# Numerical study of the effect of secondary electron emission on the dynamics of electron clouds in gyrotron guns

S. Guinchard[1], G. Le Bars[2]

[1] Ecole Polytechnique Fédérale de Lausanne (EPFL), Physics Section (SPH), CH-1015 Lausanne, Switzerland
[2] Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

October 13, 2022

# Problem description

- Code espic2D does not take account (yet) for secondary electron emissions, induced by ions collected at the electrodes. Let us denote these ion-induced electron emissions by IIEE from now on.
- Goal: Implement a module to add those IIEE to espic2D

# Model to be used

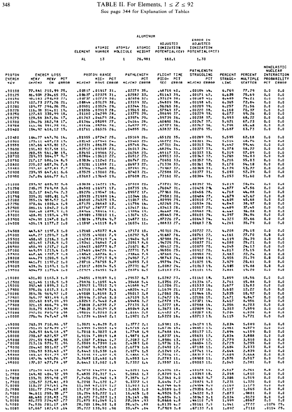
- We seek an expression for the **electron yield** $\gamma$
- It is expected that $\gamma$ depends on the **incident particle energy**, the target density i.e a **material parameter** including cross sections for particle interactions, as well as **transport phenomena** occurring for produced electrons.
- Semi-empirical model: **Schou** (1988) [Hassel92]

$$\gamma = \Lambda \cdot \beta \cdot \left.\frac{dE}{dx}\right|_e \tag{1}$$

- In the above Eq.(1), $\Lambda$ includes the cross sections for collisions with energy deposition, $\beta$ accounts for energy transport by recoil electrons, and $dE/dx$ corresponds to the energy deposed in the solid by the ion colliding with electrons (subscript $e$).

# Empirical values for model parameters

- Research of tabulated values (semi-empirical model) for the physical parameters:
  - $dE/dx$ from [Janni]
  - $\beta$ and $\Lambda = \Lambda_{exp}$ from [Hassel92]



348

TABLE II. For Elements, $1 \le Z \le 92$

See page 344 for Explanation of Tables

ALUMINUM

| ELEMENT | ATOMIC NUMBER | ATOMS/MOLECULE | ATOMIC WEIGHT | ADJUSTED IONIZATION POTENTIAL(EV) | ERROR IN ADJUSTED IONIZATION POTENTIAL(PCT) |
|---|---|---|---|---|---|
| AL | 13 | 1 | 26.981 | 160.1 | 1.30 |

| PROTON ENERGY MEV | ENERGY LOSS MEV/GM/CM2 | ENERGY LOSS MEV/CM | ENERGY LOSS PCT ERROR | PROTON RANGE MG/CM2 | PROTON RANGE MICRONS | PROTON RANGE PCT ERROR | PATHLENGTH MG/CM2 | PATHLENGTH PCT ERROR | FLIGHT TIME PICO-SEC | FLIGHT TIME PCT ERROR | PATHLENGTH STRAGGLING MG/CM2 | PATHLENGTH STRAGGLING PCT ERROR | PERCENT STRAGG-LING | PERCENT MULTIPLE SCATTER | NONELASTIC NUCLEAR INTERACTION PROBABILITY PCT | NONELASTIC NUCLEAR INTERACTION PROBABILITY ERROR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| .00100 | 77.841 | 210.09 | 25. | .00517 | .01917 | 31. | .02278 | 35. | .48715 | 40. | .00154 | 44. | 6.769 | 77.29 | 0.0 | 0.0 |
| .00125 | 86.938 | 234.65 | 23. | .00627 | .02325 | 31. | .02582 | 33. | .51143 | 39. | .00171 | 42. | 6.620 | 75.69 | 0.0 | 0.0 |
| .00150 | 95.163 | 256.85 | 22. | .00737 | .02729 | 30. | .02856 | 32. | .53129 | 38. | .00185 | 41. | 6.485 | 74.21 | 0.0 | 0.0 |
| .00175 | 102.73 | 277.26 | 21. | .00844 | .03129 | 30. | .03109 | 32. | .54809 | 38. | .00198 | 40. | 6.365 | 72.84 | 0.0 | 0.0 |
| .00200 | 109.77 | 296.28 | 20. | .00951 | .03524 | 29. | .03344 | 31. | .56265 | 38. | .00209 | 39. | 6.257 | 71.56 | 0.0 | 0.0 |
| .00225 | 116.38 | 314.11 | 19. | .01056 | .03913 | 28. | .03565 | 30. | .57549 | 37. | .00220 | 38. | 6.160 | 70.37 | 0.0 | 0.0 |
| .00250 | 122.63 | 330.99 | 18. | .01160 | .04299 | 28. | .03775 | 29. | .58699 | 37. | .00229 | 38. | 6.072 | 69.26 | 0.0 | 0.0 |
| .00275 | 128.58 | 347.04 | 17. | .01263 | .04679 | 28. | .03974 | 29. | .59739 | 36. | .00238 | 37. | 5.993 | 68.22 | 0.0 | 0.0 |
| .00300 | 134.26 | 362.38 | 17. | .01364 | .05055 | 27. | .04164 | 28. | .60690 | 36. | .00247 | 37. | 5.921 | 67.23 | 0.0 | 0.0 |
| .00350 | 144.96 | 391.25 | 16. | .01564 | .05796 | 26. | .04522 | 27. | .62373 | 36. | .00262 | 36. | 5.795 | 65.40 | 0.0 | 0.0 |
| .00400 | 154.92 | 418.12 | 15. | .01761 | .06526 | 26. | .04855 | 26. | .63832 | 35. | .00276 | 35. | 5.687 | 63.73 | 0.0 | 0.0 |
| .00450 | 164.27 | 443.36 | 14. | .01955 | .07242 | 25. | .05169 | 26. | .65120 | 35. | .00289 | 35. | 5.595 | 62.18 | 0.0 | 0.0 |
| .00500 | 173.11 | 467.23 | 13. | .02145 | .07946 | 24. | .05469 | 25. | .66272 | 34. | .00301 | 34. | 5.514 | 60.76 | 0.0 | 0.0 |
| .00550 | 182.66 | 493.00 | 12. | .02331 | .08635 | 24. | .05746 | 24. | .67311 | 34. | .00313 | 34. | 5.442 | 59.44 | 0.0 | 0.0 |
| .00600 | 191.80 | 517.68 | 11. | .02512 | .09308 | 23. | .06013 | 24. | .68254 | 34. | .00323 | 33. | 5.378 | 58.22 | 0.0 | 0.0 |
| .00650 | 200.53 | 541.38 | 10. | .02690 | .09966 | 22. | .06268 | 23. | .69117 | 33. | .00333 | 33. | 5.319 | 57.09 | 0.0 | 0.0 |
| .00700 | 209.03 | 564.17 | 9.2 | .02864 | .10610 | 22. | .06512 | 23. | .69913 | 33. | .00343 | 32. | 5.265 | 56.03 | 0.0 | 0.0 |
| .00750 | 217.17 | 586.14 | 8.5 | .03034 | .11240 | 21. | .06747 | 22. | .70650 | 33. | .00352 | 32. | 5.216 | 55.03 | 0.0 | 0.0 |
| .00800 | 225.02 | 607.34 | 7.8 | .03201 | .11858 | 21. | .06973 | 22. | .71338 | 33. | .00361 | 32. | 5.170 | 54.10 | 0.0 | 0.0 |
| .00850 | 232.61 | 627.81 | 7.2 | .03364 | .12465 | 20. | .07191 | 21. | .71982 | 32. | .00369 | 31. | 5.129 | 53.22 | 0.0 | 0.0 |
| .00900 | 239.95 | 647.61 | 6.6 | .03525 | .13060 | 20. | .07403 | 21. | .72588 | 32. | .00377 | 31. | 5.090 | 52.39 | 0.0 | 0.0 |
| .00950 | 247.04 | 666.77 | 6.1 | .03683 | .13645 | 19. | .07608 | 21. | .73160 | 32. | .00384 | 31. | 5.053 | 51.60 | 0.0 | 0.0 |
| .01000 | 253.92 | 685.32 | 5.6 | .03838 | .14221 | 19. | .07808 | 20. | .73701 | 32. | .00392 | 30. | 5.019 | 50.84 | 0.0 | 0.0 |
| .01250 | 285.25 | 769.88 | 3.6 | .04580 | .16971 | 17. | .08735 | 19. | .76047 | 31. | .00426 | 29. | 4.877 | 47.56 | 0.0 | 0.0 |
| .01500 | 312.17 | 842.54 | 2.3 | .05276 | .19547 | 16. | .09572 | 17. | .77960 | 30. | .00456 | 28. | 4.768 | 44.88 | 0.0 | 0.0 |
| .01750 | 335.31 | 905.01 | 1.5 | .05935 | .21989 | 14. | .10344 | 16. | .79583 | 30. | .00484 | 27. | 4.679 | 42.62 | 0.0 | 0.0 |
| .02000 | 355.14 | 958.52 | 1.0 | .06565 | .24325 | 13. | .11067 | 15. | .80999 | 29. | .00510 | 27. | 4.605 | 40.68 | 0.0 | 0.0 |
| .02250 | 370.64 | 1000.4 | 1.0 | .07175 | .26583 | 12. | .11756 | 14. | .82265 | 29. | .00534 | 26. | 4.543 | 38.97 | 0.0 | 0.0 |
| .02500 | 386.14 | 1042.2 | 1.0 | .07767 | .28777 | 12. | .12417 | 14. | .83413 | 28. | .00557 | 25. | 4.489 | 37.45 | 0.0 | 0.0 |
| .02750 | 398.40 | 1075.3 | 1.0 | .08344 | .30914 | 11. | .13056 | 13. | .84467 | 28. | .00580 | 25. | 4.441 | 36.08 | 0.0 | 0.0 |
| .03000 | 408.81 | 1103.4 | .99 | .08909 | .33010 | 11. | .13674 | 12. | .85445 | 28. | .00601 | 24. | 4.397 | 34.84 | 0.0 | 0.0 |
| .03500 | 424.98 | 1147.0 | 1.0 | .10014 | .37104 | 9.7 | .14872 | 11. | .87226 | 27. | .00643 | 24. | 4.323 | 32.66 | 0.0 | 0.0 |
| .04000 | 436.19 | 1177.2 | 1.0 | .11097 | .41115 | 8.9 | .16034 | 11. | .88833 | 27. | .00683 | 23. | 4.261 | 30.79 | 0.0 | 0.0 |
| .04500 | 443.62 | 1197.3 | 1.0 | .12165 | .45072 | 8.4 | .17170 | 10. | .90310 | 26. | .00722 | 22. | 4.208 | 29.15 | 0.0 | 0.0 |
| .05000 | 448.22 | 1209.7 | 1.0 | .13225 | .49001 | 7.9 | .18292 | 9.5 | .91687 | 26. | .00761 | 22. | 4.161 | 27.70 | 0.0 | 0.0 |
| .05500 | 450.65 | 1216.3 | 1.0 | .14283 | .52919 | 7.4 | .19404 | 9.0 | .92988 | 26. | .00799 | 21. | 4.119 | 26.39 | 0.0 | 0.0 |
| .06000 | 451.45 | 1218.5 | 1.0 | .15341 | .56840 | 7.0 | .20513 | 8.6 | .94225 | 25. | .00837 | 21. | 4.080 | 25.21 | 0.0 | 0.0 |
| .06500 | 450.99 | 1217.2 | 1.0 | .16403 | .60773 | 6.7 | .21621 | 8.2 | .95412 | 25. | .00875 | 20. | 4.045 | 24.13 | 0.0 | 0.0 |
| .07000 | 449.55 | 1213.4 | 1.0 | .17469 | .64726 | 6.4 | .22731 | 7.9 | .96556 | 25. | .00912 | 20. | 4.013 | 23.15 | 0.0 | 0.0 |
| .07500 | 447.46 | 1207.7 | 1.0 | .18543 | .68704 | 6.1 | .23846 | 7.5 | .97666 | 24. | .00950 | 20. | 3.983 | 22.24 | 0.0 | 0.0 |
| .08000 | 444.79 | 1200.5 | 1.0 | .19625 | .72713 | 5.9 | .24967 | 7.2 | .98743 | 24. | .00988 | 19. | 3.956 | 21.39 | 0.0 | 0.0 |
| .08500 | 441.71 | 1192.2 | 1.0 | .20716 | .76755 | 5.7 | .26095 | 7.0 | .99794 | 24. | .01025 | 19. | 3.929 | 20.61 | 0.0 | 0.0 |
| .09000 | 438.34 | 1183.1 | 1.0 | .21817 | .80834 | 5.5 | .27231 | 6.7 | 1.0082 | 24. | .01063 | 19. | 3.905 | 19.88 | 0.0 | 0.0 |
| .09500 | 434.75 | 1173.4 | 1.0 | .22929 | .84951 | 5.3 | .28376 | 6.5 | 1.0183 | 23. | .01101 | 18. | 3.881 | 19.20 | 0.0 | 0.0 |
| .10000 | 431.00 | 1163.3 | 1.0 | .24051 | .89109 | 5.1 | .29532 | 6.3 | 1.0282 | 23. | .01140 | 18. | 3.859 | 18.56 | 0.0 | 0.0 |
| .12500 | 411.46 | 1110.5 | 1.0 | .29836 | 1.1055 | 4.4 | .35468 | 5.4 | 1.0756 | 22. | .01334 | 17. | 3.761 | 15.88 | 0.0 | 0.0 |
| .15000 | 392.48 | 1059.3 | 1.0 | .35923 | 1.3310 | 3.9 | .41688 | 4.7 | 1.1206 | 21. | .01533 | 16. | 3.677 | 13.83 | 0.0 | 0.0 |
| .17500 | 375.06 | 1012.3 | 1.0 | .42315 | 1.5678 | 3.6 | .48204 | 4.2 | 1.1639 | 21. | .01737 | 16. | 3.603 | 12.22 | 0.0 | 0.0 |
| .20000 | 359.36 | 969.92 | 1.0 | .49008 | 1.8158 | 3.3 | .55013 | 3.8 | 1.2060 | 20. | .01944 | 15. | 3.535 | 10.92 | 0.0 | 0.0 |
| .22500 | 345.27 | 931.89 | 1.0 | .55994 | 2.0746 | 3.0 | .62109 | 3.5 | 1.2472 | 19. | .02156 | 15. | 3.471 | 9.847 | 0.0 | 0.0 |
| .25000 | 332.60 | 897.69 | .99 | .63263 | 2.3440 | 2.8 | .69486 | 3.2 | 1.2878 | 19. | .02371 | 14. | 3.412 | 8.956 | 0.0 | 0.0 |
| .27500 | 321.15 | 866.79 | .99 | .70808 | 2.6235 | 2.7 | .77135 | 3.0 | 1.3277 | 18. | .02588 | 14. | 3.356 | 8.203 | 0.0 | 0.0 |
| .30000 | 310.75 | 838.72 | .98 | .78620 | 2.9129 | 2.5 | .85049 | 2.8 | 1.3673 | 18. | .02809 | 14. | 3.303 | 7.559 | 0.0 | 0.0 |
| .35000 | 292.51 | 789.50 | .98 | .95014 | 3.5203 | 2.3 | 1.0164 | 2.5 | 1.4452 | 17. | .03257 | 13. | 3.204 | 6.520 | 0.0 | 0.0 |
| .40000 | 276.94 | 747.47 | .98 | 1.1239 | 4.1640 | 2.1 | 1.1921 | 2.3 | 1.5220 | 16. | .03713 | 13. | 3.115 | 5.721 | 0.0 | 0.0 |
| .45000 | 263.39 | 710.86 | .97 | 1.3071 | 4.8428 | 2.0 | 1.3772 | 2.1 | 1.5981 | 15. | .04179 | 13. | 3.034 | 5.089 | 0.0 | 0.0 |
| .50000 | 251.35 | 678.39 | .97 | 1.4995 | 5.5558 | 1.9 | 1.5715 | 2.0 | 1.6736 | 15. | .04653 | 13. | 2.961 | 4.579 | 0.0 | 0.0 |
| .55000 | 240.53 | 649.18 | .97 | 1.7010 | 6.3023 | 1.8 | 1.7748 | 1.9 | 1.7488 | 14. | .05137 | 12. | 2.894 | 4.159 | 0.0 | 0.0 |
| .60000 | 230.67 | 622.57 | .97 | 1.9114 | 7.0819 | 1.8 | 1.9871 | 1.8 | 1.8237 | 14. | .05631 | 12. | 2.834 | 3.808 | 0.0 | 0.0 |
| .65000 | 221.59 | 598.07 | .96 | 2.1307 | 7.8944 | 1.7 | 2.2082 | 1.7 | 1.8986 | 13. | .06137 | 12. | 2.779 | 3.510 | 0.0 | 0.0 |
| .70000 | 213.16 | 575.31 | .96 | 2.3589 | 8.7399 | 1.6 | 2.4383 | 1.6 | 1.9736 | 13. | .06654 | 12. | 2.729 | 3.255 | 0.0 | 0.0 |
| .75000 | 204.40 | 551.67 | .97 | 2.5967 | 9.6208 | 1.6 | 2.6779 | 1.6 | 2.0490 | 12. | .07188 | 11. | 2.684 | 3.033 | 0.0 | 0.0 |
| .80000 | 196.53 | 530.43 | .97 | 2.8443 | 10.538 | 1.6 | 2.9274 | 1.5 | 2.1249 | 12. | .07741 | 11. | 2.644 | 2.839 | 0.0 | 0.0 |
| .85000 | 189.41 | 511.23 | .97 | 3.1016 | 11.492 | 1.5 | 3.1866 | 1.5 | 2.2014 | 11. | .08312 | 11. | 2.609 | 2.668 | 0.0 | 0.0 |
| .90000 | 182.94 | 493.76 | .97 | 3.3683 | 12.480 | 1.5 | 3.4553 | 1.4 | 2.2783 | 11. | .08900 | 11. | 2.576 | 2.517 | 0.0 | 0.0 |
| .95000 | 177.02 | 477.78 | .97 | 3.6443 | 13.502 | 1.5 | 3.7332 | 1.4 | 2.3557 | 11. | .09503 | 11. | 2.545 | 2.381 | 0.0 | 0.0 |
| 1.0000 | 171.59 | 463.16 | .96 | 3.9293 | 14.558 | 1.4 | 4.0201 | 1.4 | 2.4336 | 10. | .10120 | 11. | 2.517 | 2.261 | 0.0 | 0.0 |
| 1.2500 | 149.80 | 404.32 | .99 | 5.4835 | 20.317 | 1.4 | 5.5846 | 1.3 | 2.8289 | 9.1 | .13393 | 10. | 2.398 | 1.810 | 0.0 | 0.0 |
| 1.5000 | 133.31 | 359.80 | .95 | 7.2456 | 26.845 | 1.3 | 7.3574 | 1.2 | 3.2341 | 8.0 | .16963 | 9.7 | 2.306 | 1.519 | 0.0 | 0.0 |
| 1.7500 | 120.57 | 325.41 | .89 | 9.2091 | 34.120 | 1.2 | 9.3322 | 1.1 | 3.6494 | 7.2 | .20821 | 9.3 | 2.231 | 1.320 | 0.0 | 0.0 |
| 2.0000 | 110.27 | 297.61 | .84 | 11.368 | 42.119 | 1.2 | 11.503 | 1.1 | 4.0744 | 6.6 | .24954 | 8.9 | 2.169 | 1.175 | 0.0 | 0.0 |
| 2.2500 | 101.77 | 274.67 | .80 | 13.717 | 50.824 | 1.2 | 13.865 | 1.0 | 4.5089 | 6.0 | .29356 | 8.6 | 2.117 | 1.065 | 0.0 | 0.0 |
| 2.5000 | 94.611 | 255.35 | .77 | 16.254 | 60.222 | 1.1 | 16.415 | 1.0 | 4.9526 | 5.5 | .34020 | 8.3 | 2.073 | .9801 | 0.0 | 0.0 |
| 2.7500 | 88.488 | 238.83 | .75 | 18.975 | 70.303 | 1.1 | 19.149 | .96 | 5.4054 | 5.1 | .38943 | 8.1 | 2.034 | .9120 | 0.0 | 0.0 |
| 3.0000 | 83.223 | 224.62 | .72 | 21.875 | 81.049 | 1.1 | 22.064 | .93 | 5.8666 | 4.8 | .44110 | 7.9 | 1.999 | .8567 | 0.0 | 0.0 |
| 3.5000 | 74.536 | 201.17 | .68 | 28.205 | 104.50 | 1.0 | 28.424 | .88 | 6.8135 | 4.2 | .55161 | 7.5 | 1.941 | .7722 | .0076 | 25. |
| 4.0000 | 67.667 | 182.63 | .64 | 35.222 | 130.50 | .96 | 35.474 | .84 | 7.7909 | 3.8 | .67133 | 7.1 | 1.892 | .7110 | .0114 | 25. |

Figure: Energy loss values from [Janni82]

EPFL

# Appropriate fit for the data

- In order to implement the energy loss of deposed ions, we need to find the appropriate fit:
  To do so, one has to determine the **energy distribution of ions collected at the electrode**, and match it with the energy loss curve.
- In Fig.(2), the energy loss of protons in Aluminum has been plotted on the expected energy range of 20 keV to 1 GeV (see red curve).
  E.g if the protons are mainly distributed in parabolic region (green) $\rightarrow$ quadratic fit
  Else a linear fit may be more appropriate.

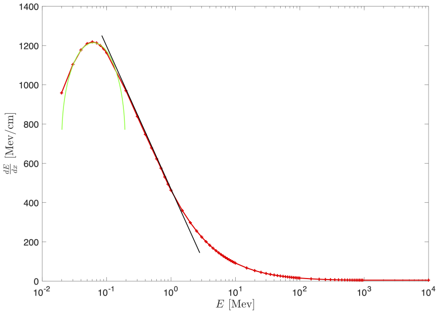



Figure: Energy loss for protons in aluminum (red) - possible fits for the data in interesting regions (green - black)

# Initial configuration

- Initial configuration: generation of ions with maxwelian velocity profile
- Cylindrical symmetry and ions generated at different $r = R_0$
- Potential bias of $20kV$ - radial $\mathbf{E}$

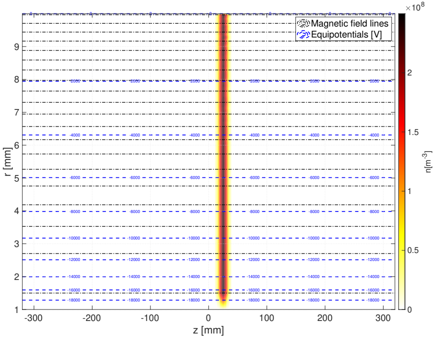



Figure: Initial ion density profile

# Energy collected at the electrode

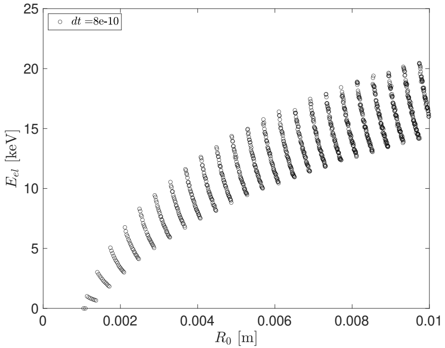



Figure: Energy collected at the electrode - $dt = 8e^{-10}$

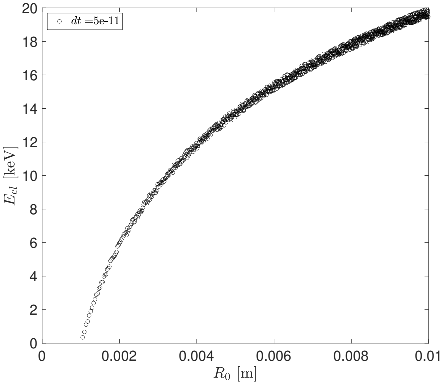



Figure: Energy collected at the electrode - $dt = 1e^{-11}$

# Kinetic energy and energy loss $dE/dx$

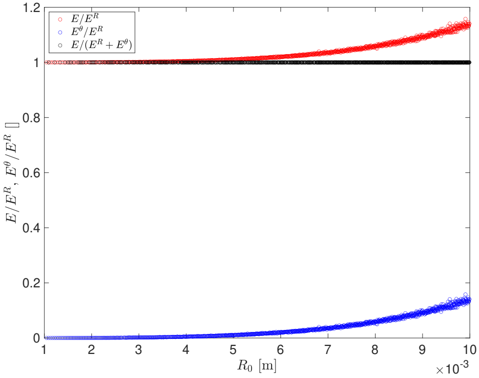



Figure: Ratio of the different components of kinetic energy

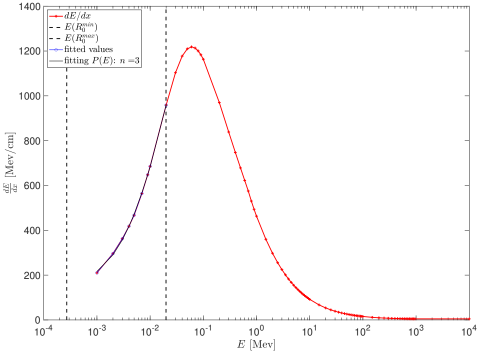



Figure: Energy loss and energy range of interest with polynomial fit

# Electron yield - Kinetic theory

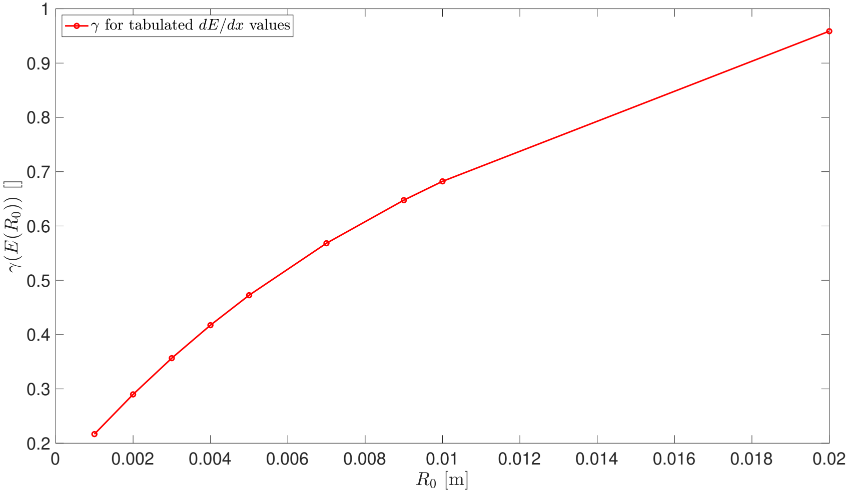



Figure: Yield over the fitted energy interval, given as a function of the energy through $R_0$