Radiation and Field emission in RF structures

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Outlook

1. The Optical fibre detector (Beam Loss Monitor) system + motivation

2. Simulations with FLUKA

3. Measurements with a T24 at the dogleg
    - Electron field emission
    - RF Breakdown
    - Pre-Breakdown study

4. Measurements with a T24 CC at XBOX 2

5. Conclusions / next steps

How it all started: Beam Loss Monitors (BLM)

Radiation detectors installed along the machine

1. Machine Protection
   - **Detect potentially dangerous instabilities**
     (destruction of the surrounding materials, activation of machine components)
   - **Prevent subsequent injections /dump the beam**
2. Beam Diagnostics
   - The fraction of beam particles lost has to be carefully controlled to achieve **good beam transmission**
   - Localise and characterise the beam loss distribution

<u>Motivation</u>

A 3 TeV CLIC machine will have more than 140000 accelerating structures

1. Electron field emission
   - Accelerating electric field
   - → Dark current has been measured ~mA
   - → Electrons lost inside the cavity?
2. RF Breakdown
   - ~100 A
   - Field collapses

Do BLMs detect these phenomena?
Are field emitted electrons limiting the BLM sensitivity?

Optical fibre detectors

Pure Silica core multimode fibres as Cherenkov radiators. Both ends of fiber couples to photon-sensors.

Operation principle

i. Beam loss shower particles cross the optical fibre → **Cherenkov photons**

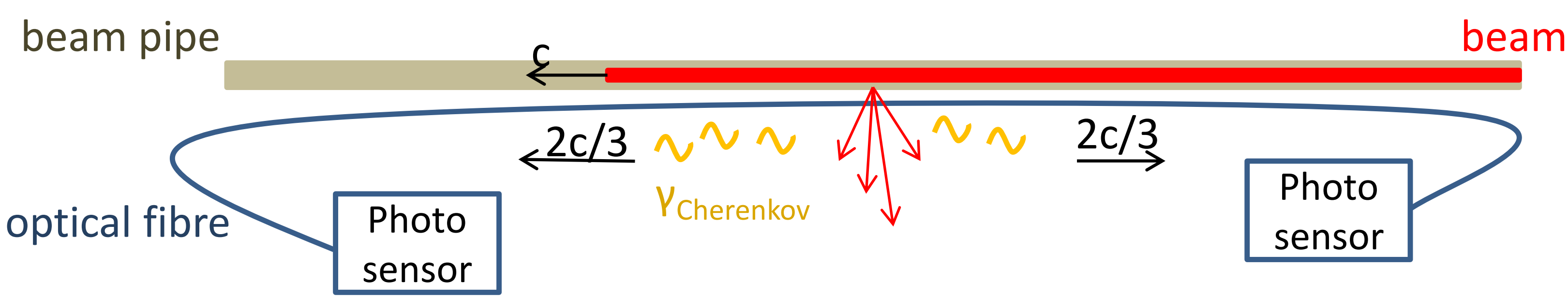
ii. Cherenkov photons propagate in the optical fibre → **photosensor!**

- ✓ Cost-effective - Covering large distances (~100 m)
- ✓ Insensitive to neutral radiation (n, γ)
- ✓ Position resolution of ~30 cm has been demonstrated

} Ideal for high energy linacs !

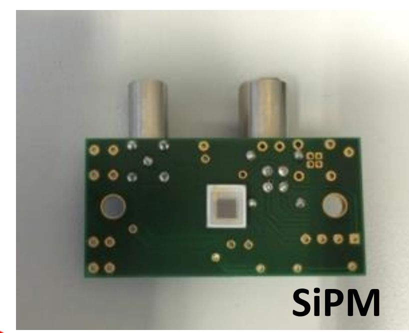
Monitors:

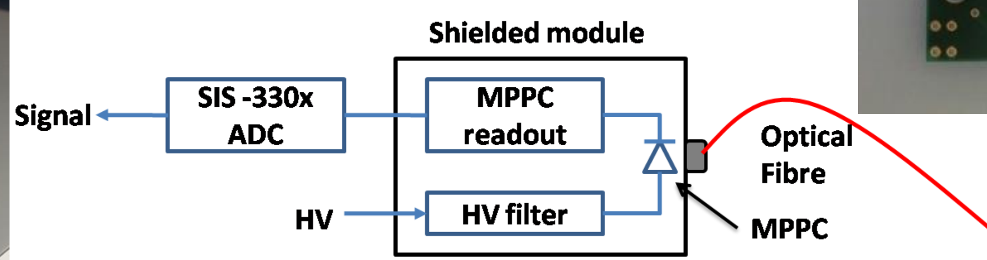
- ○ Charged particles (here: e^+, e^-, $\boldsymbol{E_{kin,\,th} = 0.186}$ ***MeV***)



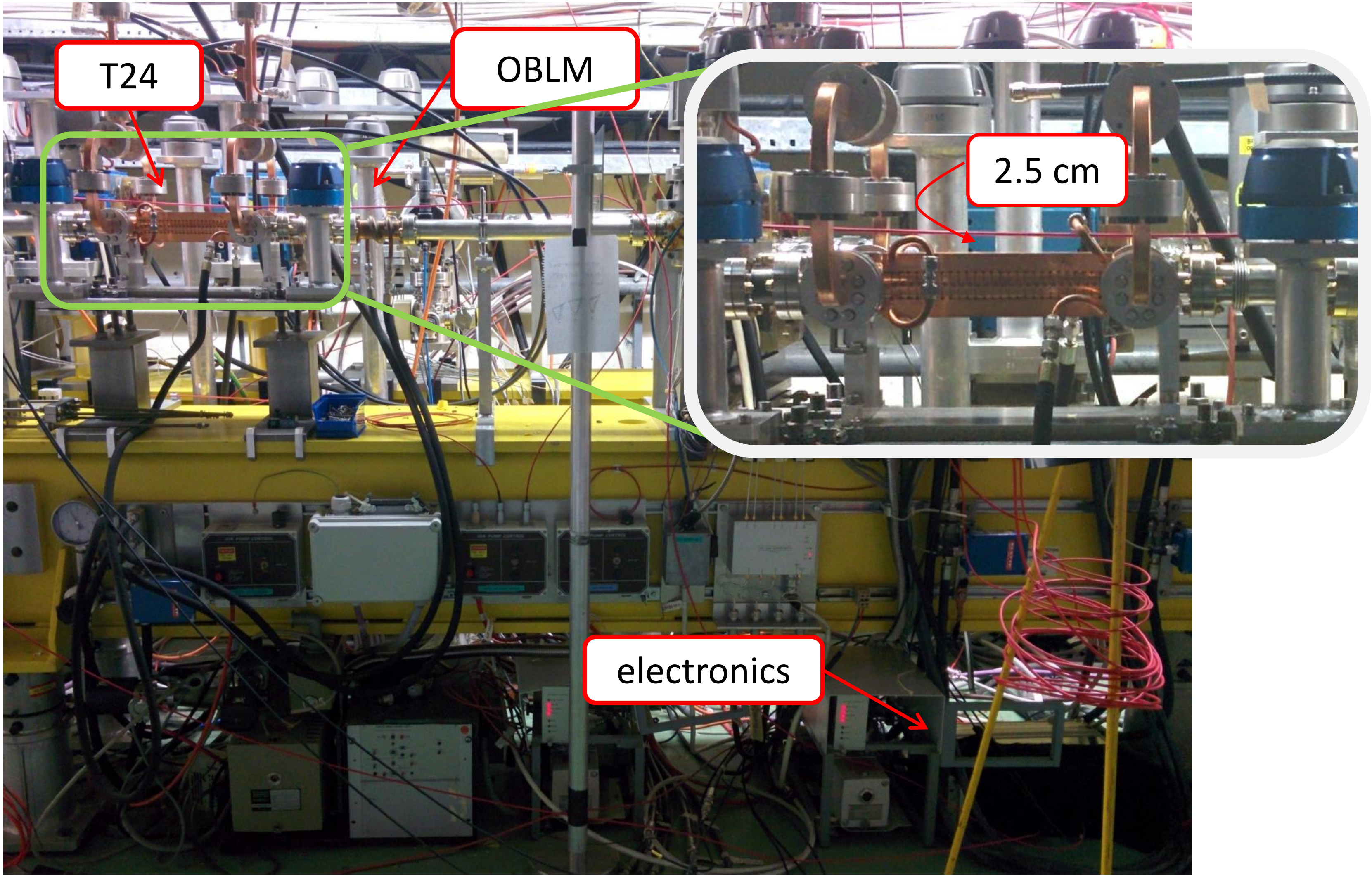
Detector characteristics

- System sensitive to low electron signals
- Optical fibre:
  - Core Ø 900 µm multimode pure silica
- Development of **custom made, shielded** photon sensing modules
  - Silicon PhotoMultiplier (SiPM) ($3x3\ mm^2$, 3600 pixels, $G = 10^{+5} - 10^{+6}$)
  - Transimpedance amplifier, feedback resistor $R_F = 0.5\ k\Omega$
  - Low pass filters (bias input) for noise filtering
- Design of **RF shielded chassis** to include the modules



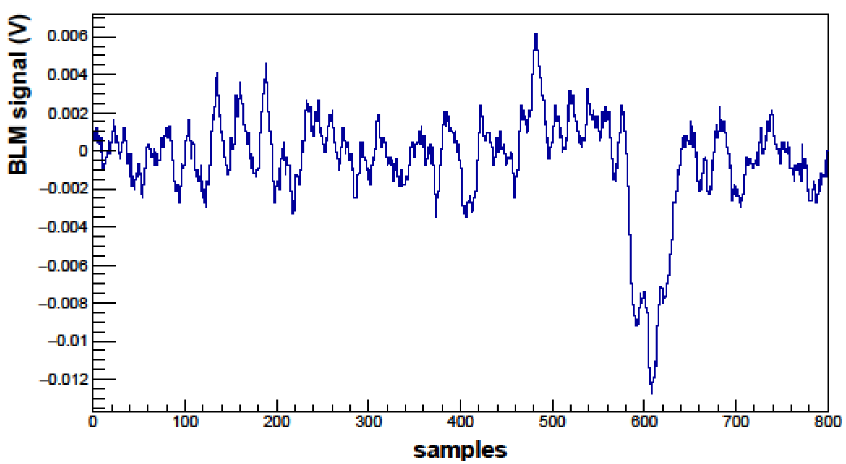


Installation at the dogleg experiment

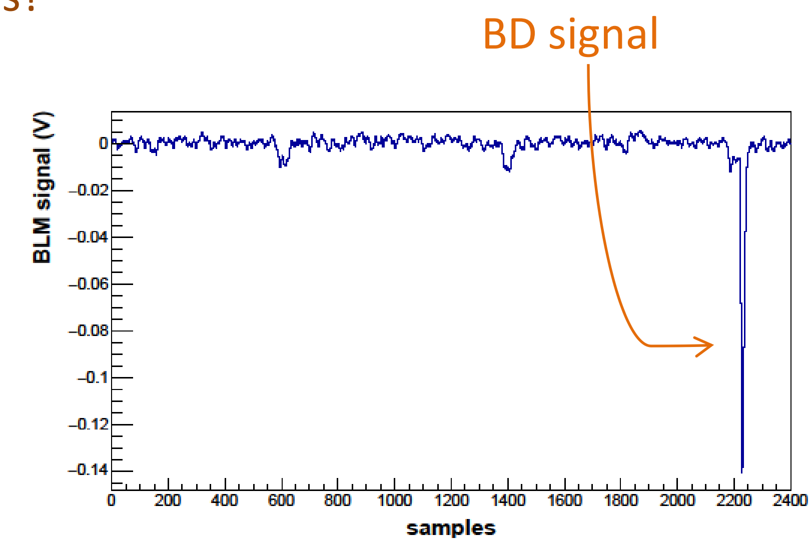


Observed signals

- Measurements in an unloaded structure
- Significant signals observed during operation
  - Can it be electrons?
- High signals during RF Breakdown
  - What is the energy of these particles?



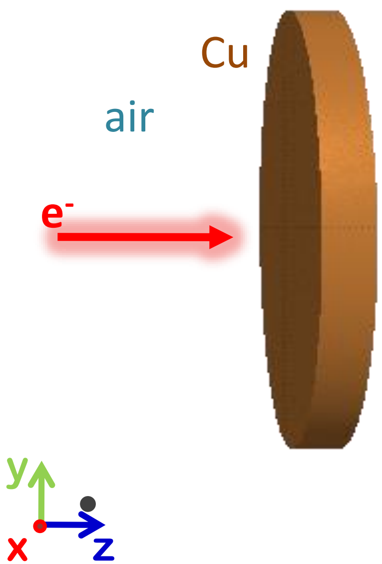
normal operation

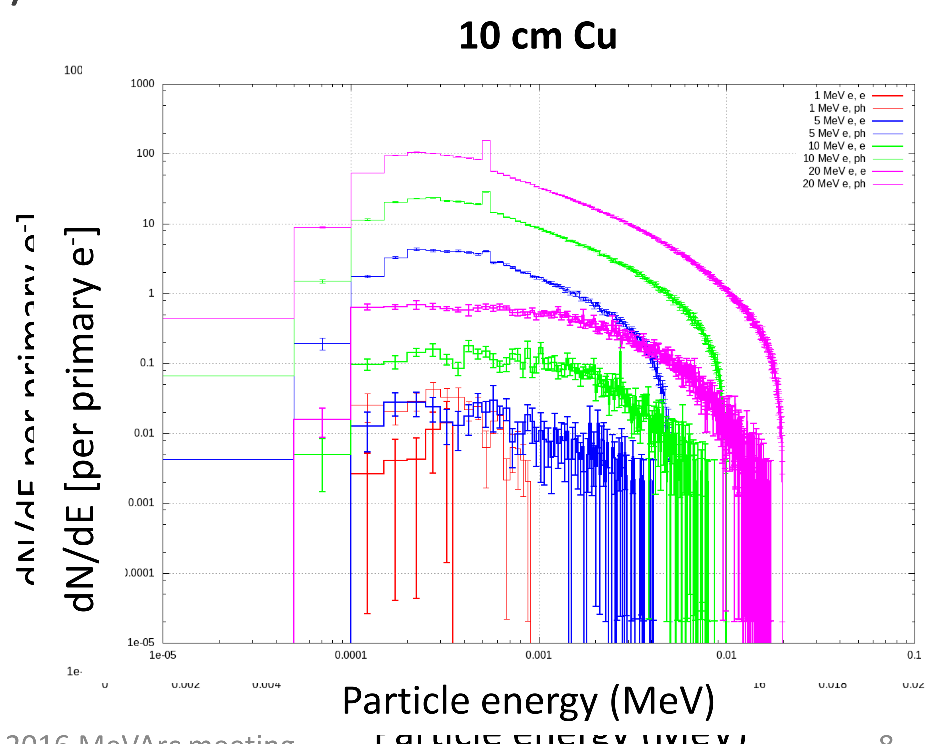


RF breakdown

FLUKA simulations: Electrons on Copper

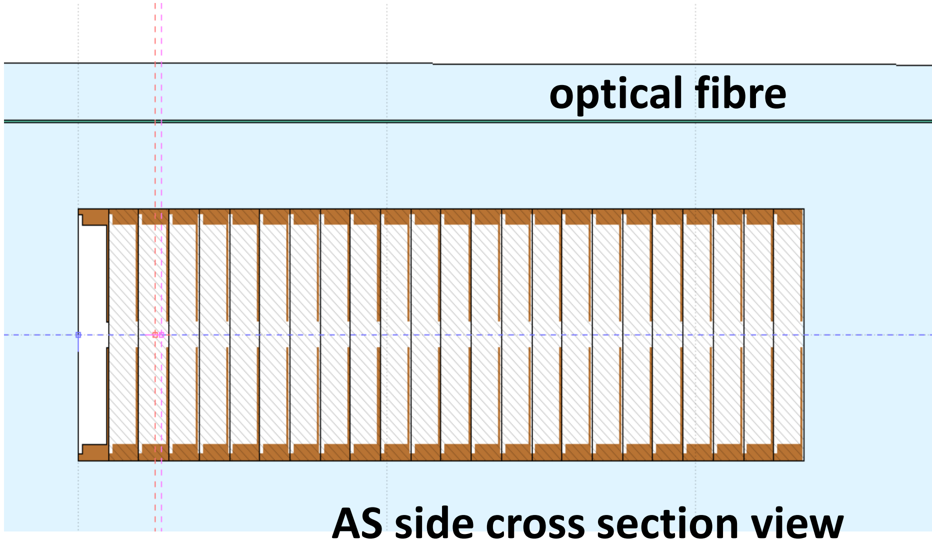
- FLUKA: Monte Carlo simulation package
  - Interactions of particle with matter
  - Particle tracking
- Electrons on Cu disk: Can we see electrons on the other side?
- Variable disk lengths 1/3/10 cm
- Variable beam energies 1/5/10/20 MeV
- **disk** ⟶ **air** particle fluence

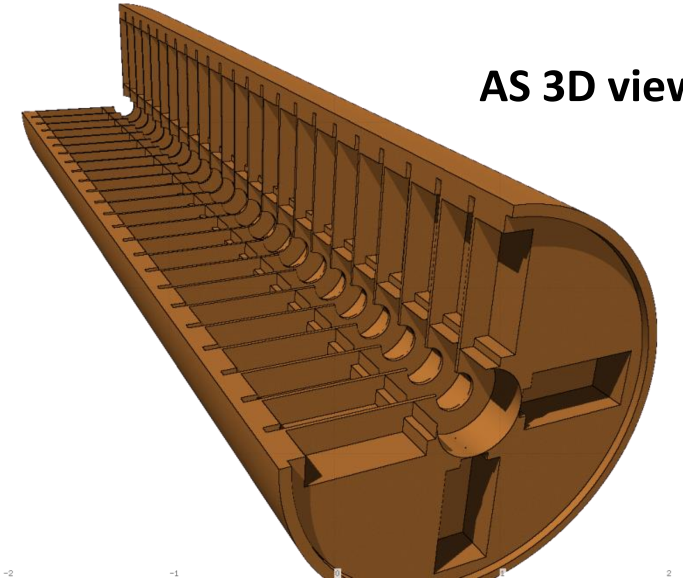


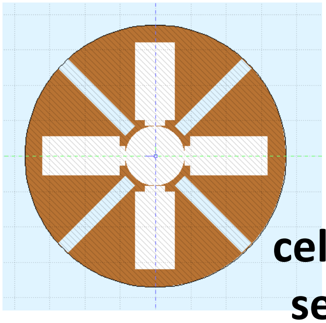


FLUKA simulations: geometry

- Basic geometry simulation
  - CLIC TD24 AS, copper
    - No couplers
    - No Beam pipe
  - Optical fibre (900 μm SiO_2) covers the structure and extends 15 cm downstream, 5 cm upstream
  - Can electrons from inside the AS reach the fibre with energies **>200 keV** (Cherenkov threshold)







cell cross section

FLUKA simulations: settings

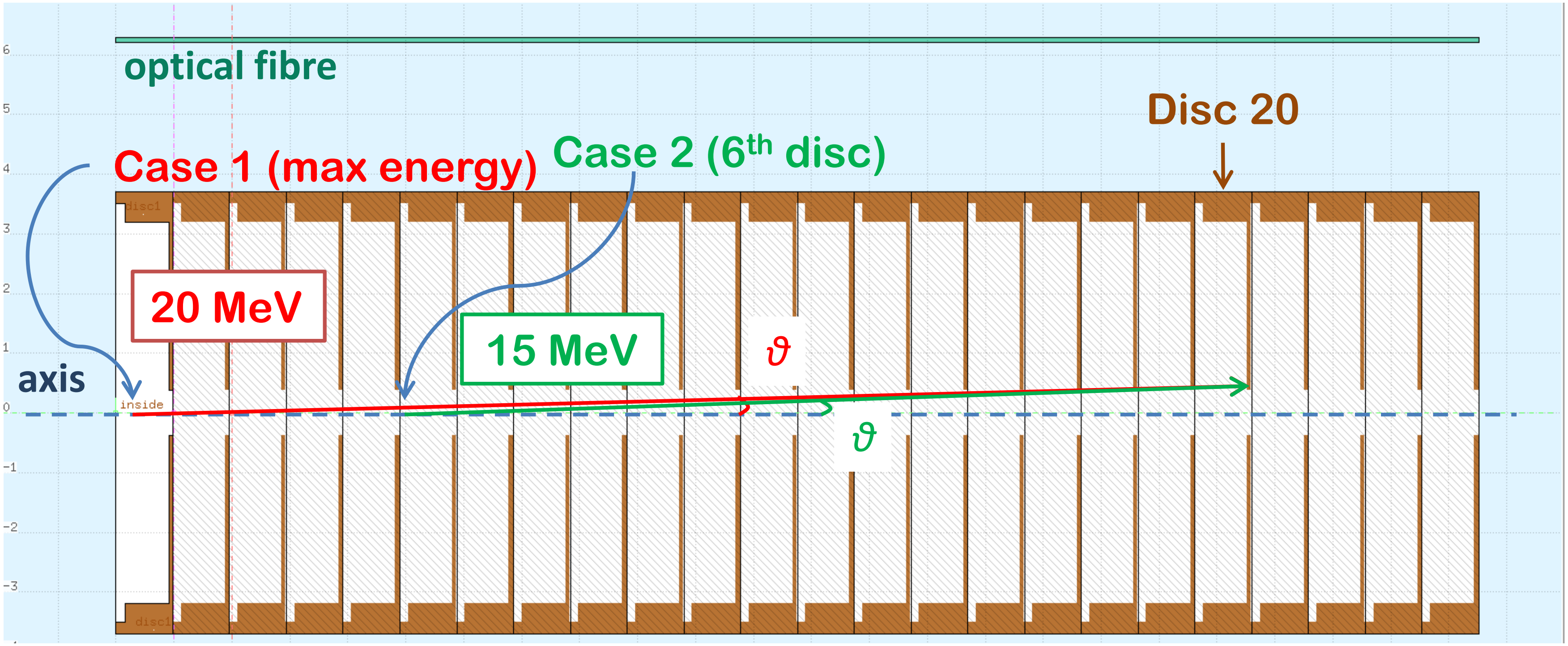
100 MV/m, cell length ~1 cm —1 e^-→ 1 MeV/cell

Assumptions:

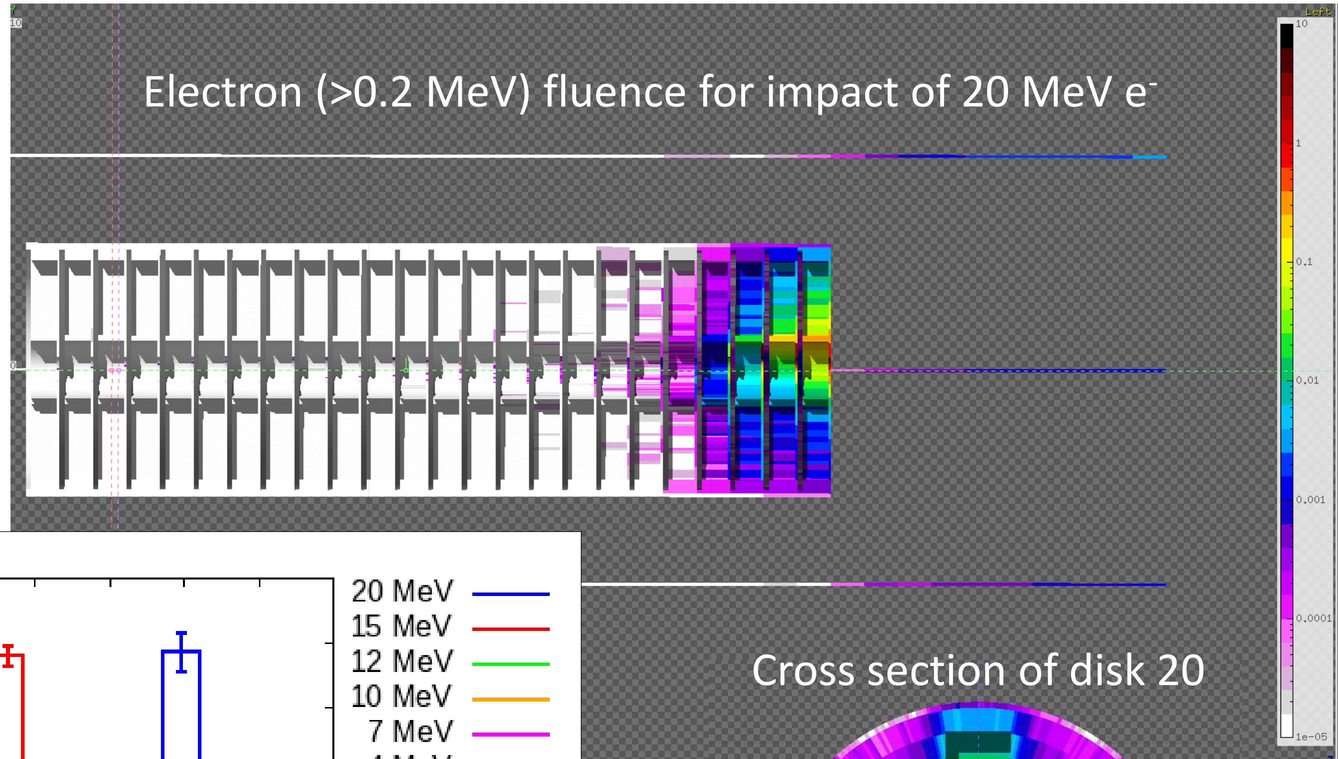
- Emitted electrons start from the axis of the cavity
- They all hit the iris of disc 20

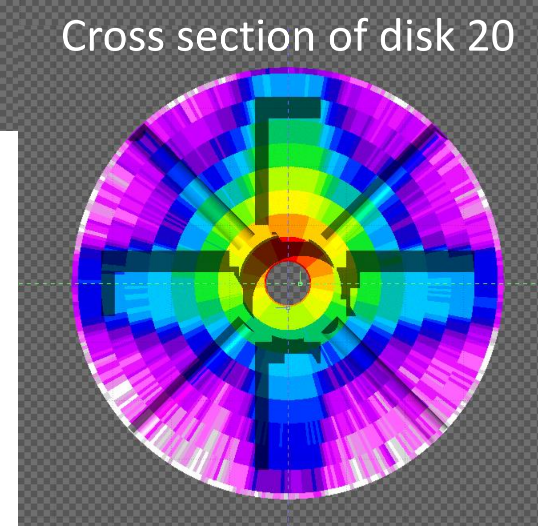
Distance $x = 0.98 \cdot N_{cells}$

- Energy depending on N_{cells} travelled, $E = N_{cells} \cdot 1$ *MeV/cell*
- Interaction angle depending on the starting position of the electron $\vartheta = \arctan(d_{iris}/2x)$

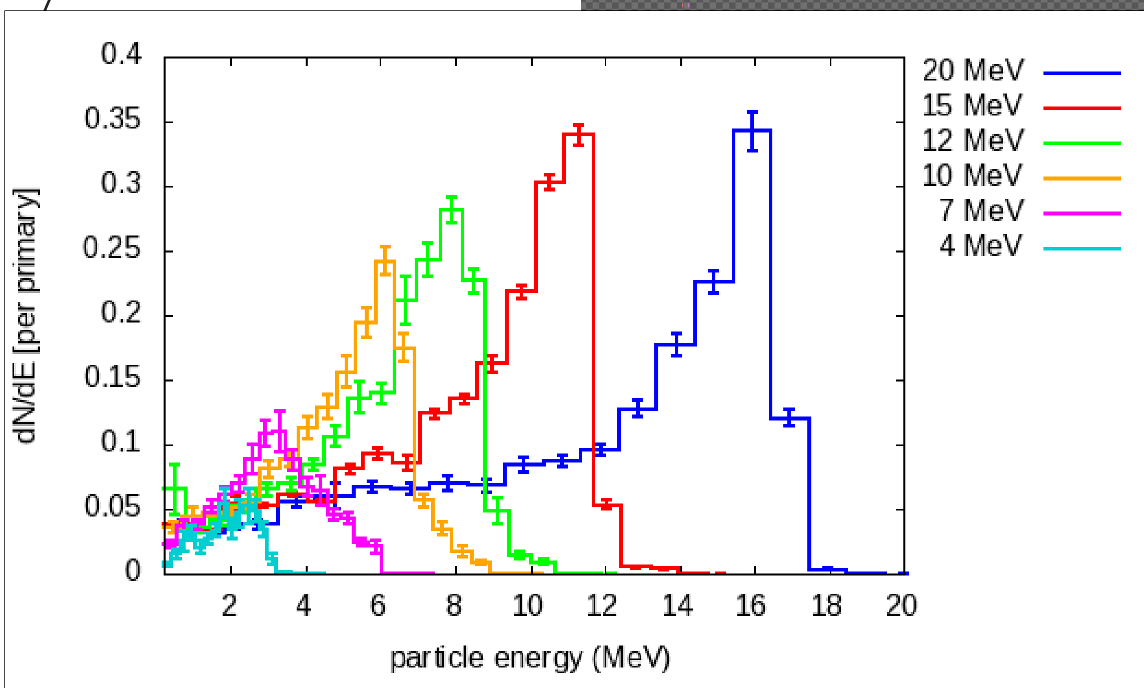


FLUKA simulation: results

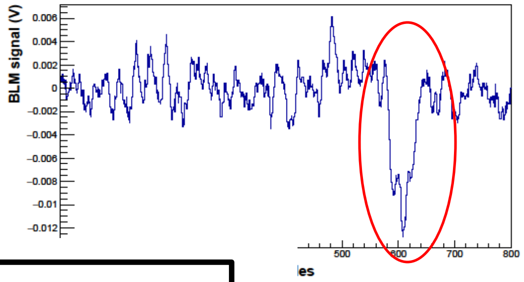




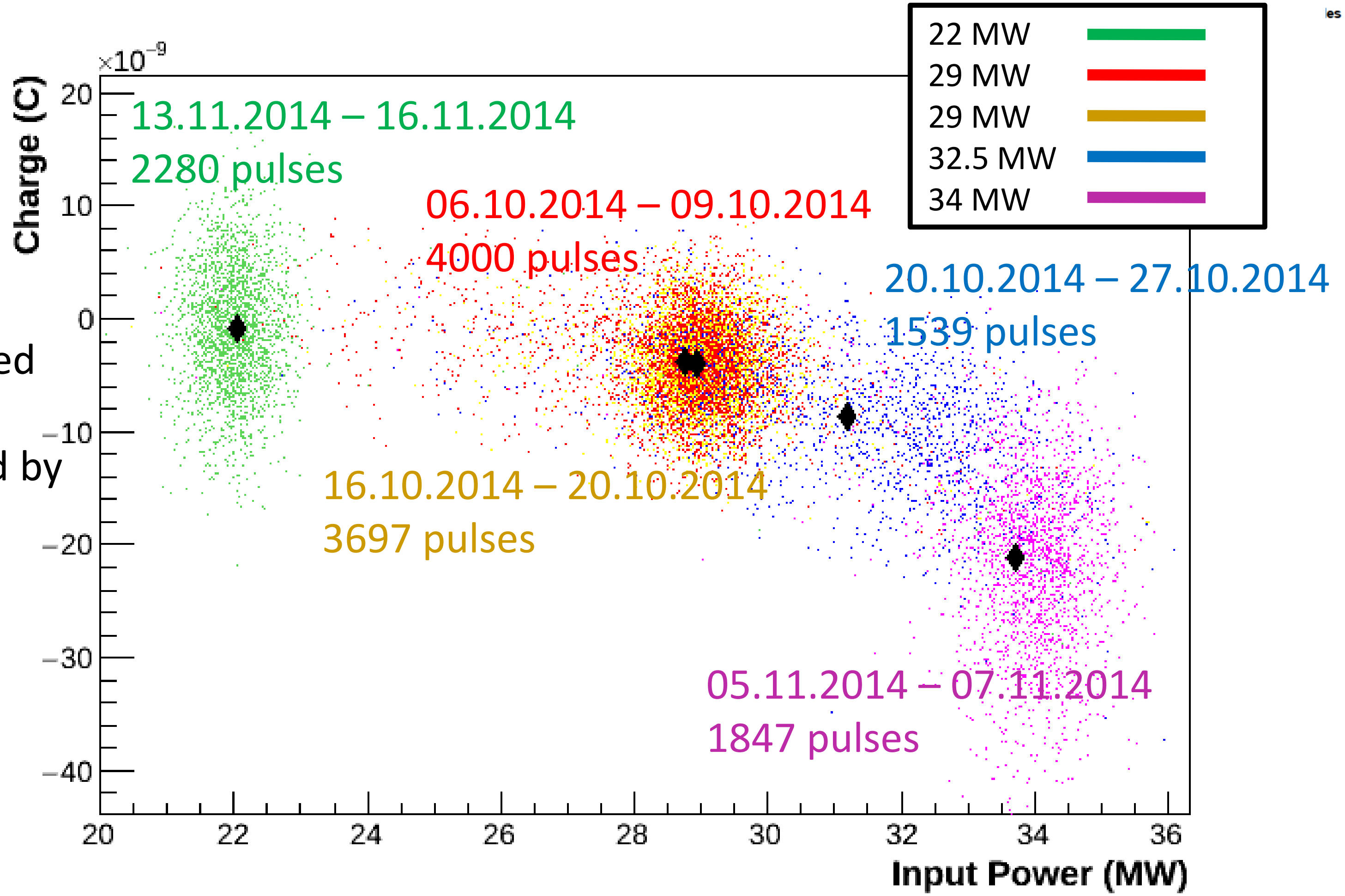
e^- crossing the fibre per primary electron impacting on the iris



Signal – Input Power Correlation

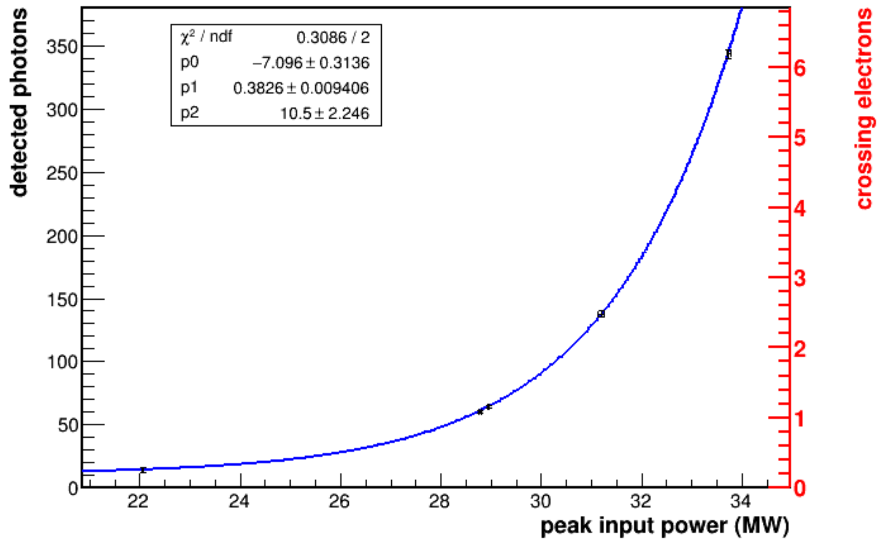


Integrated charge detected by the BLM

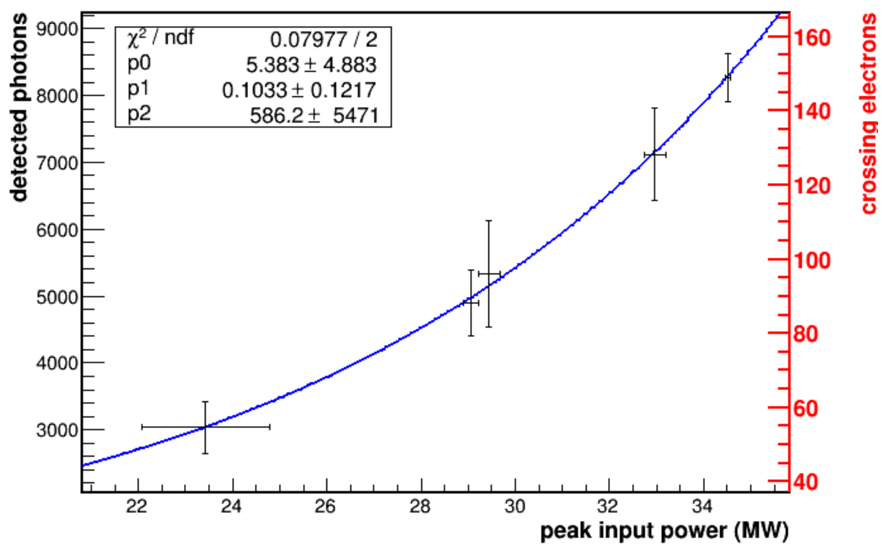


Results

Electron field emission



RF breakdown



Mathematical estimation of what our signals corresponds to in terms of **detected Cherenkov photons**, and electrons crossing the optical fibre .

- Fit function :

$$N(x) = \exp(p0 + p1 \cdot x) + p2$$

- Agrees with I_F of electron field emission theory

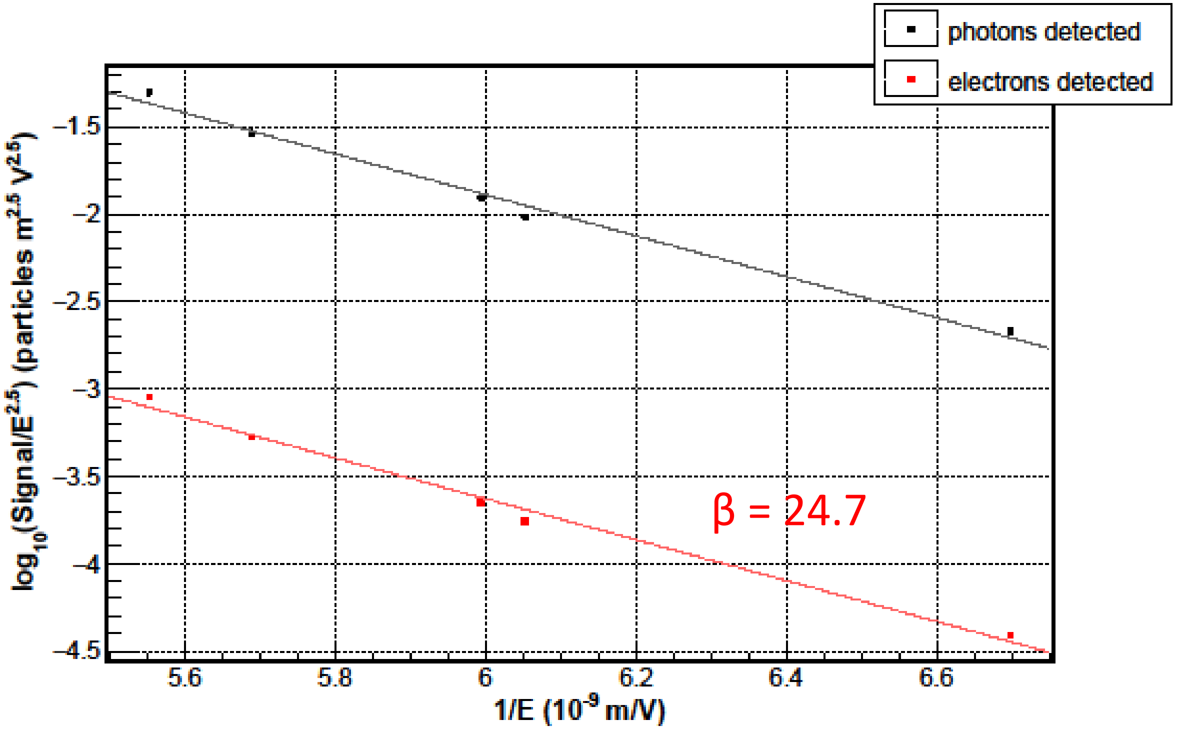
- RF Breakdown:
  - Low statistics, high errors
  - Can also be fitted by an exponential

Electrons detected outside the cavities during RF Breakdowns. Physics yet to be understood

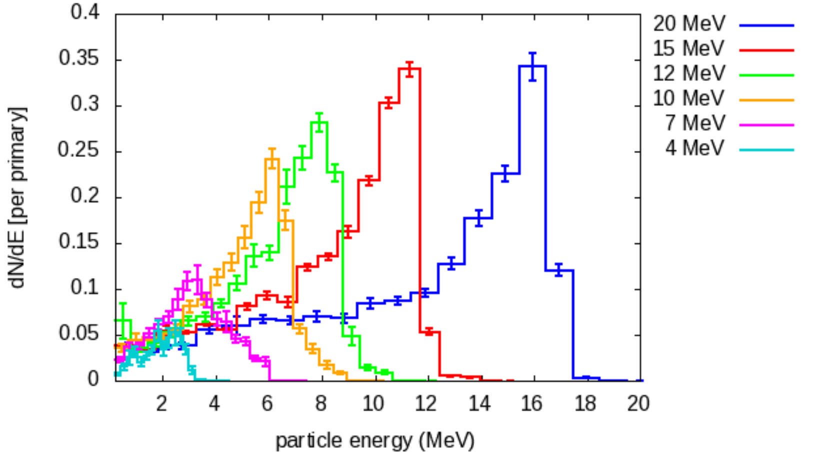
Fowler-Nordheim calculcation

- Calculations for photons detected / electrons outside the cavity
- E: mean surface electric field
- $\beta = 24.7$

However: The range of particles in matter is not taken under consideration

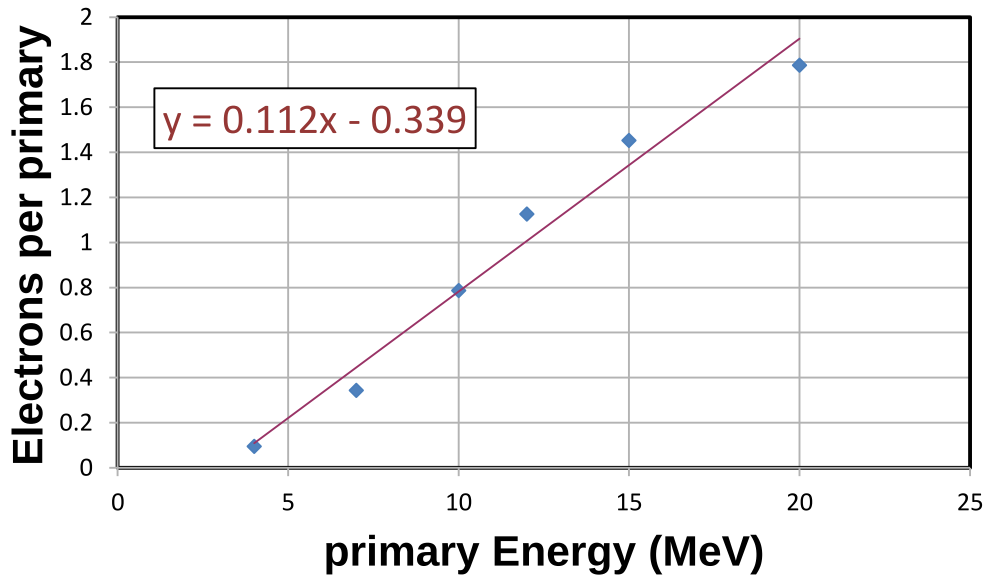


Fowler-Nordheim calculcation (II)



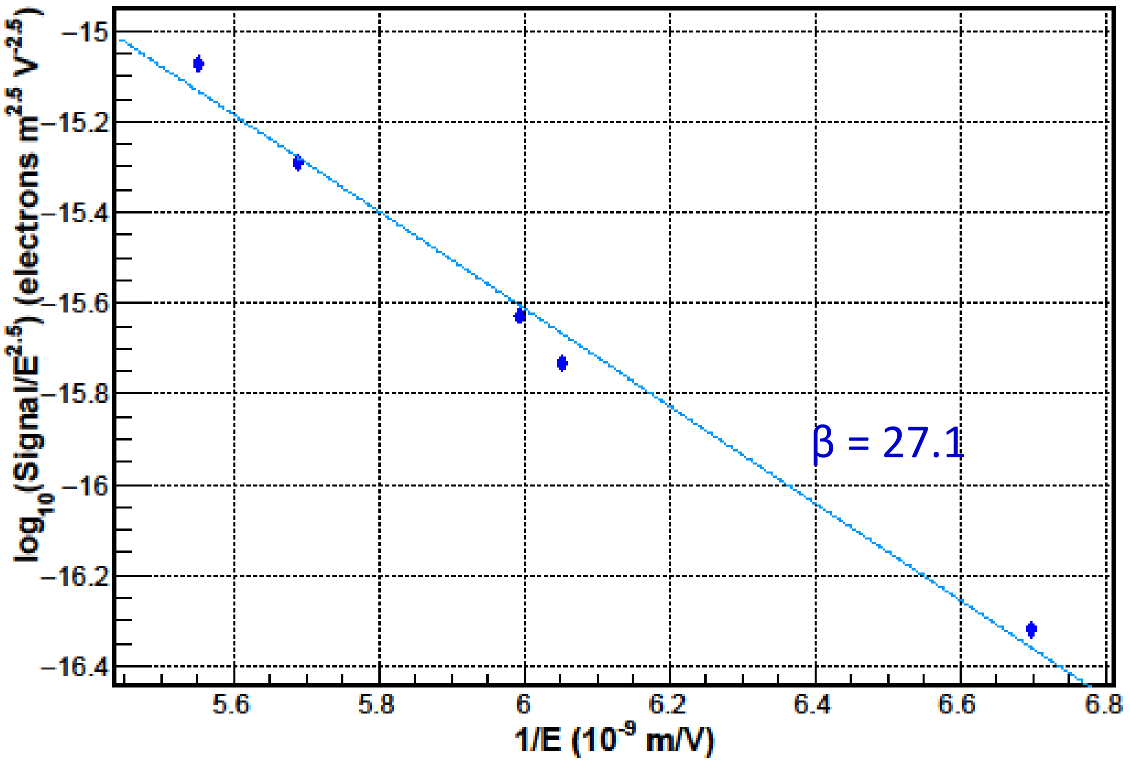
From the FLUKA simulations we can make an approximate calculation of the electrons lost within the cavity

(correlation of electrons detected per primary to energy)

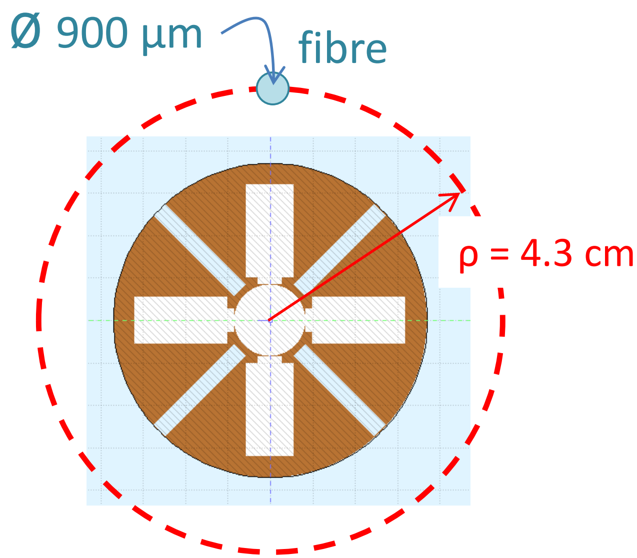


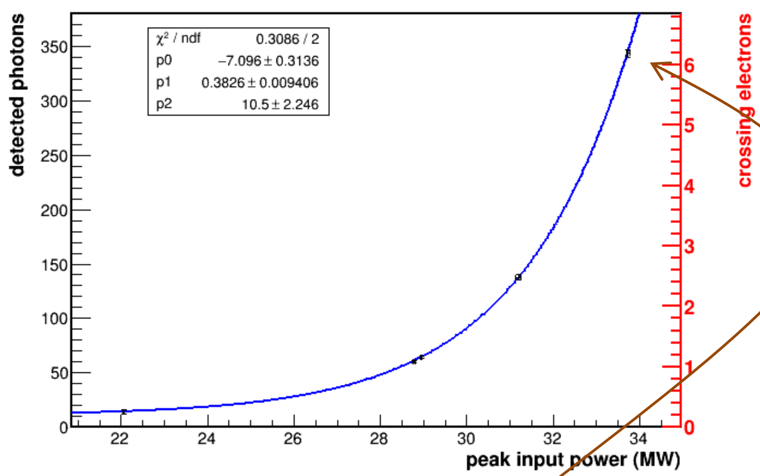
Fowler-Nordheim calculcation (III)

- Estimation for electrons within the RF cavity
  - Primary energy: the energy after 12 cm in the structure
- β = 27.1 ⟶ Higher than the β for signal outside the cavity



Estimations of radiation around the cavity





$$\frac{d}{2\pi\rho} = 0.33\%$$

$$1Gy = 3.1\times10^{9}\,\frac{MIP}{cm^{2}}$$

@ 34 MW → ~ 6.6 e^- in fibre

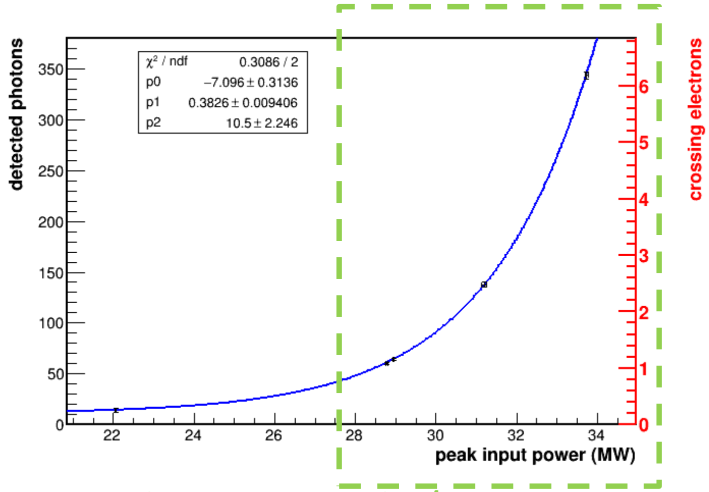
→2 x10^3 e^- around the cavity

Considering a length of 30 cm of the fibre leads to a dose of **0.8 nGy per pulse**.

The corresponding value for the case of RF Breakdown @ 34 MW:

~10^7 e^- around the cavity , ~**0.1 µGy per breakdown**

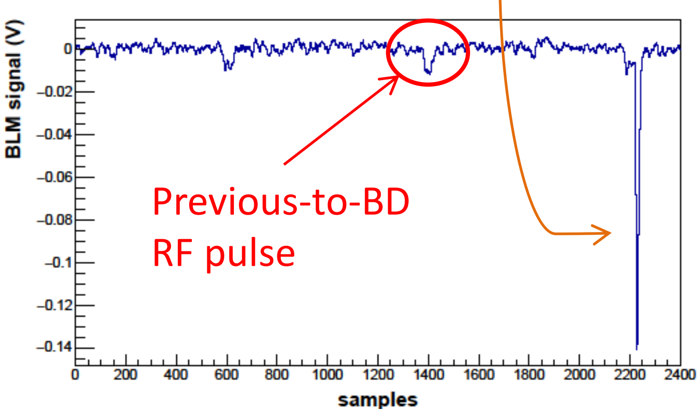
Charge accumulation prior a BD



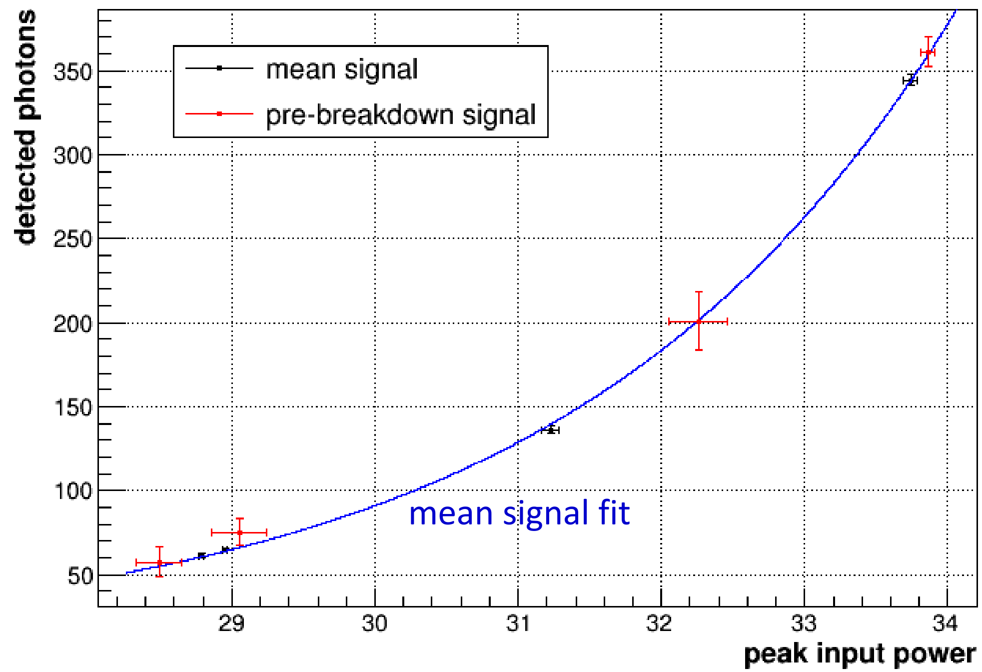
Cleaner signals / Higher statistics

- Comparison of the previous-to-BD BLM signals to the mean value of all pulses.
- No accumulation of charge observed.

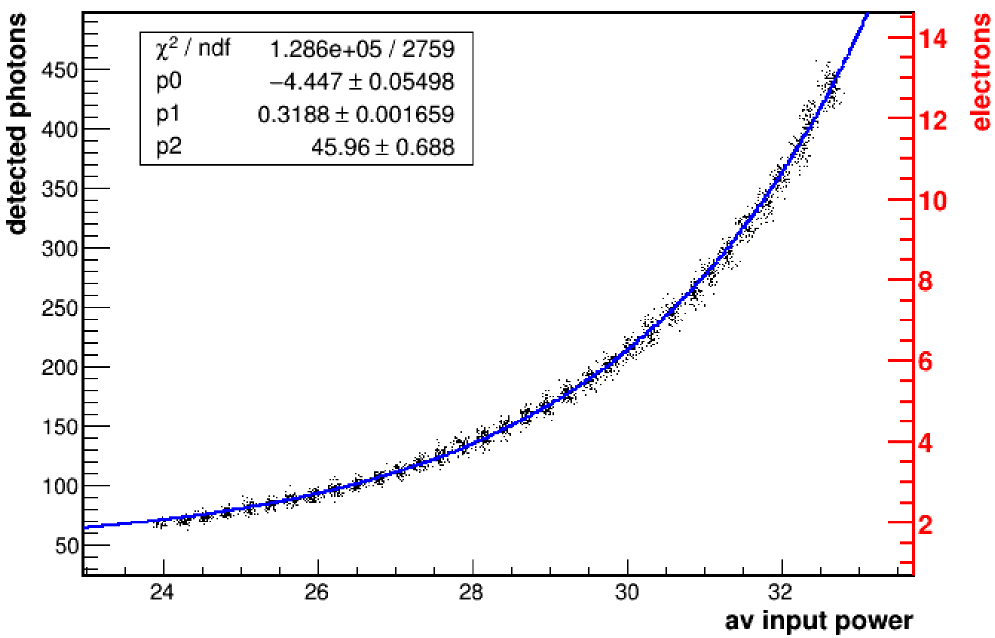
BD signal



Previous-to-BD RF pulse



Installation & energy scan at XBOX2

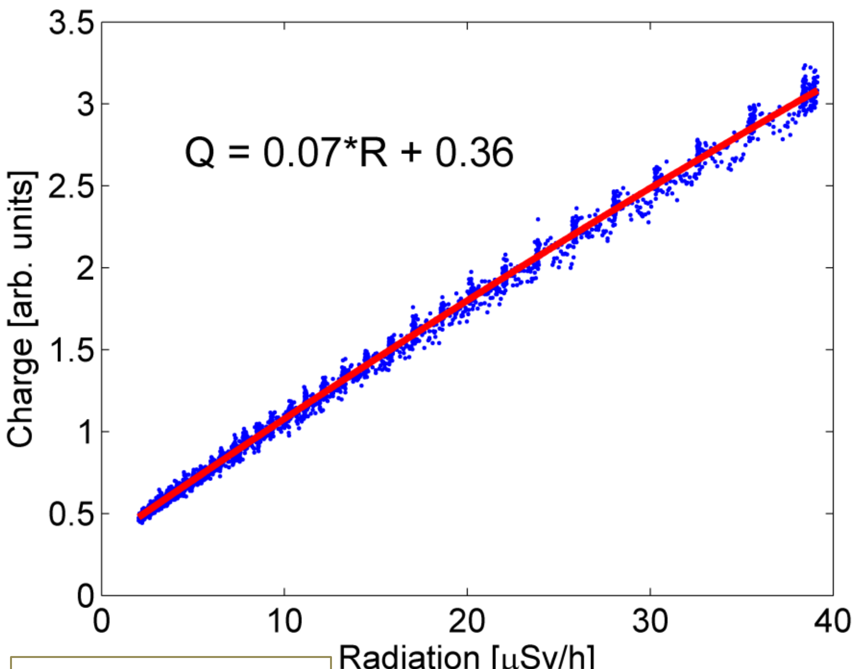


- Installation at XBOX2 of a smaller (Ø 550 μm) fibre
- Radiation monitor installed
- Energy scan
- Detector saturates at breakdowns
  → Improvements are necessary

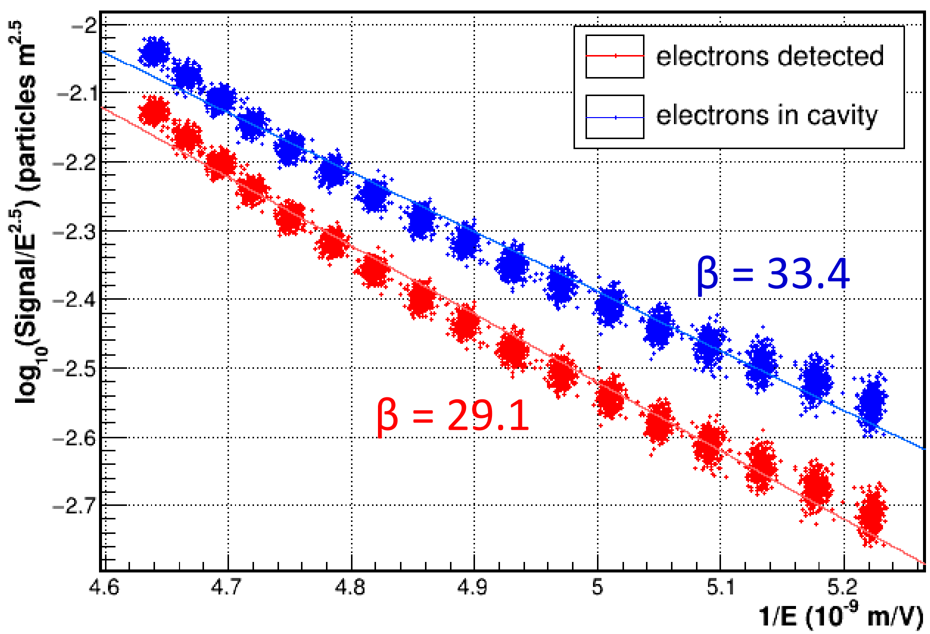
- <u>Field emission</u>
  Exponential fit function: parametres similar to the ones of T24 at dogleg.

Calculations for XBOX2

- Linear relation to the radiation monitor
- F-N plot gives a β = 29,close to the β for the T24 structure at the dogleg



T. Argyropoulos



Conclusions / plans

- Optical fibre detectors can be an useful tool for RF cavity diagnostics
- Detection of electrons outside the RF cavity both during normal operation (electron field emission) and RF breakdowns
- Agreement of measurements with Fowler-Nordheim
- No charge accumularion prior a breakdown has been observed

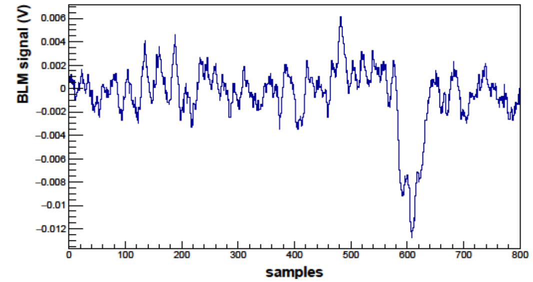
- TD26 installed @ the dogleg – new data to be analysed

- Plans for measurements @ XBOX 2!
    - Studies to estimate the energy of the electrons during RF Breakdowns
    - Attempt to make breakdown position studies???

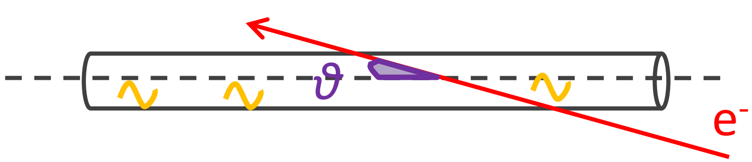
Thank you for your attention!

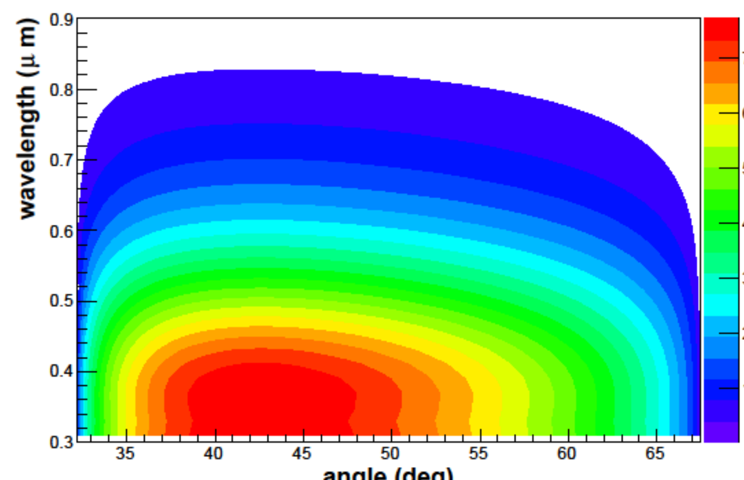
Backup slides

Calculations

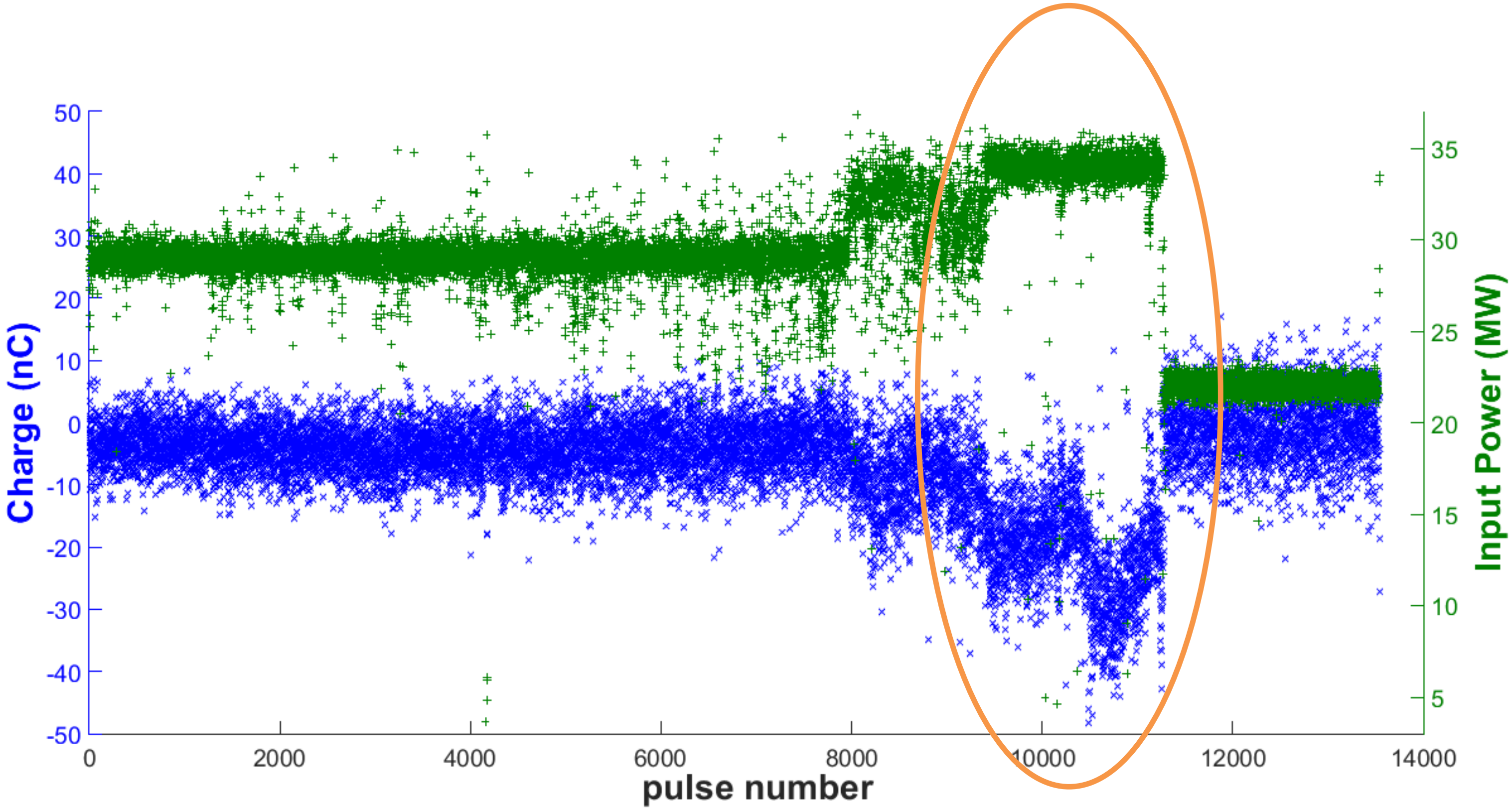


- Mean value of the detected charge (C)
- Calculation of the Cherenkov photons that have given this signal
  - Readout circuit design
  - SiPM Gain
- Estimation of the number of electrons that, if crossing the fibre, would have resulted in this number of Cherenkov photons in the end of the fibre, taking into account
  - Light attenuation in the OF
  - Wavelength distribution of photon yield (~$1/\lambda^2$)
  - Angular dependency of photon yield and photon propagation
  - SiPM efficiency dependence on wavelength
  - <u>Assumption 1</u> : β=1
  - <u>Assumption 2</u> : uniform angular distribution of e^- (0° - 90°)

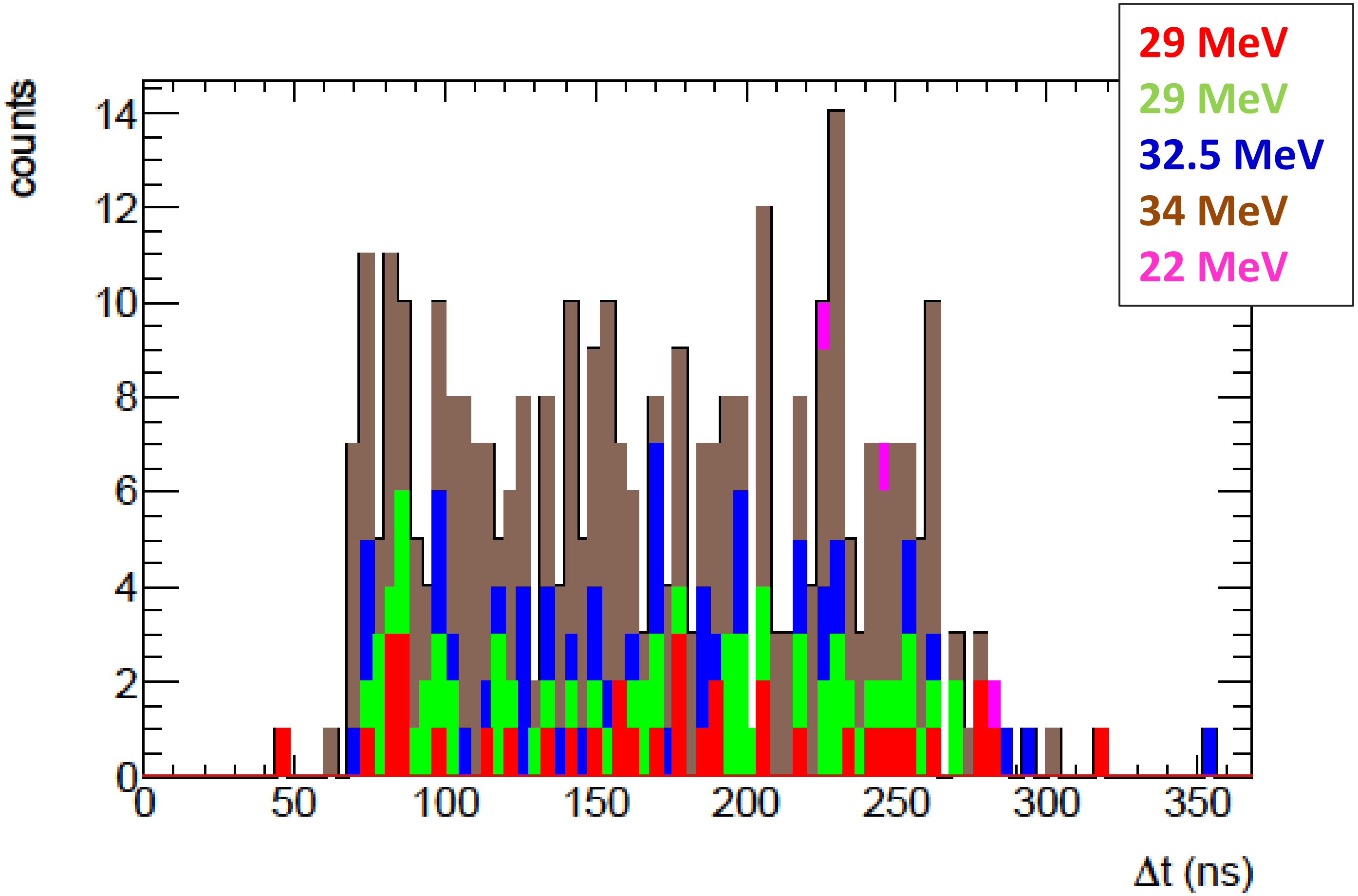




History plot



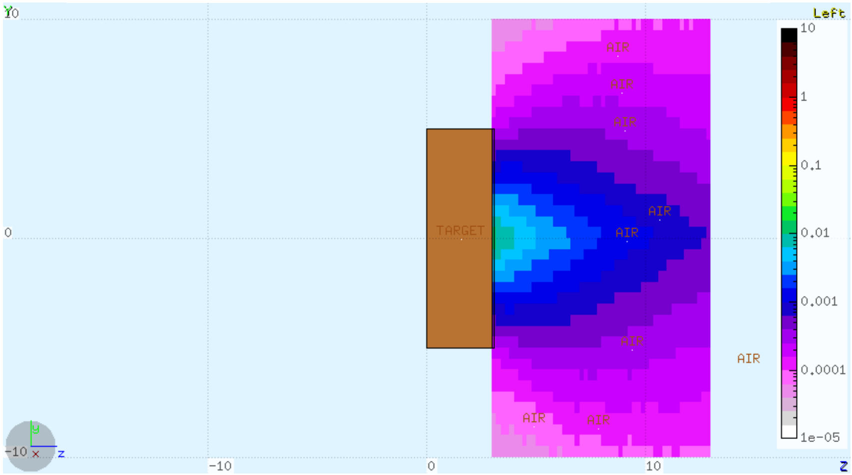
First time study



$t_{BD}(V=V_{thr,BD}) - t_{Inc}(V=V_{thr,Inc})$

FLUKA simulations: Electrons on Copper, results

e^- @ 5 MeV, 3 cm Cu, photon fluence



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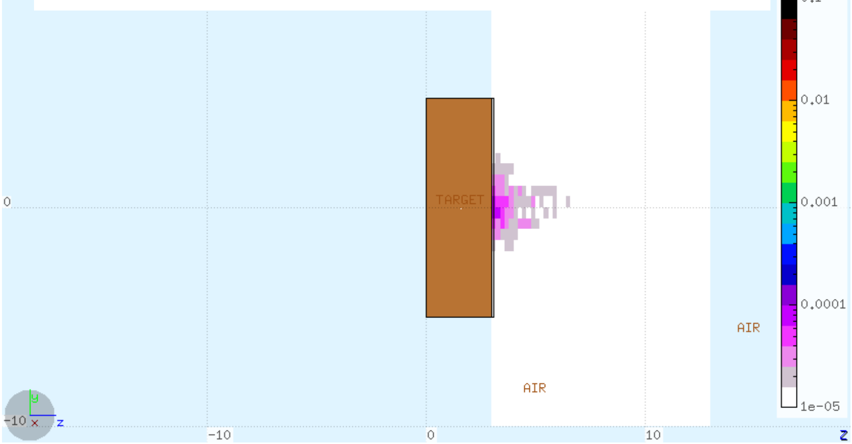

10 cm Cu