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Model of field emission and dark current simulation

Hamburg/14-15 sept 2022/Workshop on Vertical SRF Cavity Testing

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Introduction

What we currently used to analyze field emission:

1. External radiation detectors

   A part of impact electron energy
   is converted in X ray bremsstrahlung radiation.
   The maximum x ray energy (endpoint) corresponds to
   electron kinetic energy.

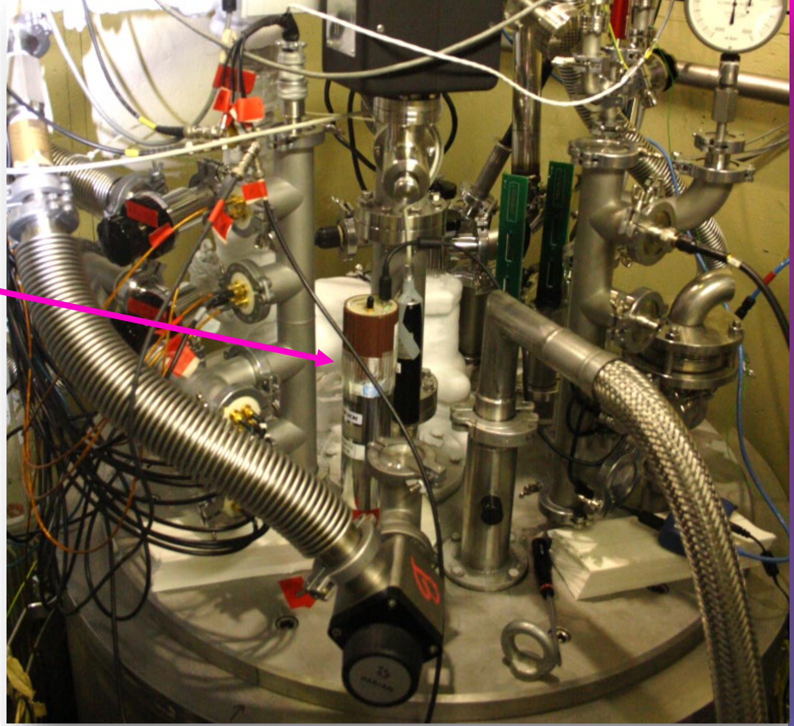
   - Proportional counter: dose rate → it (partially) mimics the power drained by electron dark current
   - Scintillator (NaI(Tl)) → it gives the X Ray spectrum therefore allowing endpoint evaluation (a part from severe pile-up events)

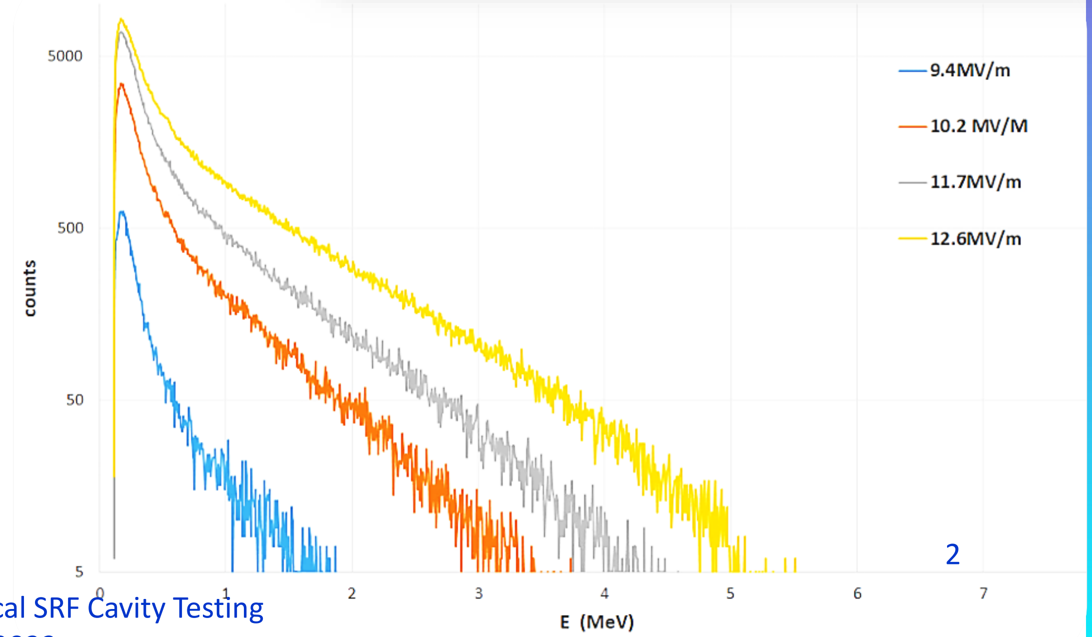
2. Inner diagnostic:
   - electron pick-up
   - Photodiodes array

3. Cavity Q drop → offers a way to evaluate the overall field emission power if this phenomenon is the dominant one in limiting the performance

$$\boxed{\frac{1}{Q(E_{acc})} = \frac{1}{Q_0} + \frac{R}{Q}\frac{P_{FE}}{(E_{acc}\,l)^2}}$$

Scintillator and proportional counter on cryostat cover





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Problem: how to evaluate the REAL FE impact?

- *Field Emission* can be invisible to external detectors if impact energies are too low
- External detectors can view only a limited part of emission pattern.
- Difficult to localize "a priori" the activated emitter position. Inner detectors like photodiodes can help to reconstruct the pattern but a quantitative calibration of these sensors is still missing (but it's under way)
- *FE* can be coupled with other phenomena like secondary emission (multipacting), parasitic mode excitation, thermal induced quench in points with high impact current → these may complicate a full modeling of cavity behavior

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Model of FE

Our goal is to exploit the experimental observables (*dose rate, energy endpoint and Q-drop*) to develop an self-consistent model of FE inside the cavity (*emitter position and size, field enhancement factor*)

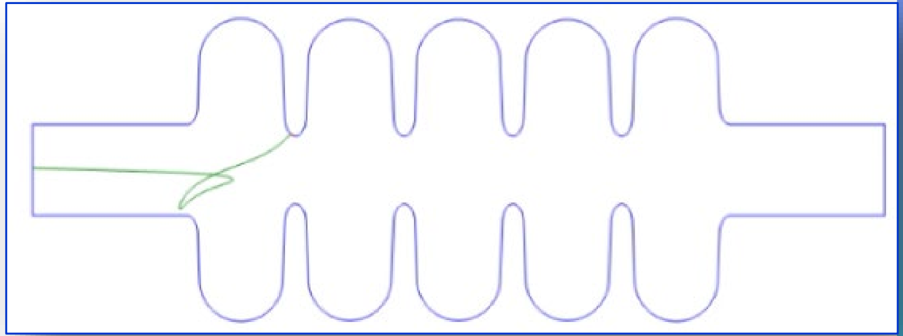
Fishpact (2D model) → electron energy and tracking

In this case Multipacting events are neglected (impact number = 1), so to simulate sheer field emission events: the electron "dies" after the first impact against cavity walls.

Pro/cons:

- Limited post-processing features
- No emission models available

… BUT noticeably faster than other more advanced program!



Steps

For each E_{acc}:

1) Several emitter sites are tested along the cavity profile
2) Electron current is modeled according to the Fowler Nordheim emission law
3) Colliding electrons trajectories are collected on a cavity surface region according to external detector angle of view
4) The simulated data are post-processed to obtain **overall electron impact energy spectrum** as function of E_{acc}

- The highest impact energy corresponds to maximum X-ray Bremsstrahlung Energy

→ **1st cross-check with experimental data:** X-ray energy spectrum σ(E)

- Pfe depends on the emitter site area

5) P_{FE} (power drained by electron dark current) calculation by summing up on the whole cavity surface as a function of E_{acc}

$$P_{FE} = \frac{1}{T_{RF}} \sum_i N(\varphi_i) E(\varphi_i)$$ E: final impact energy

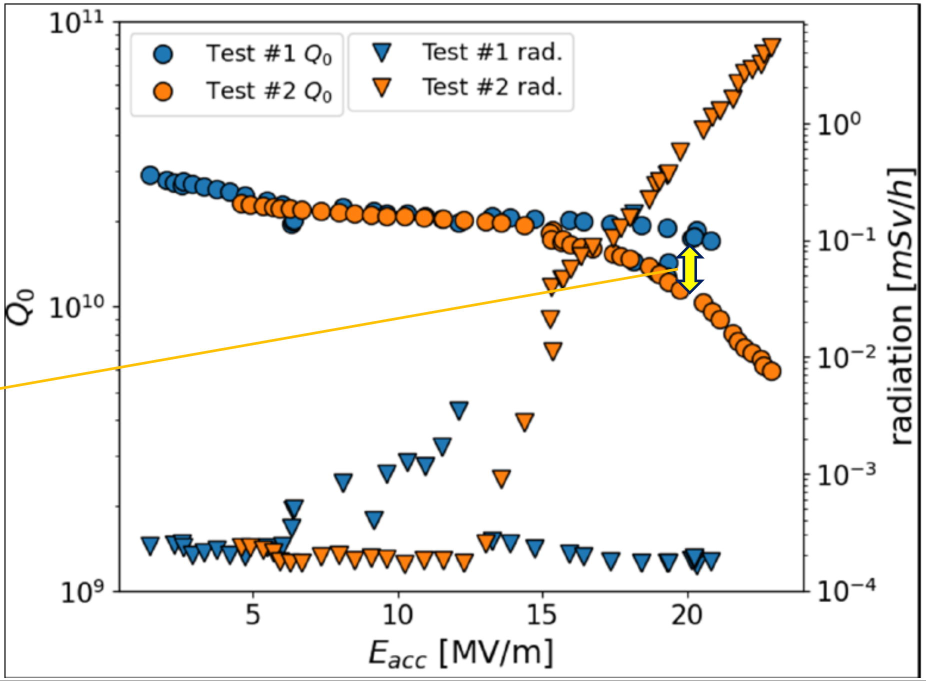
Q_0 vs E_{acc} trend can be reconstructed

→ **2nd cross-check with experimental data:** simulated Q compared to experimental Q

CASE STUDY – PIP II EZ-002 CAVITY

- 1^{st} test: some MP with radiation, then sudden rise of radiation at 20.8 MV/m and testing instabilities
- Test repeated from low fields
- 2^{nd} test: same behavior as the 1^{st} test up to until 14 MV/m …
- … then, sudden rise of radiation and drop of Q_0
- Cavity quench at 23 MV/m with **FE**
- **Irreversible activation of a field emitter!**

The Q variation only due to Field Emission, considering the same value of E_{acc}



→ Ideal test bench to check the model self-consistency
By means of P_{FE} computation

Assuming Q-degradation only due to FE, P_{FE} FE dissipated power, Q_0 low field Q, R/Q fixed parameter

$$\frac{1}{Q(E_{acc})} = \frac{1}{Q_0} + \frac{R}{Q}\frac{P_{FE}}{(E_{acc}\, l)^2}$$

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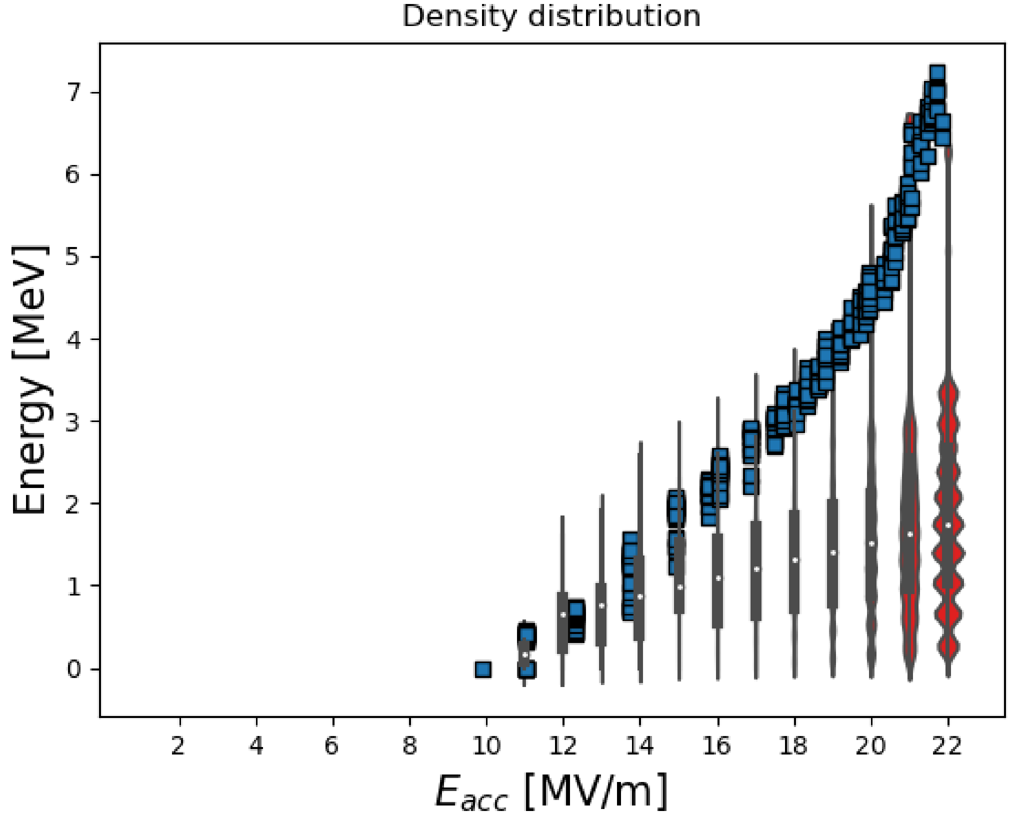
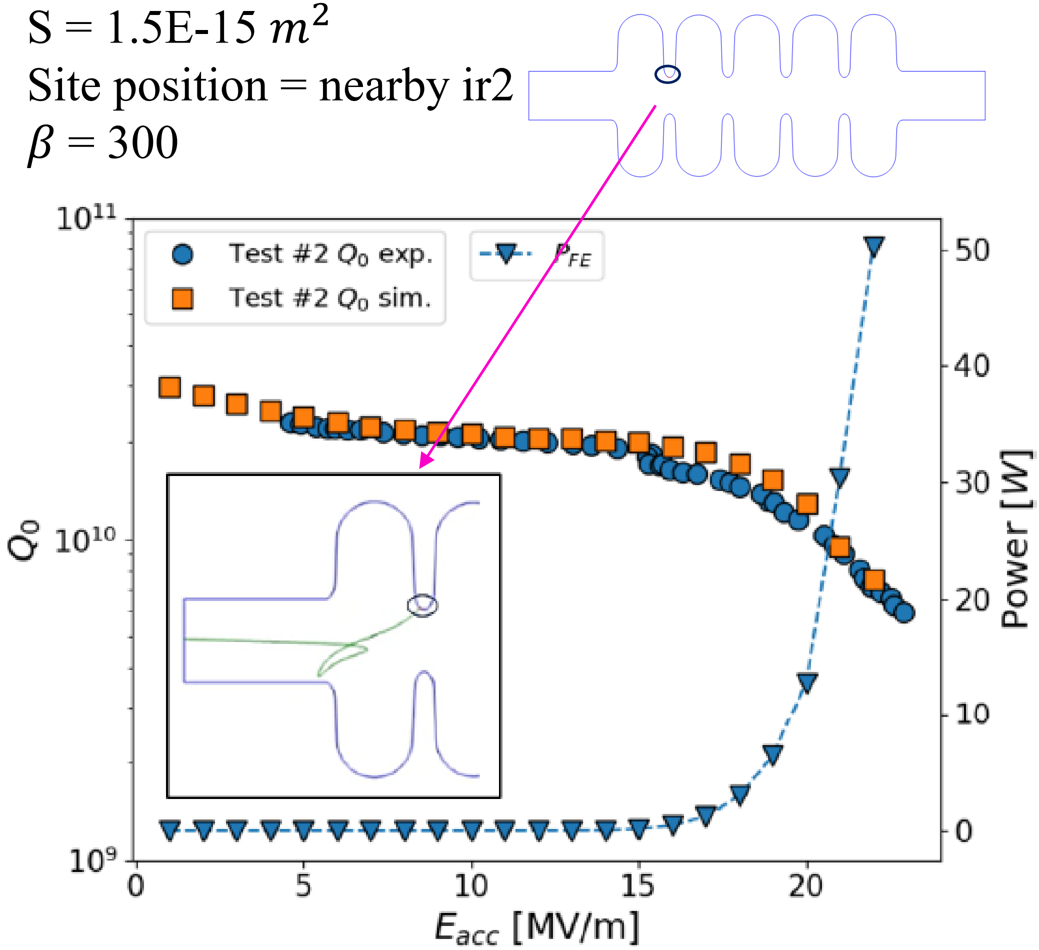
CASE STUDY – PIP II EZ-002 CAVITY (2)

S = 1.5E-15 m^2
Site position = nearby ir2
β = 300





Power FE @ 20 MV/m = 12 W

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Conclusions

- A program to reconstruct field emission behavior has been developed starting from already existing Fishpact code

- The program allows also to evaluate some physical parameters corresponding to experimental observables like: *energy spectrum* and *total dissipated FE power* → *external dose evaluation* on progress

  i. Analytical
  ii. Simulation with dedicated sofware

- The model self-consistency has been cross-checked thanks to the case of PIP-II cavity EZ-002 for which data are available with and without field emission: data for impact energy distributions and field emitting power are nearly coherent for every Eacc.

To do list:

- Model electron to photon count deconvolution so to exploit also dose rate measurements
- Evaluate Pile-up statistics for detector at high count rates
- Study model convergence when sampling with smaller phase steps so to find a trade-off between calculation speed and model accuracy

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Thank You

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under GA No 101004730.

Backup slides

External radiation detectors

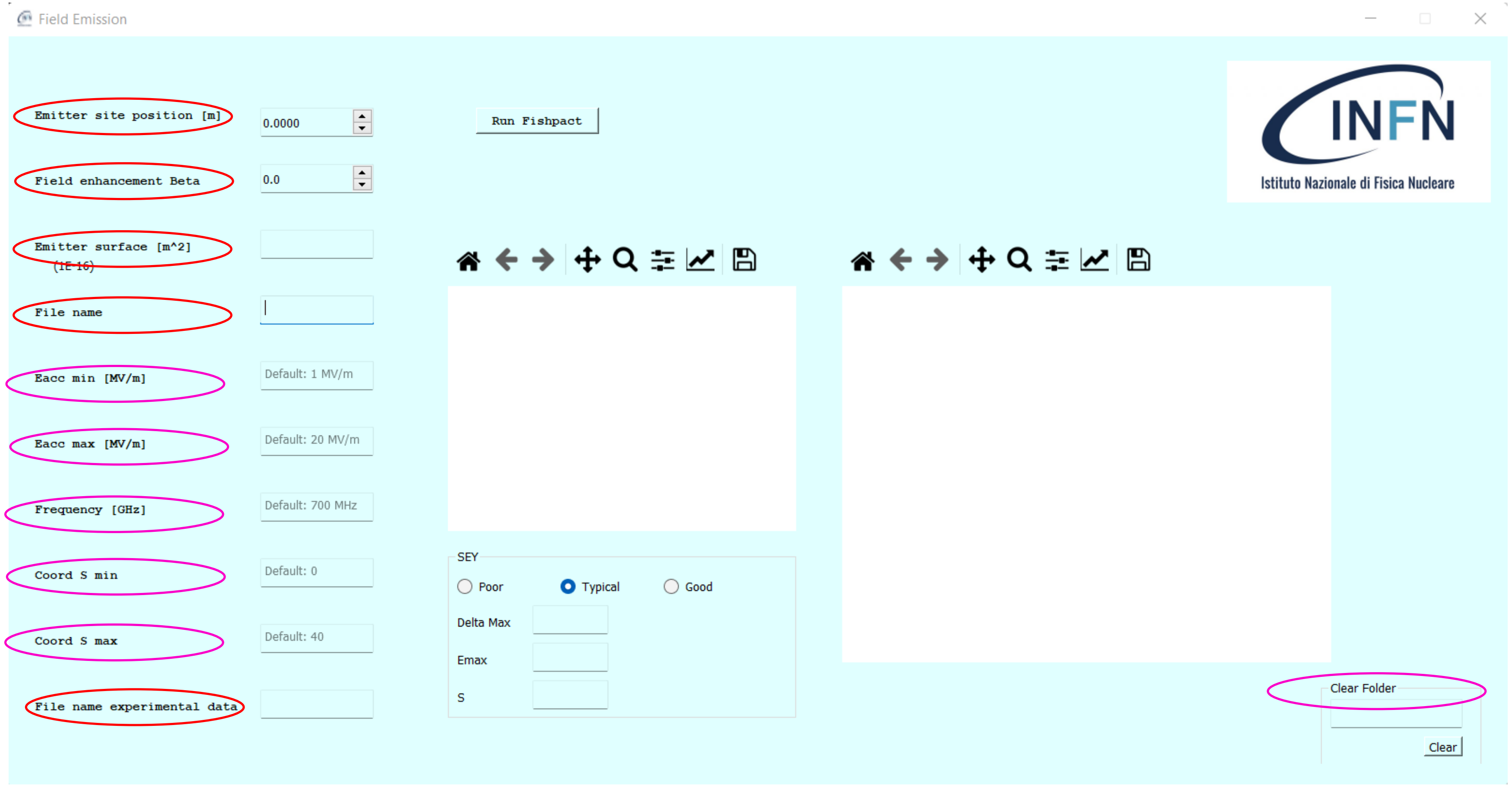
- Gas-filled (Xe) proportional counter (Thermo Electron FH 40-G) for dose measurement:
  - Measurement range from 100 nSv/h to 1 Sv/h
  - Continuous aquisition every 1 sec.
  - Energy range from 45 keV to 1 MeV→ poor sensitivity for higher energies
- NaI(Tl) scintillator (Ortec 905-3) for measuring X-ray spectrum
  - Maximum count rate 10^6 counts/sec
  - Energy range from few keV to 10 MeV
  - Due to its high sensitivity to radiation, for high doses detector saturates producing count pile-up: screening with high Z material is needed!

Graphic Interface

Mandatory to be compiled

Not Mandatory to be compiled

Mandatory to be compiled



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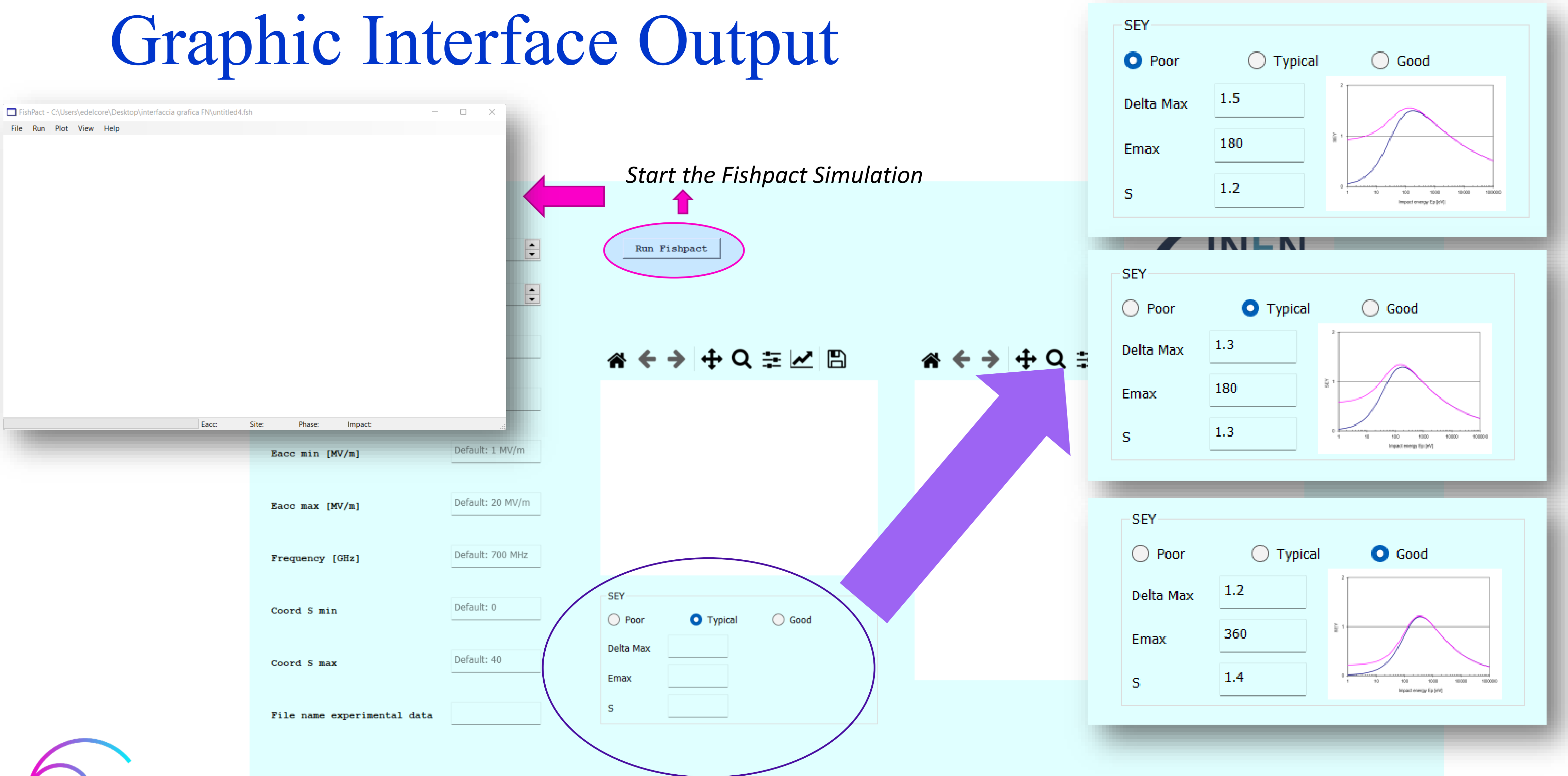
Graphic Interface Output



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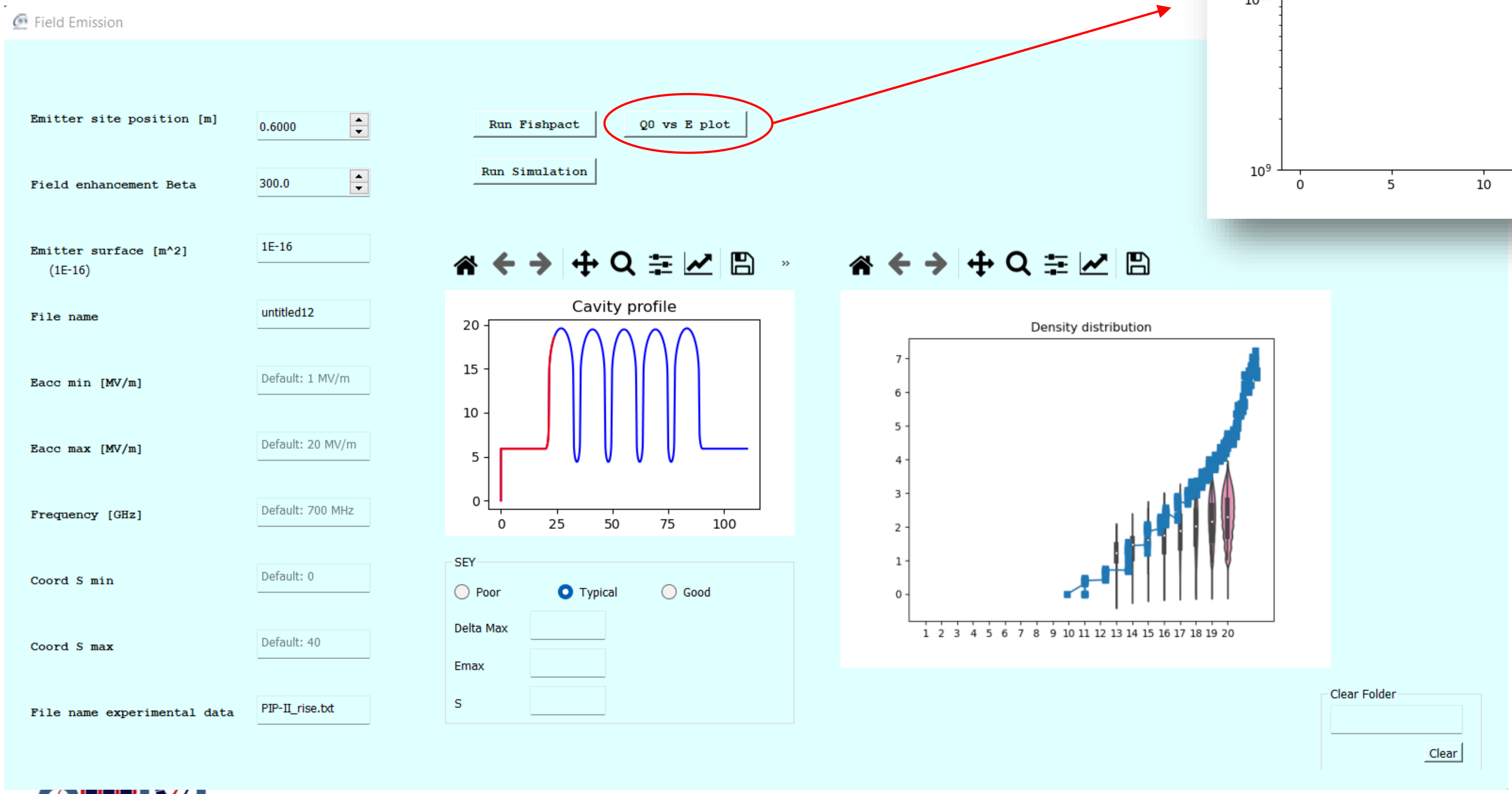
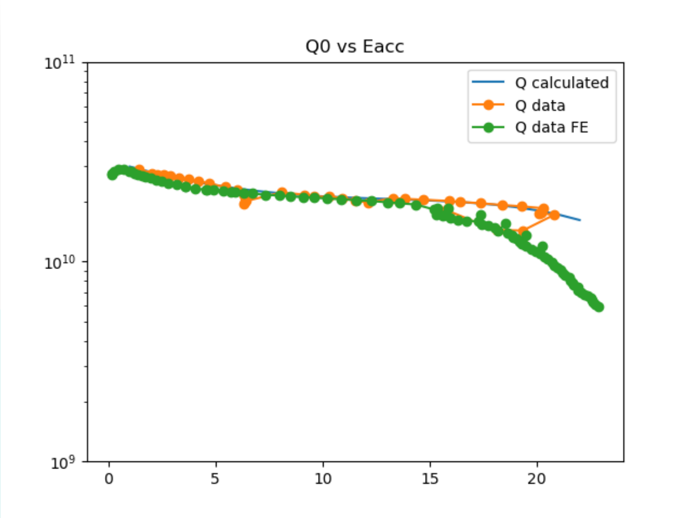
Graphic Interface Output (2)

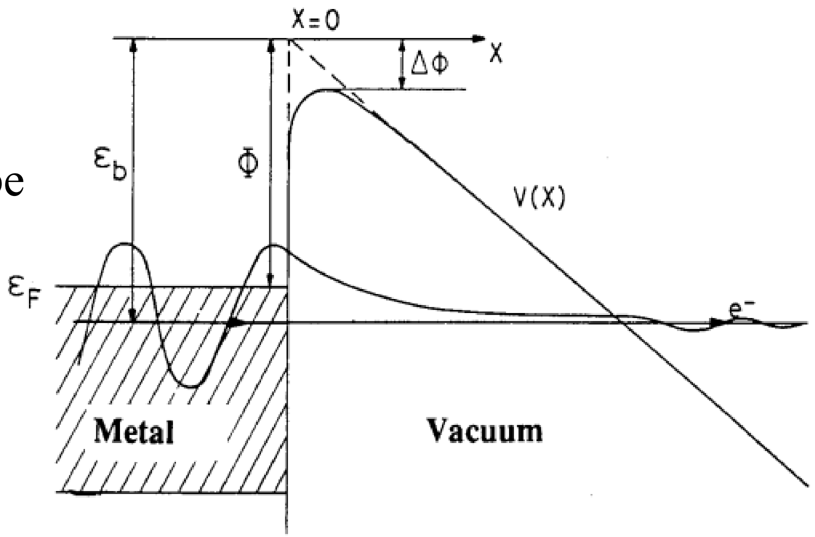




Field Emission

- Emission of electrons induced by an electric field → electrons accelerated by RF fields until their impact on the surface

Fowler-Nordheim law to describe the phenomenon

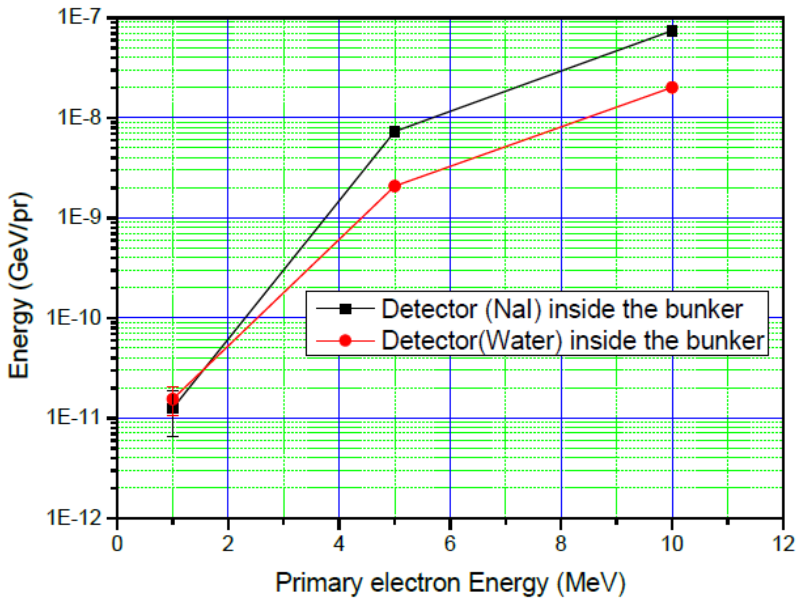


Field emission problems:

- Limits the accelerating gradient
- Degradation of the Q value
- Higher cryogenic consumption

Lasa VTS radiation scenario

- FLUKA model: 10^7 electrons at 10 MeV hitting the cavity beam tube flange, then generating Bremsstrahlung X-rays, which are then attenuated by thermal shields, the cryostat cover, ecc
- External detectors (NaI and tissue equivalent (H_2O)) to collect counts and dose rate
- Total counts in detector: $^{N_{det.}}/_{N_{tot}} \sim 10^{-4}$
- Energy deposited on detector: $^{E}/_{E_{tot}} \sim 10^{-6}$



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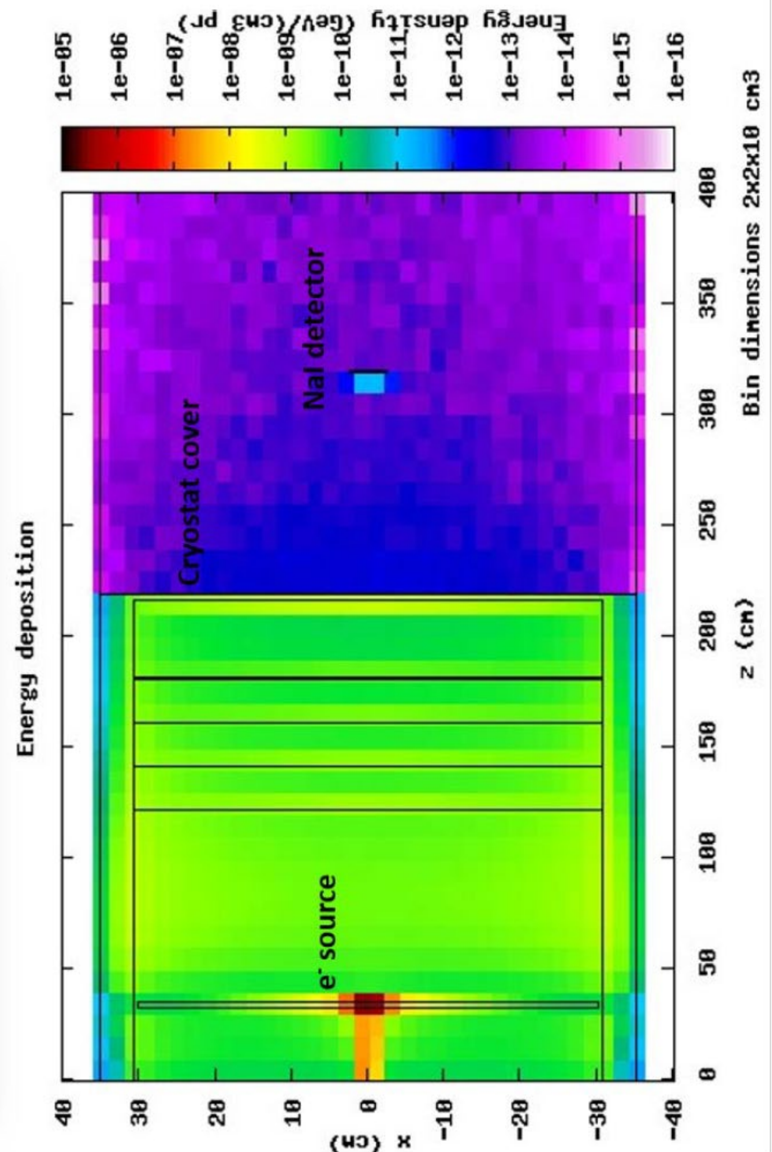


Field enhancement β

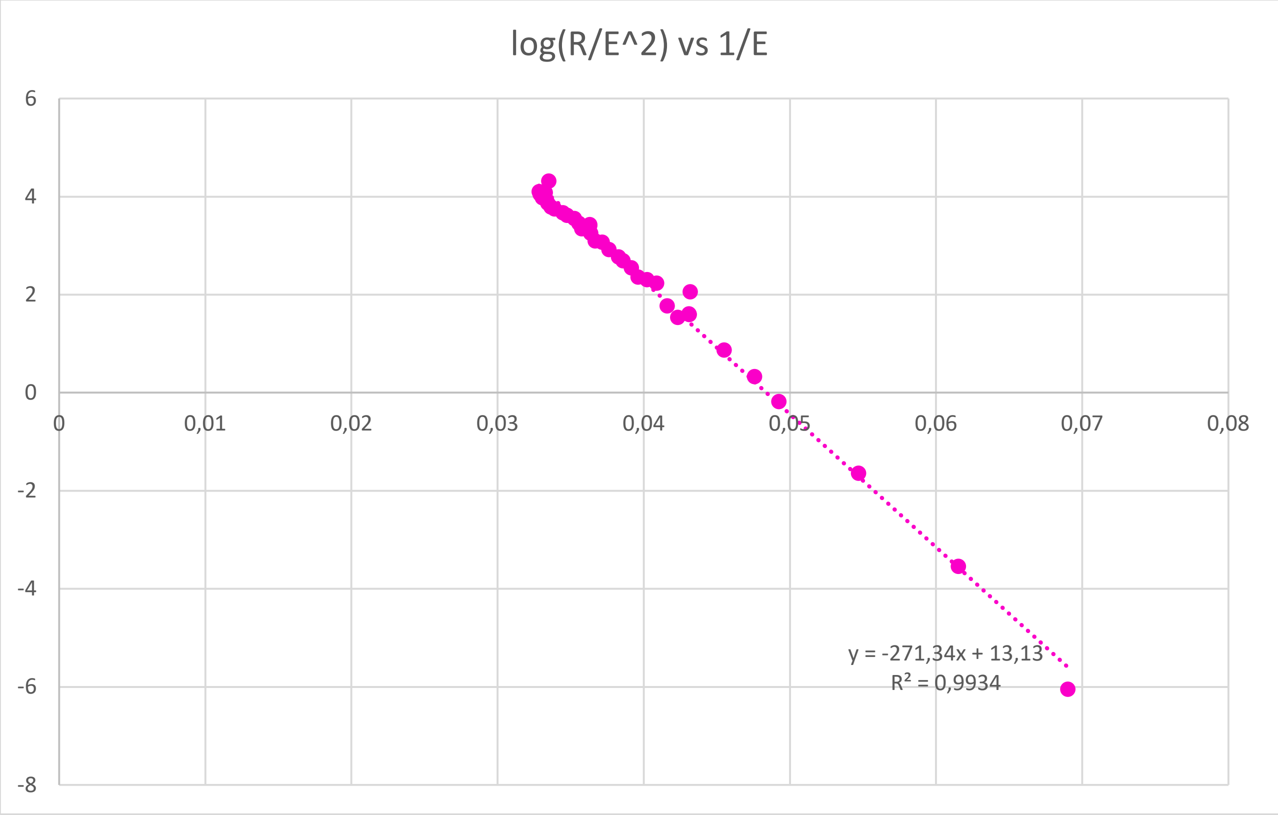
→ *Fit of Fowler-Nordheim equation*

$$I \propto (\beta_{FN} E)^{2.5} e^{-B_{FN}\frac{\Phi^{3/2}}{\beta_{FN} E}}$$

$$dose \ \propto current$$

$$\mathrm{R} \propto \frac{1}{T}\int N(E)E\,dE$$

$$\log\frac{R}{E^2} = \log A - \frac{B}{\beta E}$$



$\beta \sim 250/300$

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