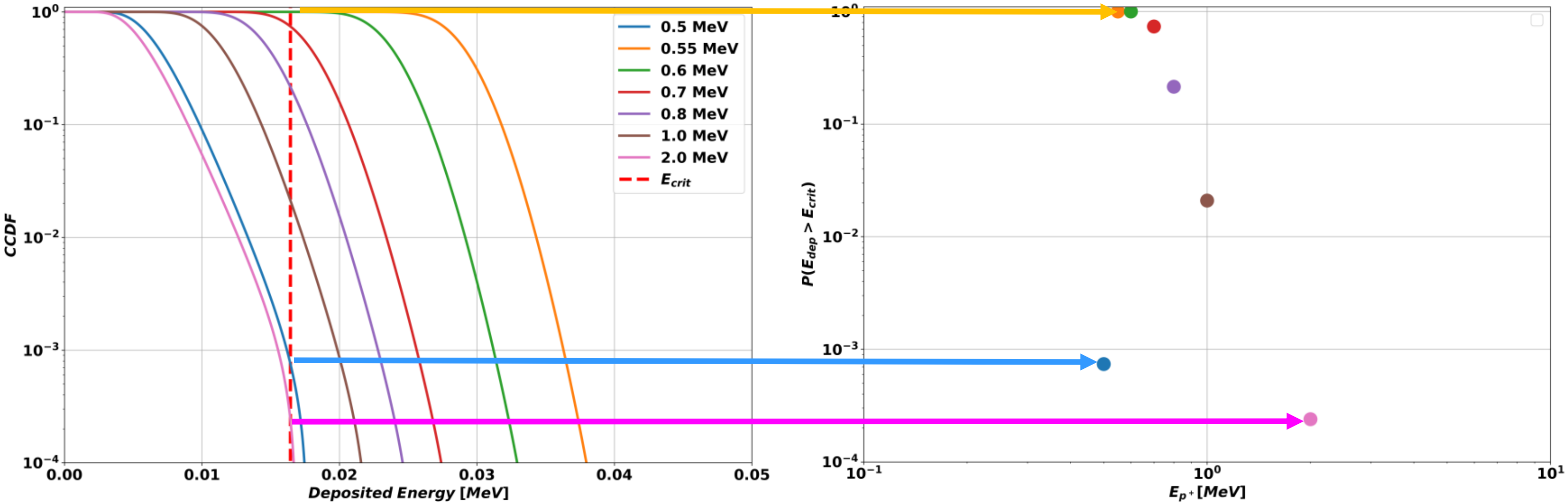
Straggling model vs. Geant4 simulations



Proton Direct Ionization Cross Section Model

From *tail distributions* for energy deposition…

…to deduce the SEU x-section vs. energy



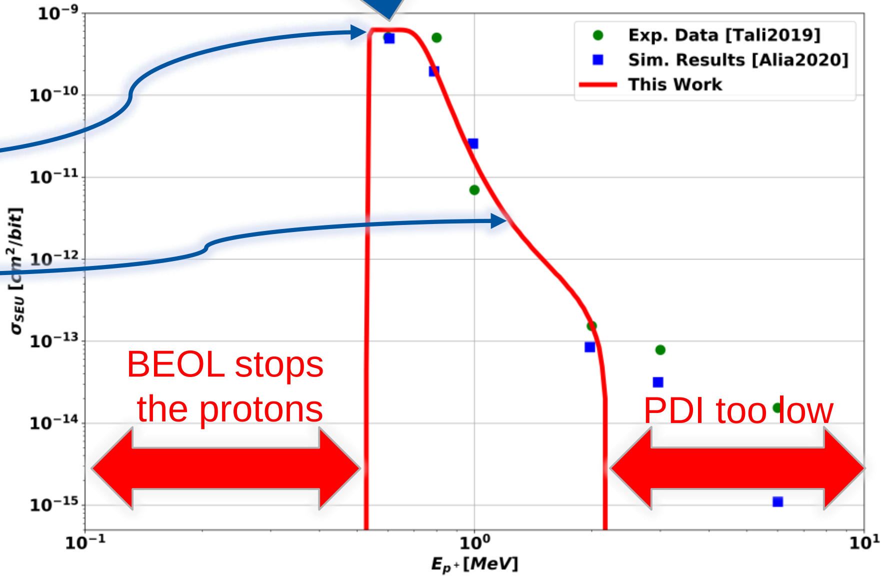
CCDF = ***Complementary Cumulative Density Function*** or ***Tail distribution***

Proton Direct Ionization Cross Section Model

Energy @ peak --> BEOL

Max. xsection --> aSV (lateral dims. For SV)

Peak shape --> hSV (thickness of SV) + Qcrit



Proton Direct Ionization Cross Section Model

- Numerical approach to determine PDI cross sections as a function of (E_p, *SV size, BEOL*, Q_{crit}) or ***vice versa (via minimization)***

- Reduces the need of Monte Carlo simulations
  - Easier to implement
  - ***Less time consuming***

- Plans to implement similar approach for heavy-ion cross sections as well

- Public Python package in progress

Proton Direct Ionization Test Guidelines

- ESA-funded project with ALTER Technologies
  - Started in 2020
  - "*Estimation of proton induced Single Event Effect rates in very deep submicron technologies*"
    - SEE test procedures with LEP shall be defined in order to obtain meaningful and reproducible test results
    - Standard method to estimate the in-flight SEE rates induced by proton via direct ionization shall be defined in order to get accurate and reliable predictions.
- The developed model(s) will be utilized in this study
- Includes both experiments and simulations

THANK YOU

Any questions?

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