Multipactor simulations for particle accelerators

Adrien Plaçais*

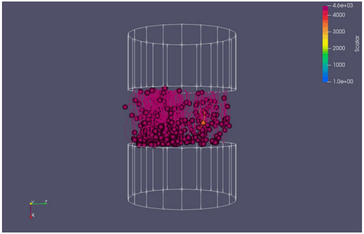
October 2024

* Univ. Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 38000 Grenoble, France
Participation to this workshop is supported by the Sébastien Bousson grant

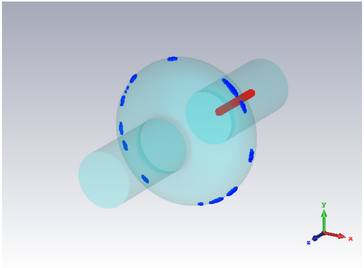
Outline

Multipactor in particle accelerators

Multipactor is an electron avalanche in vacuum RF systems



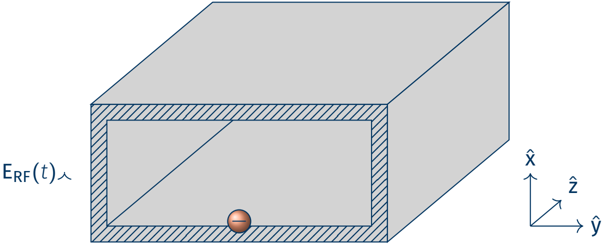
(a) Animation of multipactor at the center of a circulator. A magnetic field confines the electrons. Result of a POTOMAC simulation.



(b) Tesla cavity accelerating particle bunches (red), subject to multipacting (electrons in blue). Result of a CST simulation.

Multipactor phenomenon is also studied in spatial telecommunications and nuclear fusion communities.

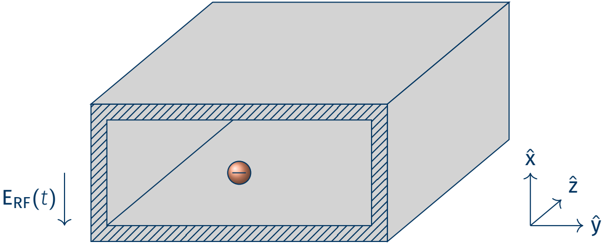
Multipactor occurs due to electron emission and RF/electrons synchronism



Multipactor created by two phenomena:

- Electron Emission (EE).
- Resonance between electrons and the RF signal.

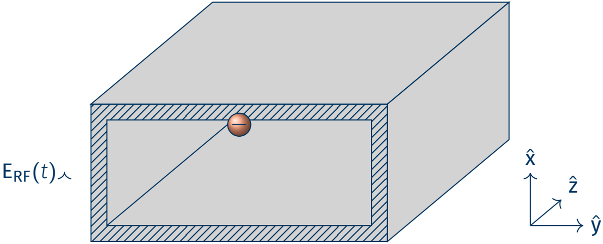
Multipactor occurs due to electron emission and RF/electrons synchronism



Multipactor created by two phenomena:

- Electron Emission (EE).
- Resonance between electrons and the RF signal.

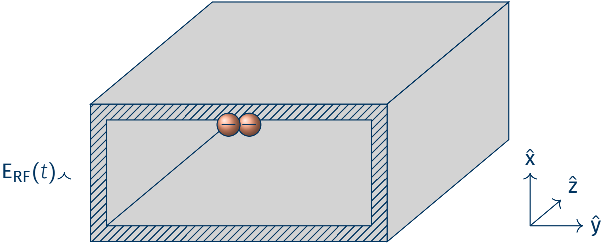
Multipactor occurs due to electron emission and RF/electrons synchronism



Multipactor created by two phenomena:

- Electron Emission (EE).
- Resonance between electrons and the RF signal.

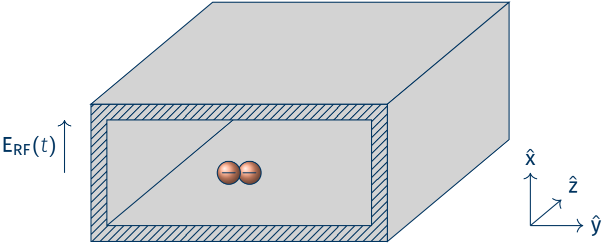
Multipactor occurs due to electron emission and RF/electrons synchronism



Multipactor created by two phenomena:

- Electron Emission (EE).
- Resonance between electrons and the RF signal.

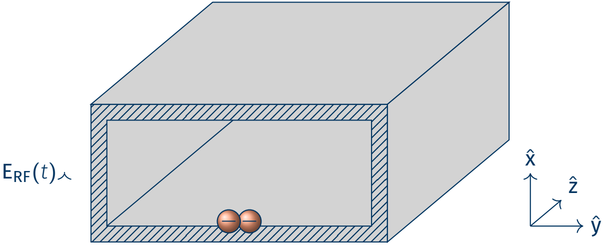
Multipactor occurs due to electron emission and RF/electrons synchronism



Multipactor created by two phenomena:

- Electron Emission (EE).
- Resonance between electrons and the RF signal.

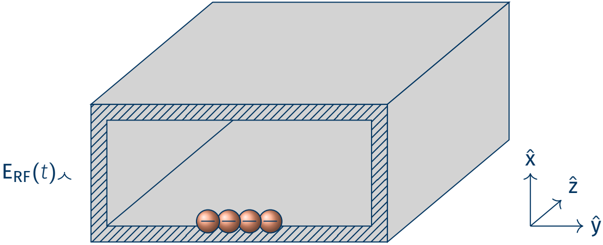
Multipactor occurs due to electron emission and RF/electrons synchronism



Multipactor created by two phenomena:

- Electron Emission (EE).
- Resonance between electrons and the RF signal.

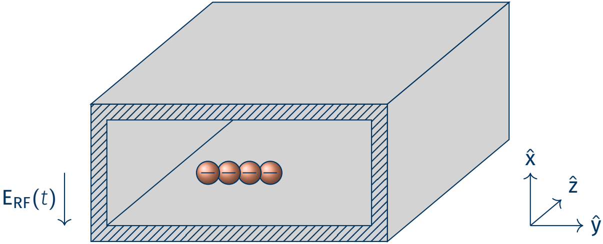
Multipactor occurs due to electron emission and RF/electrons synchronism



Multipactor created by two phenomena:

- Electron Emission (EE).
- Resonance between electrons and the RF signal.

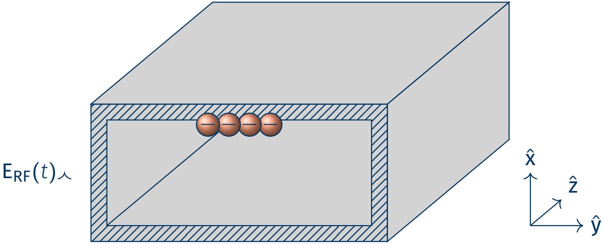
Multipactor occurs due to electron emission and RF/electrons synchronism



Multipactor created by two phenomena:

- Electron Emission (EE).
- Resonance between electrons and the RF signal.

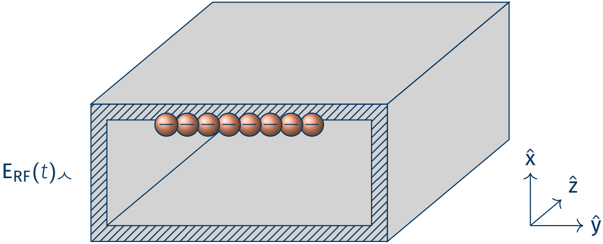
Multipactor occurs due to electron emission and RF/electrons synchronism



Multipactor created by two phenomena:

- Electron Emission (EE).
- Resonance between electrons and the RF signal.

Multipactor occurs due to electron emission and RF/electrons synchronism



Multipactor created by two phenomena:

- Electron Emission (EE).
- Resonance between electrons and the RF signal.

Multipactor cannot always be processed through

- In particle accelerators, multipactor can generally be processed through.
- This is not the case for spacecrafts.
  - High-frequency, lower RF power, and significant safety margins.

  ⇒ These factors must be considered when using space-oriented multipactor tools.

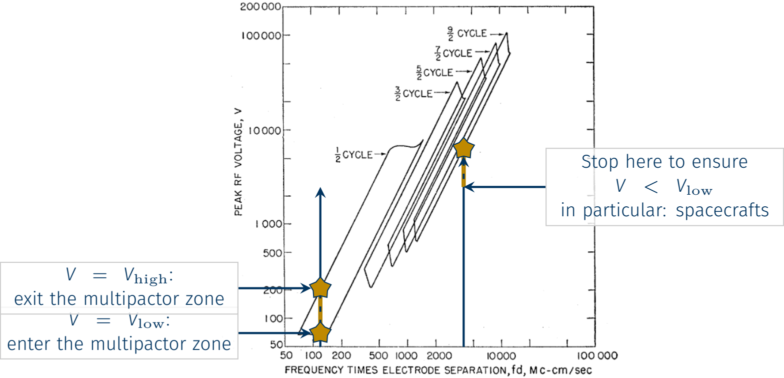


Figure 2: Hatch diagram representing multipactor zones. x-axis is the product of RF frequency and the distance between plates. y-axis is RF voltage. The diagram is obtained by solving equations of resonant motion in a rectangular waveguide with strong assumptions.

Tools for the numerical simulation of multipactor

CST Microwave Studio

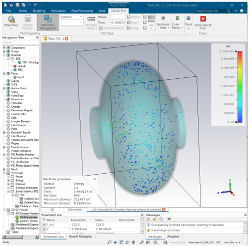


Figure 3: CST PIC screenshot.

- EM field solver (eigenmode or frequency domain solver).
- PIC solver.

✅ Generally considered a reference code.

✅ EE models: Furman & Pivi (+ Vaughan, file interpolation).

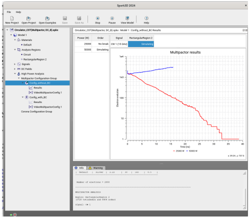
❌ License is expensive.

❌ Not a multipactor-specific tool.

- Configuration is complex.
- Lacks multipactor-specific diagnostics: recording of impact angles, electrons trajectories.

Plaçais (2024), *Simulia Multipactor lib*, `https://github.com/AdrienPlacais/Simulia_Multipactor_lib`

SPARK3D



- EM field to be imported from CST, HFSS, FEST3D.
- PIC solver.

✅ Specialized.
  - Easy to use.
  - Fast.

❌ Same license as CST.

❌ EE models: Vaughan, file interpolation.

❌ Lacks diagnostics.

❌ Developed for spatial field.
  - Designed to find the first multipactor threshold.

Plaçais et al. (2023), *Spark3DBatch*, `https://github.com/AdrienPlacais/Spark3DBatch`

Ansys HFSS

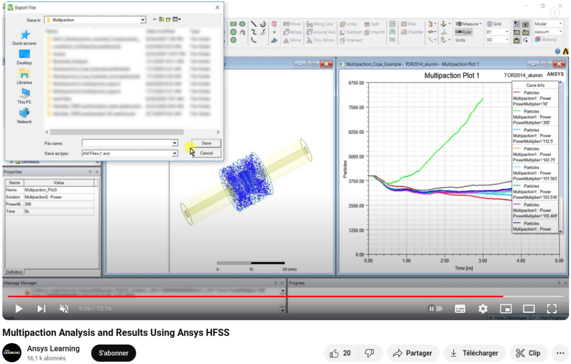


Figure 4: Screenshot of an Ansys HFSS multipactor video tutorial.

- Disclaimer: I have never used it.

❌ EE models: Vaughan, file interpolation.

✅ Dedicated module, easy to configure.

❓ Support for dielectric materials (influence of charge on the electric field).

Free and open-source tools

- ECSS Multipactor Tool: determines if a spacecraft adheres to ECSS multipactor standards.
    - Free, maintained and developed by a company.
- MULH: multipactor in rectangular waveguides.
    - Open-source, unmaintained.
- POTOMAC: multipactor with a basic model for dielectrics.
    - CNES closed license, may be released in the future, unmaintained.
- SPIS-multipactor: module of SPIS software, handles dielectric materials, spacecraft-oriented.
    - Open-source, but the module could not be found.
- MUSICC3D: multipactor in couplers and cavities.
    - Developed at IPN Orsay (IJCLab).

SARL (2020), *ECSS Multipactor Tool*, `https://essr.esa.int/project/multipactor-tool-version-2-0-0`

Francisquez et al. (2017), *MULH*, `https://github.com/AdrienPlacais/MULH`

Plaçais et al. (2019), "POTOMAC: Towards a Realistic Secondary and Backscattered Emission Model for the Multipactor"

Peysson (2023), "Modélisation 3D des conditions de déclenchement de décharges électrostatiques dans les composants spatiaux RF"

Hamelin et al. (2013), "MUSICC3D: a Code for Modeling the Multipacting"

Multipactor simulation good practices and electron emission

Choose the proper electron emission model

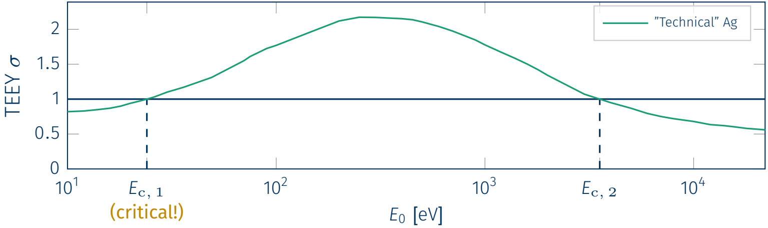


Figure 5: *Total Electron Emission Yield* as a function of incident electron energy for an Ag sample. (*TEEY*: number of emitted electrons per incident electron)

- Vaughan (for first-order studies)
  - Widely used, easy to parametrize.
  - ⚠️ Several versions of the model; verify behavior at low-energies & at $E_{c,1}$.
- File interpolation (for first-order studies)
  - ⚠️ Always verify implementation for oblique-impacting electrons.
- Furman & Pivi (for more precise studies, particularly with $\mathbf{B}_{DC}$)
  - ⚠️ 44 parameters!

Fil et al. (2020), "Erratum: "Multipactor threshold sensitivity to total electron emission yield in small gap waveguide structure and TEEY models accuracy" [Phys. Plasmas 23 , 123118 (2016)]"

Plaçais (2024), *EEmiLib*, `https://github.com/AdrienPlacais/EEmiLib`

Perform several studies with different surface states

- Electron emission processes take place on the first nanometers of the material.
- Extreme sensitivity to surface state.
- Always perform simulations for several representative surface states: pessimistic/unconditioned, realistic/conditioned, optimistic.

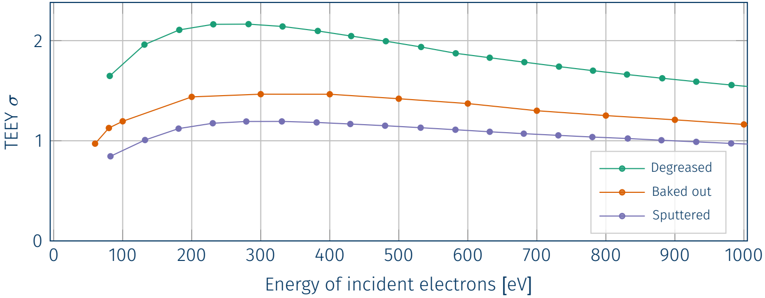


Figure 6: *Total Electron Emission Yield* as a function of incident electron energy for Nb samples. (*TEEY*: number of emitted electrons per incident electron)

Aull et al. (2015), “Secondary Electron Yield of SRF Materials”

Calder et al. (1986), “Influence of various vacuum surface treatments on the secondary electron yield of niobium”

Do not take the simulation results for granted

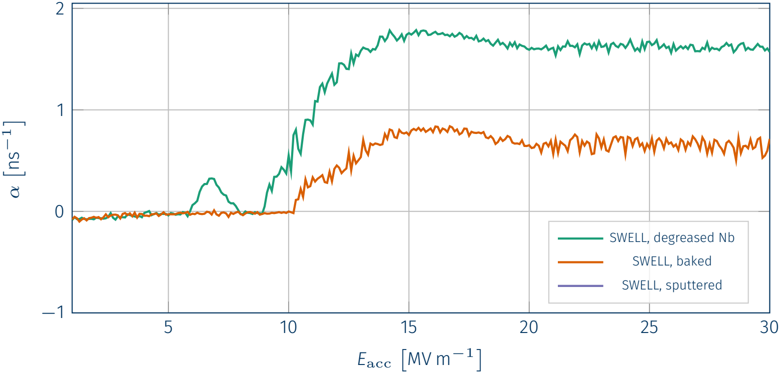


Figure 7: Evolution of exponential growth factor in a superconducting cavity called SWELL: $n_{\mathrm{electrons}}(t) = N_0 \mathrm{e}^{\alpha t}$. Results of CST simulations.

- Avoid binary reasoning (there's no multipactor from 0 to 6 MV m^{-1}, there's multipactor from 6 to 8 MV m^{-1}...).

Plaçais et al. (2023), "Multipactor Studies for the FCC-ee Superconducting SWELL cavities"

Do not take the simulation results for granted

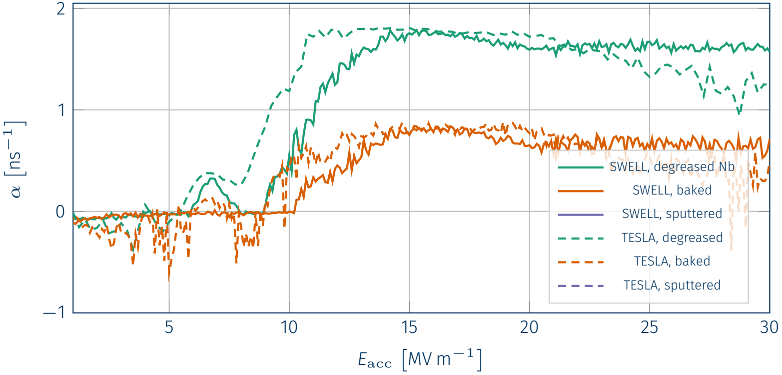


Figure 7: Evolution of exponential growth factor in a superconducting cavity called SWELL: $n_{\mathrm{electrons}}(t) = N_0 \mathrm{e}^{\alpha t}$. Results of CST simulations.

- Avoid binary reasoning (there's no multipactor from 0 to 6 MV m^{-1}, there's multipactor from 6 to 8 MV m^{-1}...).
- Perform comparative simulations on known geometries.

Plaçais et al. (2023), "Multipactor Studies for the FCC-ee Superconducting SWELL cavities"

Ensure that emission yield data is valid for energy/angle impact ranges in your geometry

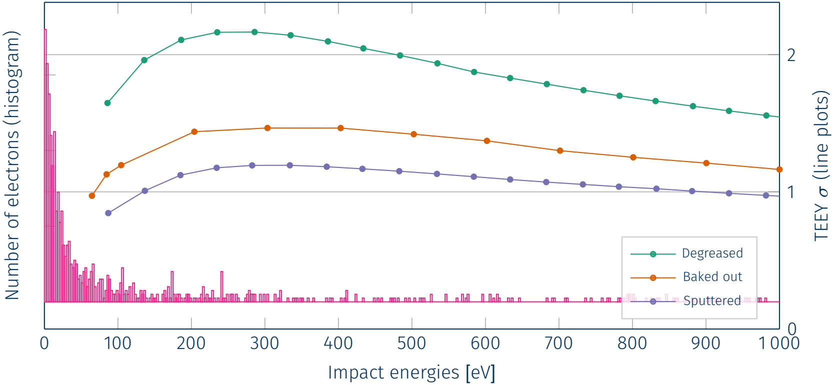
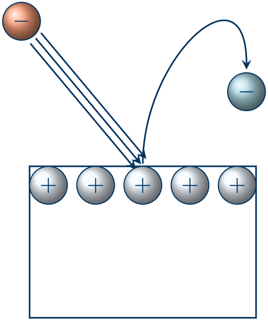


Figure 8: Left: histogram of the electrons impact energies in the SWELL prototype; CST simulation @$E_{\mathrm{acc}} = 20\,\mathrm{MV\,m^{-1}}$ with baked Nb. Right: Total Electron Emission Yield data used for the study as a function of electrons impact energies. (*TEEY*: number of emitted electrons per incident electron)

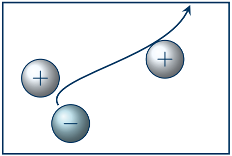
Plaçais et al. (2023), "Multipactor Studies for the FCC-ee Superconducting SWELL cavities"

The issue with dielectric materials

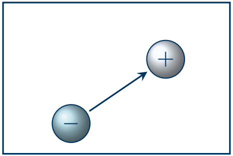
- In particle accelerators: ceramic window in couplers (in general: metallic coating).
- In contrary to metal, dielectric materials hold a net electric charge.
    - Non-uniform.
    - Varies with every collision.



(a) ”External” influence on electrons trajectories. The resonance condition is affected. Can be handled by PIC solver.



(b) Charges trapped inside the material influence electrons trajectories. To my knowledge, no model.



(c) Electrons–holes recombination (excess of holes only). Modelled by modified Dionne model (implemented in POTOMAC, SPIS-multipactor).

Balcon et al. (2013), “Secondary electron emission of cover glasses: Temperature and incident flux effects”

Plaçais et al. (2020), “A three-dimensional Dionne model for multipactor simulations”

Conclusion and perspectives

Perspectives

- Simulating multipactor is a mandatory phase in the design of a vacuum RF equipment.
- Due to the extreme variance of surfaces electron emission properties, the precise determination of when multipactor appears is a challenging task.
- Great care must be taken when modelling electron emission phenomena.
- In particular:
    - Magnetic fields (influence electrons trajectories but also electron emission!)
    - Dielectric materials.
- Need for a physical open-source tool to compute multipactor.

Fil et al. (2017), "Electron emission under uniform magnetic field of materials for fusion and space applications"

Thanks for your attention!

References

References i

[1] Adrien Plaçais. ***Simulia Multipactor lib.*** 2024 (cit. on p. 17).

[2] Adrien Plaçais and Julien Hillairet. ***Spark3DBatch.*** 2023 (cit. on p. 18).

[3] Artenum SARL. ***ECSS Multipactor Tool.*** 2020 (cit. on p. 20).

[4] Manaure Francisquez, Adrien Plaçais, and Julien Hillairet. ***MULH.*** 2017 (cit. on p. 20).

[5] Adrien Plaçais et al. **“POTOMAC: Towards a Realistic Secondary and Backscattered Emission Model for the Multipactor”.** In: *2019 IEEE Pulsed Power and Plasma Science (PPPS)*. IEEE, June 2019, pp. 1–4 (cit. on p. 20).

[6] Quentin Peysson. **“Modélisation 3D des conditions de déclenchement de décharges électrostatiques dans les composants spatiaux RF”.** In: (2023) (cit. on p. 20).

[7] T. Hamelin et al. **"MUSICC3D: a Code for Modeling the Multipacting".** In: JACoW Publishing, Geneva, Switzerland, Sept. 2013 (cit. on p. 20).

[8] Nicolas Fil et al. **"Erratum: "Multipactor threshold sensitivity to total electron emission yield in small gap waveguide structure and TEEY models accuracy" [Phys. Plasmas 23 , 123118 (2016)]".** In: *Physics of Plasmas* 27 (6 June 2020), p. 069902 (cit. on p. 22).

[9] Adrien Plaçais. ***EEmiLib*.** 2024 (cit. on p. 22).

[10] S. Aull et al. **"Secondary Electron Yield of SRF Materials".** In: *Proc. SRF'15*. Ed. by Robert E. Laxdal, Jana Thomson, and Volker RW Scha. 17th International Conference on RF Superconductivity (SRF2015), Sept. 2015 (cit. on p. 23).

[11] Roger Calder, Georges Dominichini, and Noël Hilleret. **"Influence of various vacuum surface treatments on the secondary electron yield of niobium".** In: *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 13 (1-3 Mar. 1986), pp. 631–636 (cit. on p. 23).

[12] Adrien Plaçais et al. **"Multipactor Studies for the FCC-ee Superconducting SWELL cavities".** In: *Proc. 14th Int. Particle Acc. Conf. (IPAC'23)*. JACoW Publishing, Geneva, Switzerland, 2023 (cit. on pp. 24–26).

[13] Nicolas Balcon et al. **"Secondary electron emission of cover glasses: Temperature and incident flux effects".** In: *International Symposium on Materials in the Space Environment*. Ed. by L. Ouwehand. ESA Communications, 2013 (cit. on p. 27).

[14] Adrien Plaçais et al. **"A three-dimensional Dionne model for multipactor simulations".** In: *Physics of Plasmas* 27 (5 May 2020), p. 053512 (cit. on p. 27).

[15] Nicolas Fil et al. **"Electron emission under uniform magnetic field of materials for fusion and space applications".** In: *Fusion Engineering and Design* 123 (Nov. 2017), pp. 426–430 (cit. on p. 29).

Structure of a PIC code for multipactor

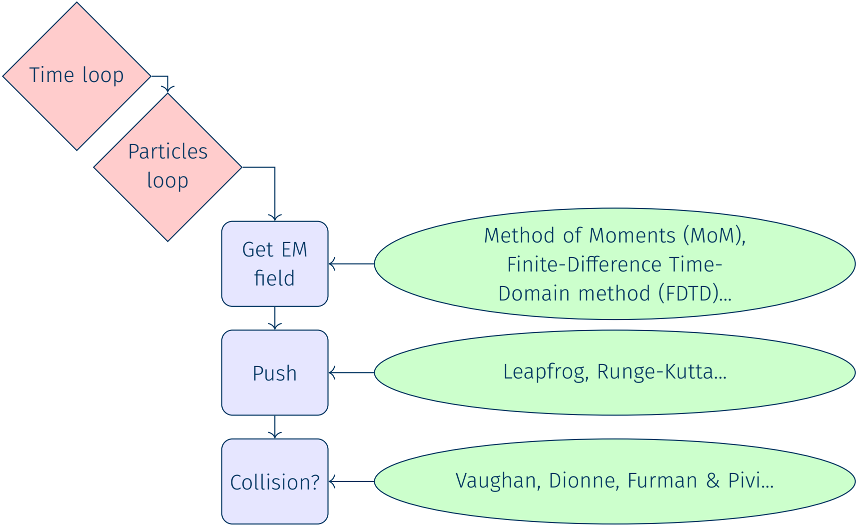
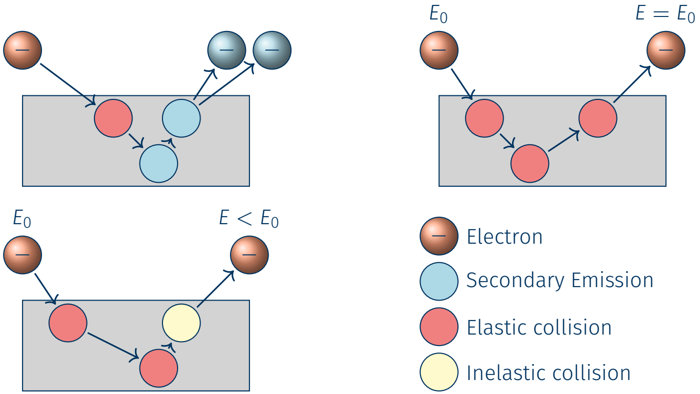


Figure 10: PIC: *Particle-in-Cell*. Three tools are required: (i) compute EM field, (ii) integrate motion, (iii) electron emission model.

Electron Emission represents several phenomena



Model	Secondary	Elastically Backscattered	Inelastically Backscattered
Vaughan	✅	❌	❌
(File interpolation)	✅	❌	❌
Furman & Pivi	✅	✅	✅