# RECONSTRUCTION OF FIELD EMISSION PATTERN FOR PIP-II LB650 CAVITY

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**Field emission** (FE) is a key limiting phenomenon in **SRF** cavities. An algorithm exploiting a self-consistent **model** of cavity FE has been developed. This method exploits **experimental observables** (such as *Q-value* , *X-ray endpoint*, and *dose rate*) to reconstruct **emitter position** and **size** as well as the **field enhancement factor**. To demonstrate the model self-consistency, the algorithm has been applied to the test results of a **PIP-II LB650** prototype cavity. The results of the procedure are here described.

## Introduction

One of the most limiting factor to the accelerating gradient in **superconducting radio-frequency** (SRF) cavity is **Field Emission** (FE).

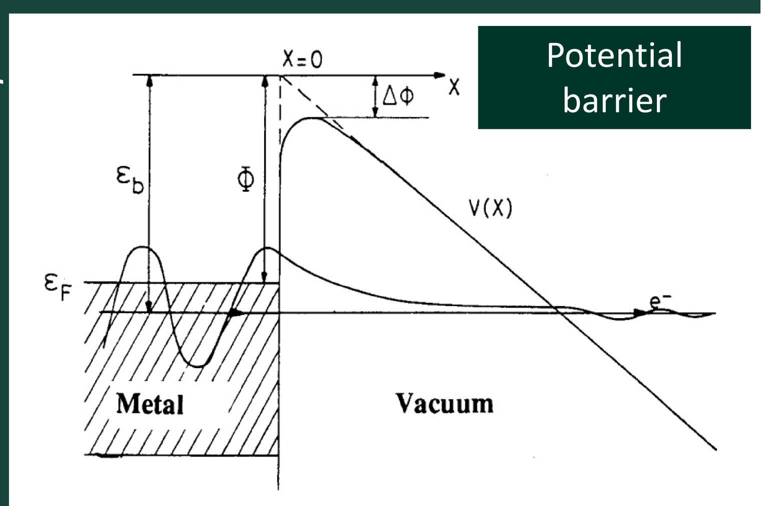
- This phenomenon is associated with the surface electric field $\vec{E}$ and refers to the **emission of electrons** from regions of **high electric field** on the cavity surface.
- These emitted electrons, originating from the **emitters** site, are accelerated by the RF field until they impact the cavity surface.
- As a result of this impact, **X-ray** radiation can be generated.
- The **power** deposited by the impacting electron depends both on the **trajectory** of the particle and on the **intrinsic properties** of the emitter.

In SRF cavities, FE scales exponentially with the $\vec{E}$ and contributes to the consume of RF power. So, it may correspond to an undesirable **degradation** of the **Q-value**, leading to an increase in **cryogenic consumption**.

In a metal, electrons are typically confined by a potential barrier that cannot be escaped in normal conditions. This gap between the **Fermi** level in the metal and the **vacuum** level (a.k.a. ***work function***) can be overcome when electrons acquire energy.

Under the influence of external $\vec{E}$, the potential barrier assumes a triangular shape and its width diminishes.

When sufficiently **thin**, there is a **non negligible probability** for electrons to **tunnel** it and **escape**.




→ <u>Fowler-Nordheim</u> (FN) equation describes the current

$$I = S\frac{A_{FN}E^2\beta^2}{\phi}e^{-\frac{B_{FN}\phi^{3/2}}{\beta E}}$$

$A_{FN} = 1.54x10^6$, $B_{FN} = 6.83x10^3$, β field enhancement factor, ϕ work function and $E_s(t) = E_{s0}\sin 2\pi f t$ electric field

## How to evaluate the REAL FE impact

- External detectors have a **limited field of view** → only a restricted portion of the emission pattern can be observed.
- The emitted radiation undergoes several **attenuation** phenomena before reaching the detector active volume.
- If the electron impact energies are <u>too</u> low: **FE** may **not** be detected

**Challenge**: determine the activated emitter positions "a priori"

- Inner detectors can assist in **reconstructing** the emission pattern; FE can be **coupled** with other phenomena → *multipacting (MP)*, *parasitic mode excitation*, *thermal-induced quench* → more **complex** to comprehensively model the cavity behavior.

## Solver steps

**Objective**: obtain the distribution probability of the emission event

For each value of the **accelerating field**:

- Multiple **emitter sites tested** along the cavity profile
- **Electron current** modeled according to the **FN** emission law
- Colliding electron **trajectories collected** within a specific region on the cavity surface. For each of them, the **impact energy** $E(\varphi_i)$ and the **number** of emitted particles $N(\varphi_i)$ are evaluated.
- Post-processing of simulated data to obtain the **overall impact electron energy spectrum**.

→ **$1^{st}$ cross-check** with experimental data: *X-ray energy spectrum*

- Compute the power drained by electron dark current $P_{FE}$ by summing up over the cavity surface → ***$Q_0$ vs $E_{acc}$ trend***

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

## Case study PIP-II EZ-002 CAVITY

**To validate the model**, the prototype multicell **B61-EZ-002 PIP-II** was used.

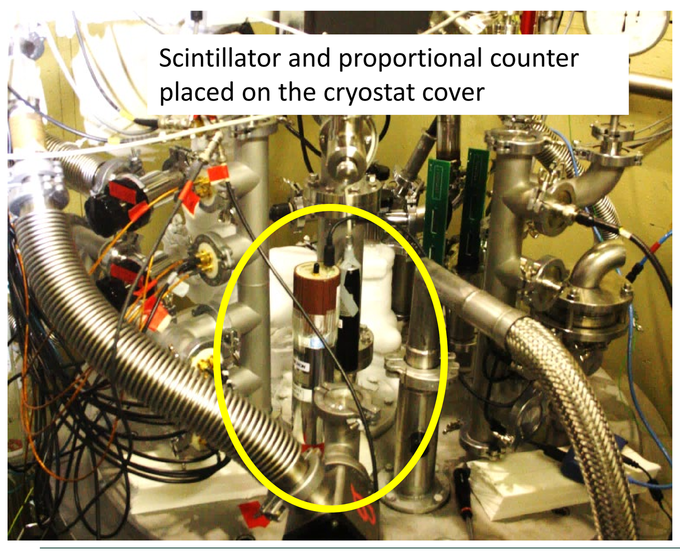
- $1^{st}$ test: some MP with radiation, then sudden rise of radiation at 20.8 MV/m
- Test repeated from low fields
- $2^{nd}$ test: same behavior as $1^{st}$ test up to until 14 MV/m… then sudden rise of radiation and $Q_0$ drop. Cavity quench at 23 MV/m with FE → <u>**irreversible activation of a field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

→ Ideal test bench to assess the self-consistency of the model because Q variation is only due to FE

## Experimental setup

To analyze **FE**, from a practical point of view:

- **External radiation detectors**: portion of the impact electron energy converted to X ray Bremsstrahlung radiation.
  1) **Gas-filled Xe proportional counter:** to monitor the **dose rate** and partially simulate the **power** drained by **electron dark current.**
  2) **NaI(Tl) scintillator:** to capture the **X-ray** spectrum, enabling the evaluation of endpoint, except in case of severe pile-up events determined by poor shielding.
- **Inner diagnostic devices**: electron pick-up probe and photodiodes.
- **Cavity Q-drop measurement**: to evaluate the **overall power** of FE if it is the dominant factor limiting the performance.




Field-dependent effect of **FE** on the quality factor evaluated as:

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

**$Q_0$**: quality factor without FE, **l**: accelerating gradient, **R/Q**: cavity geometric shunt impedance

Total dissipated power given $P_d = P_c + P_{FE}$, where $P_c$ is the power dissipated in cavity walls.

## Model of Field Emission

- Combination of experimental investigation and theoretical framework to ensure consistency between model and measurements.
- Experimental observables used to establish a self-consistent model: ***dose rate***, ***energy endpoint*** and ***Q-drop*** → determination of key parameters such as ***emitter position***, ***emitter size*** and ***field enhancement factor***.
- **FishPact** program (2D model for electron energies and tracking simulations) used as a starting point, to simulate **pure FE** events (multipacting events are neglected)

→ electron absorbed upon its first impact with the cavity walls.

**Pro** and **cons** of FishPact: lack of advanced post-processing features and emission models, but faster computational speed.

**Field enhancement factor** ($\beta$):

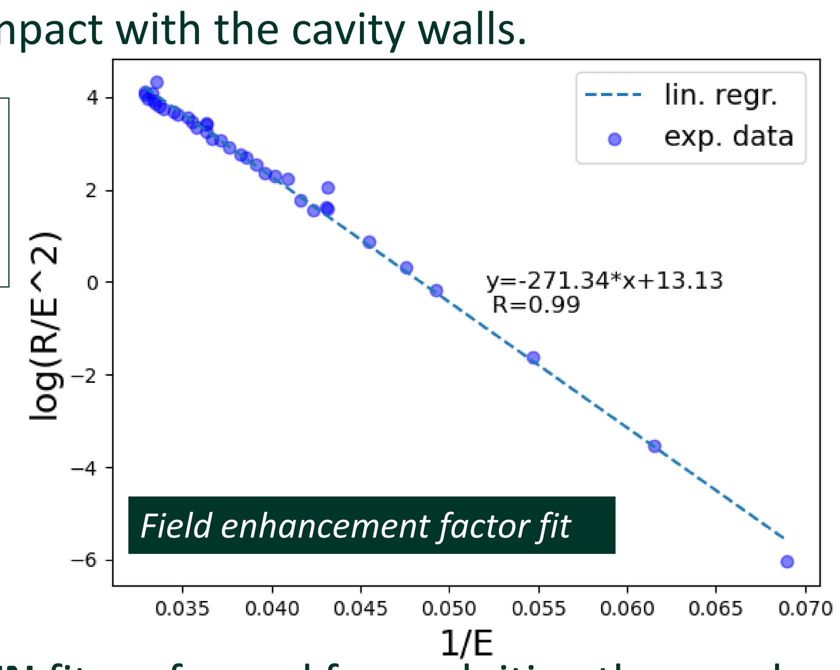
- Considers the field emitter **geometry**
- Can be computed by fitting the **FN** equation with the **dose rate**

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

A and B are coefficients

**Dose rate** expected to be proportional to the **electron current**:

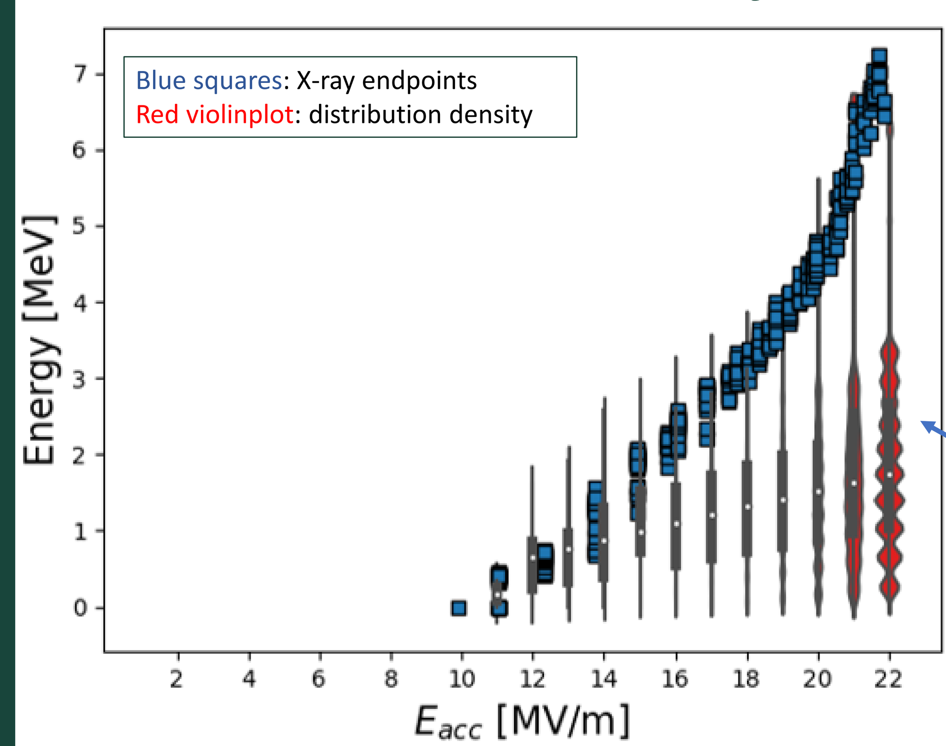
$$R \propto \frac{1}{T}\int N(E)dE$$




**FN** fit performed for exploiting the angular coefficient of the derived curve.

- Procedure applied to the case of **B61-EZ-002** PIP-II prototype cavity
- Estimated value of $\boldsymbol{\beta \sim 250 - 300}$.

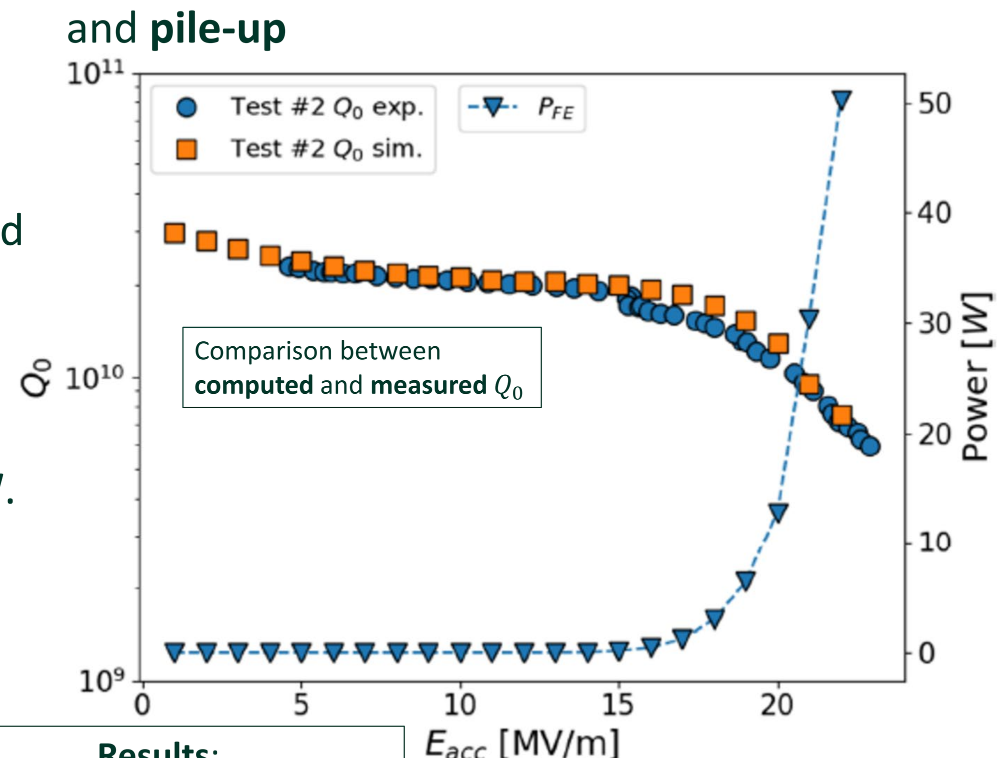
## Case study simulation results




- Numerous FishPact simulations, varying $\boldsymbol{E_{acc}}$, **emitter site position** and **size**.
- $1^{st}$ step: calculation of $\boldsymbol{E_{acc}/E_{peak}}$ for all coordinates
- Leveraging FishPact *.out* files, a script discretized **FN** law within a given range of $\boldsymbol{E_{acc}}$ and $\boldsymbol{\varphi}$ and applies it to electron trajectories to obtain the **probability** distribution.

Reconstructed **density distribution**, compared to X-ray **endpoints** → good agreement between computed and measured data up to 20 MV/m. At higher fields: detector **saturation** and **pile-up**

- Good **agreement** between computed and measured $Q_0$→ satisfactory solution for estimating position and size of the suspected emitter site.
- Computation of the **power** due to **FE** (plot in the right Fig.) → **power** begins to rise @~19 $MV/m$ and @*20 MV/m* it reaches **12 W**.




**Results**:
β=300
*emitter* $A = 1.5x10^{-15}m^2$
*emitter* position nearby iris 2

**Open points**: 1) modeling the electron-to-photon count deconvolution (to exploit dose rate measurements); 2) evaluation of pile-up statistics; 3) convergence of the model when sampling with smaller $\varphi$ steps to find a balance between computational speed and model accuracy