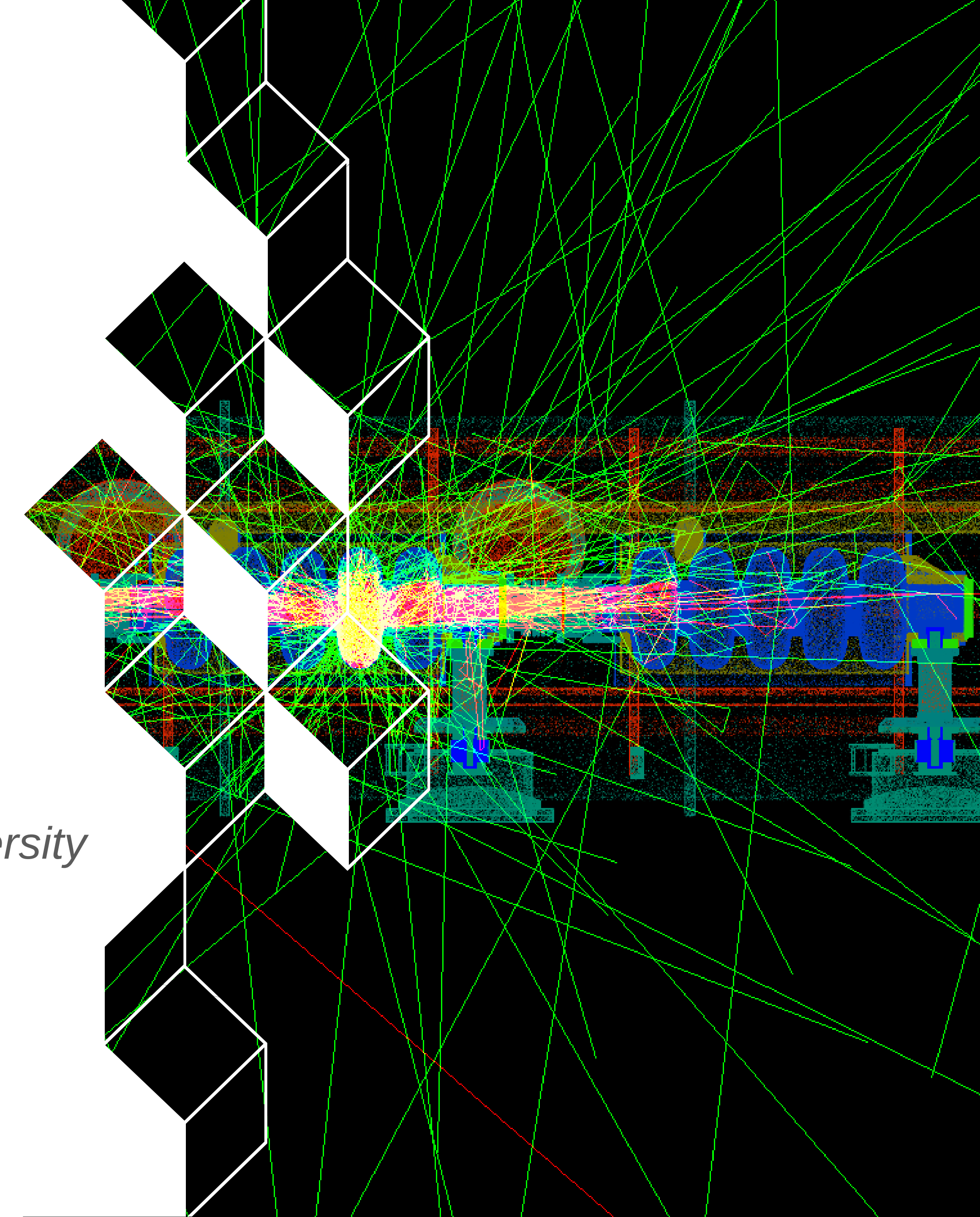
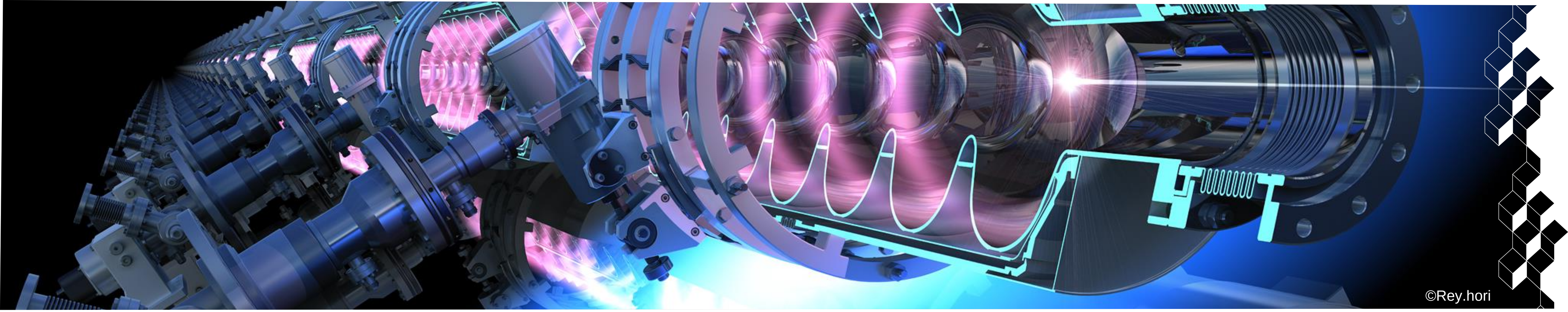
Field emission simulation for SRF cavities and Cryomodules

E. Cenni

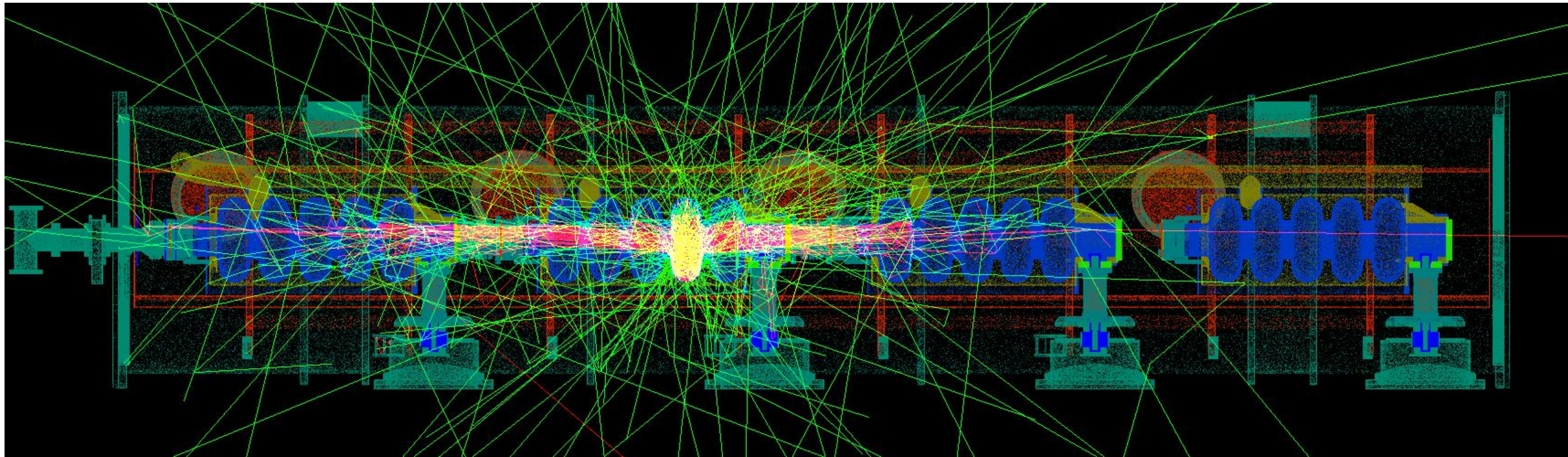
On behalf and with the support of:

G. Devanz, O. Piquet, (DACM/LISAH), Paris-Saclay University





- **Motivation**
- **Field emission process (a refresh)**
- **Case studies**
- **Outlook**



Motivation and background

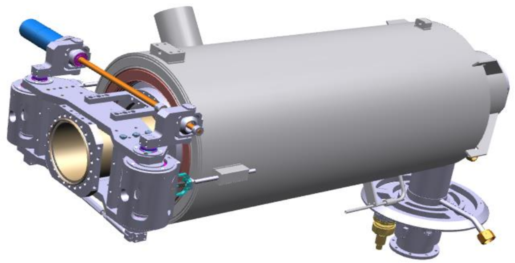
Field emission:

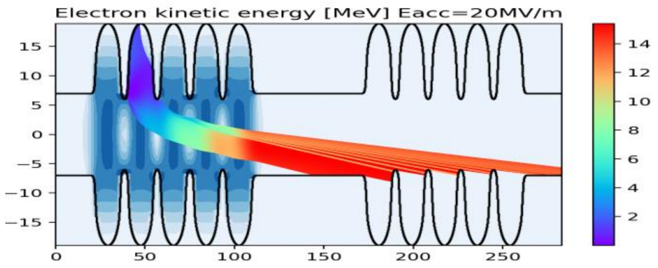
- One of the main causes for the degradation of superconducting cavity quality factor and machine final performance
- Mostly originates from “dust” particle contamination
- It can be enhanced by gas adsorption (e.g. Hydrocarbons)

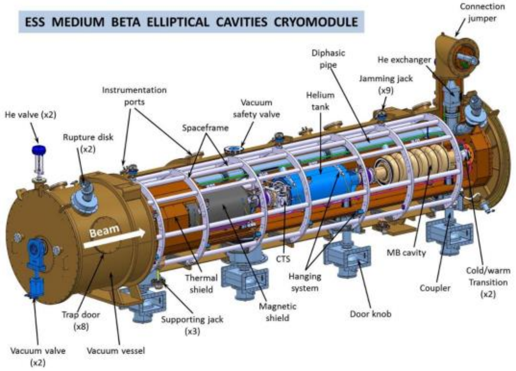
Clean room	Diagnostics	Recovery/Mitigation
Cavity preparation *Clean environment is mandatory to preserve the cavity package high performance. Improvement in manipulation, pumping/venting procedures and automation can be valuable for high performance and mass production.*	**X and γ-ray detection** *X-ray pattern emerging from the cryomodule is an effective method to diagnose field emission and evaluate recovery or mitigation methods.*	**Surface treatment** *Develop treatments capable to recover cavities performance or mitigate detrimental effects in the most cost effective way.*

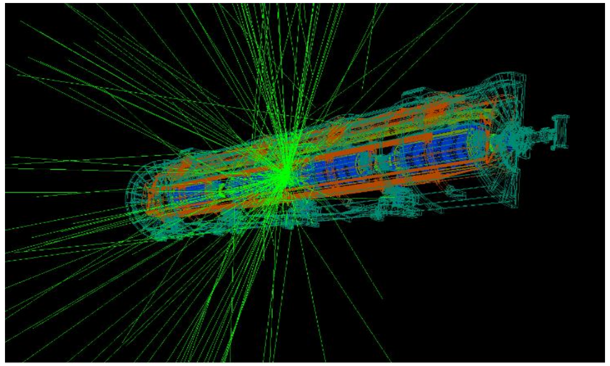
Accelerator R&D Roadmap (European Strategy for Particle Physics)

Field emission will become even more relevant for future high gradient machine



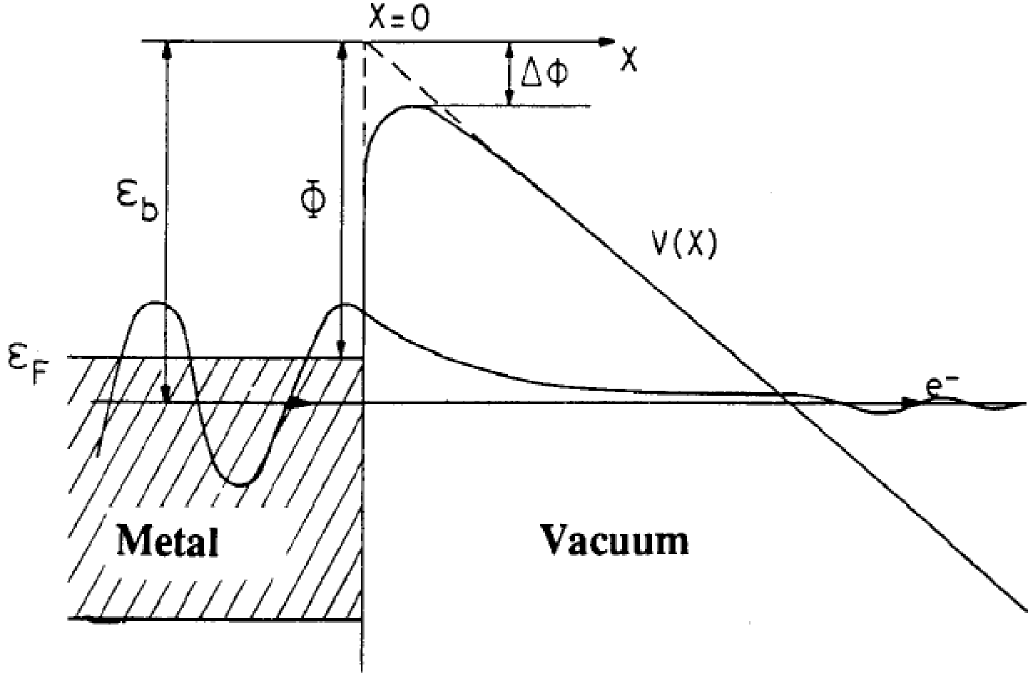






Refresh on field emission

- Electrons are emitted from the cavity surface by the tunnel effect
- It mostly* originated in high electric field regions (*FPC can also)
- The root cause can be linked to sub µm size particle contamination
- Gas adsorption can enhance the phenomenon (resonant tunneling or by reducing effective work function)



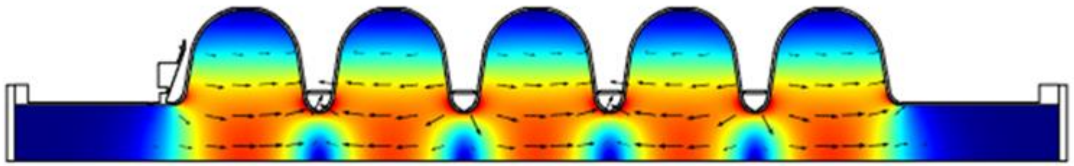
Fowler-Nordheim

Current density:

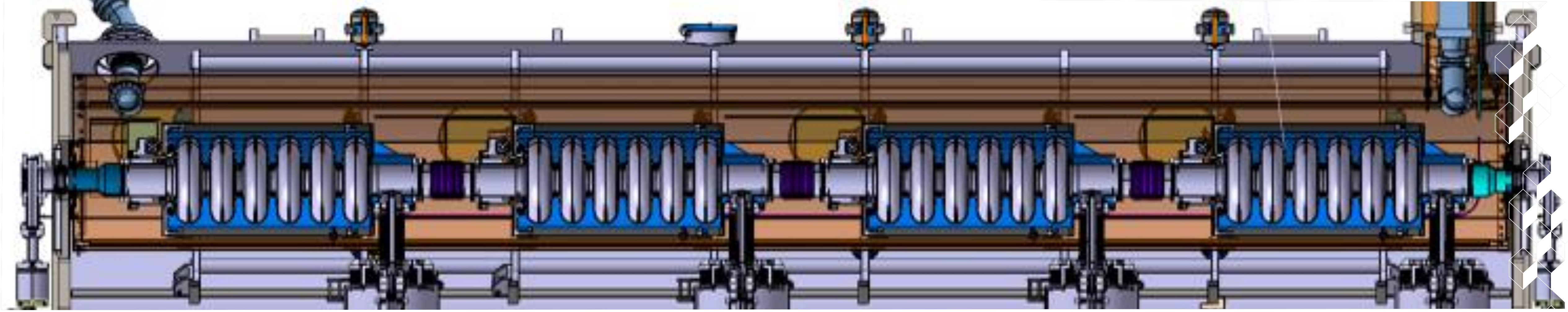
$$J = \frac{A(\beta E_{surf})^2}{\phi} e^{-\frac{B\phi^{1.5}}{\beta E_{surf}}}$$

$J(\downarrow)$
ϕ=material work function (↑)
β=geometric enhancing factor (↓)

Electric field

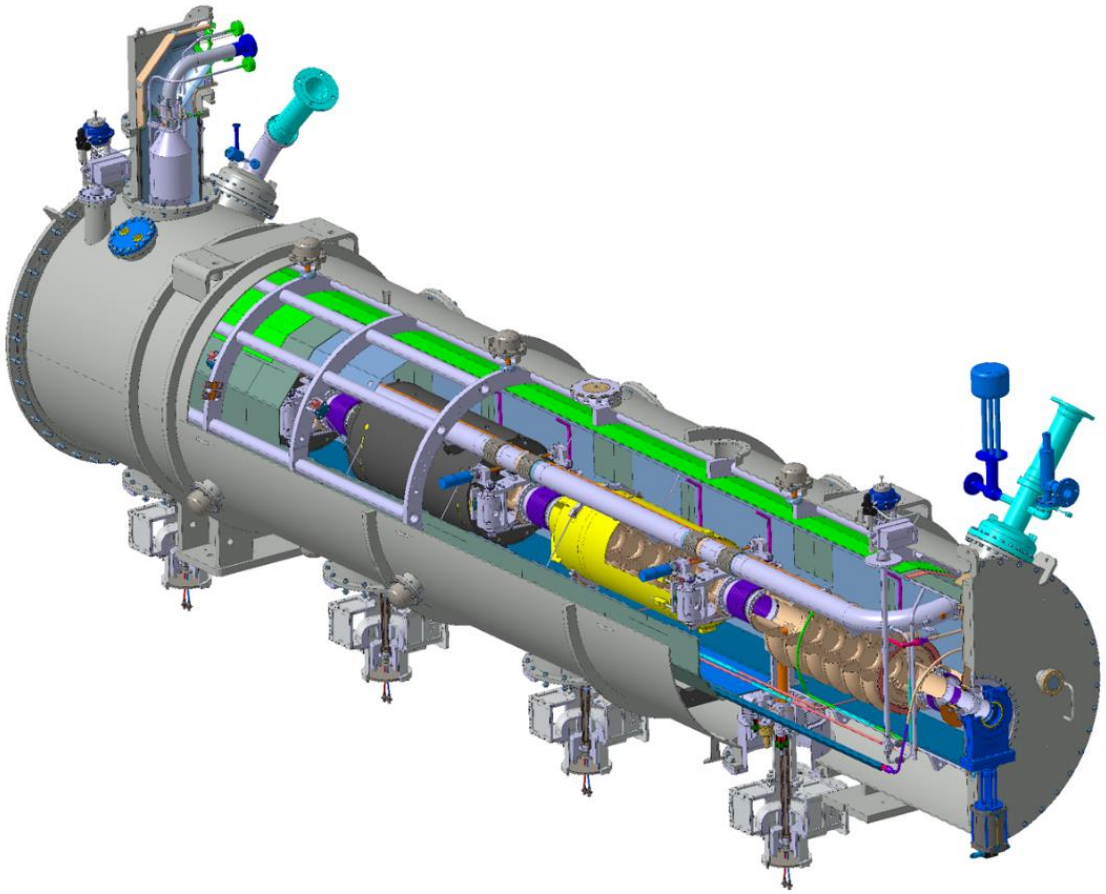


To reduce the field emission current we would like to increase the surface work function and reduce the geometric enhancing factor. E_{surf} is the surface field (e.g. ESS HB-type cavities Esurf=2.2xEacc), linked to cavity design.



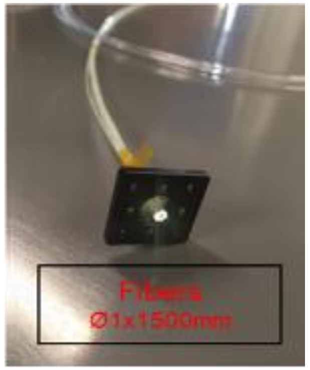
ESS CM and cavities parameters

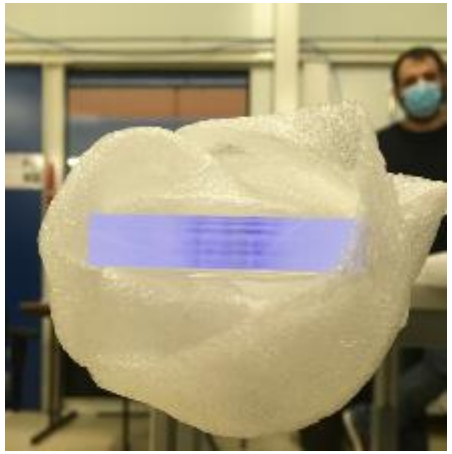
	MB	HB
β	0.67	0.86
Cell number	6	5
Eacc (MV/m)	16.7 + *10%*	19.9 + *10%*
Qo	> 5 10^9	
Rep. rate (Hz)	14	
RF pulse length (ms)	3.2 *3.6*	
italics = CM test values at Saclay		



Time-resolved γ-Diagnostic system for high-performance cavities and cryomodule

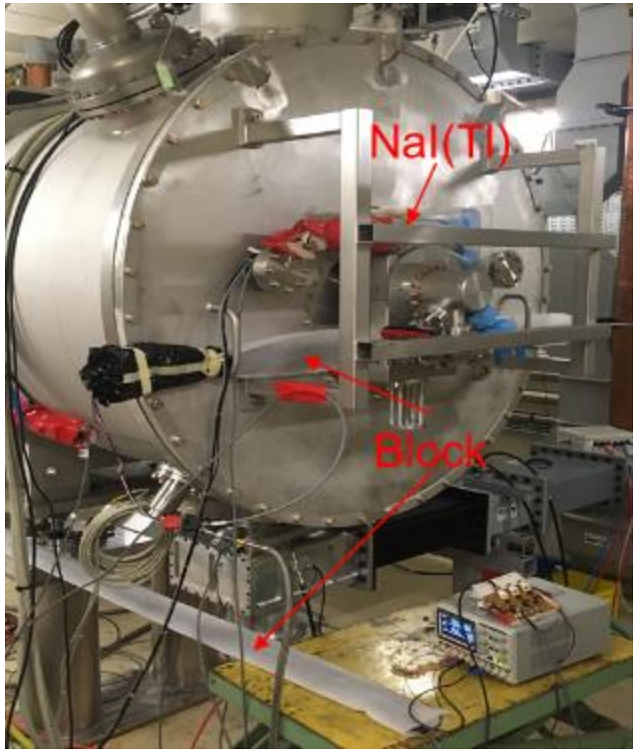
- We are interested in versatile and large-area coverage detectors:
  - Plastic scintillators can be shaped in different forms
  - Reasonably cheap with respect to the area coverage
  - Largely used in particle physics (e.g. Sci-Fi Tracker in LHCb)
- We started by testing a plastic block (10x50x1500mm) and fibers (Ø1x1500mm) as a proof of concept
- We are developing dedicated Geant4 applications for cryomodule and cavity testing allowing us to optimize detectors for the radiation emerging from the cavities





Base plastic is Polyvinyl toluene (PVT)

ESS cryomodule installed in the test stand at Saclay



Scintillator block installed on ESS cryomodule during power test in Saclay, close to a NaI(Tl) scintillator.

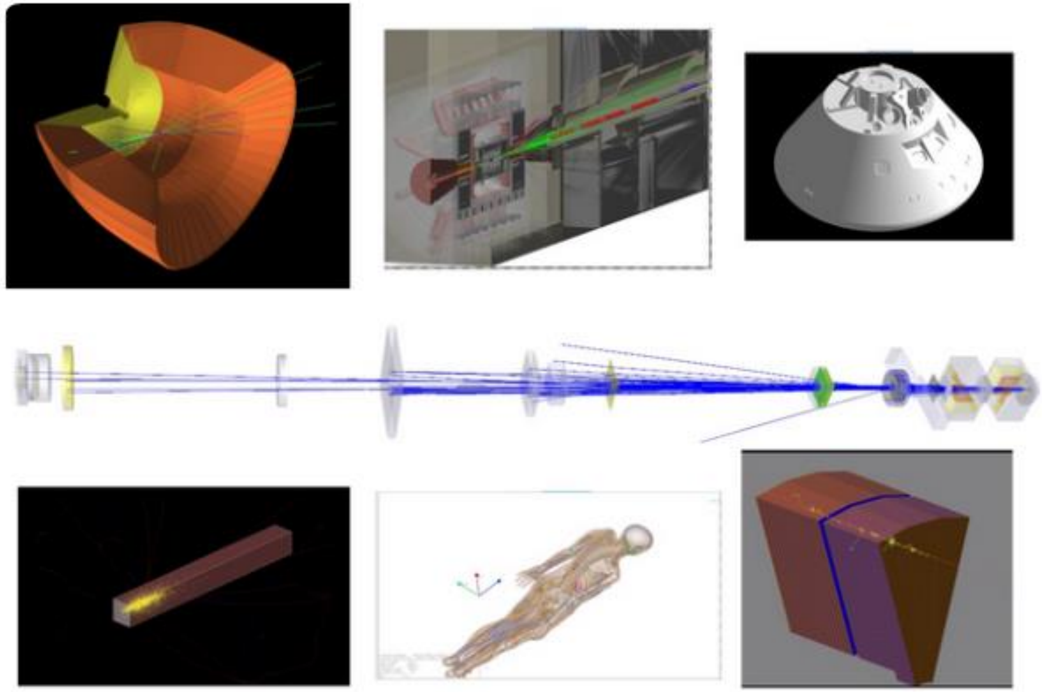
- <u>Detectors are at room temperature (easy to install and change configuration)</u>
- <u>Possibility to study field emission radiation pulse by pulse, with time resolution within the pulse</u>

Geant4 in a nutshell

Toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science.

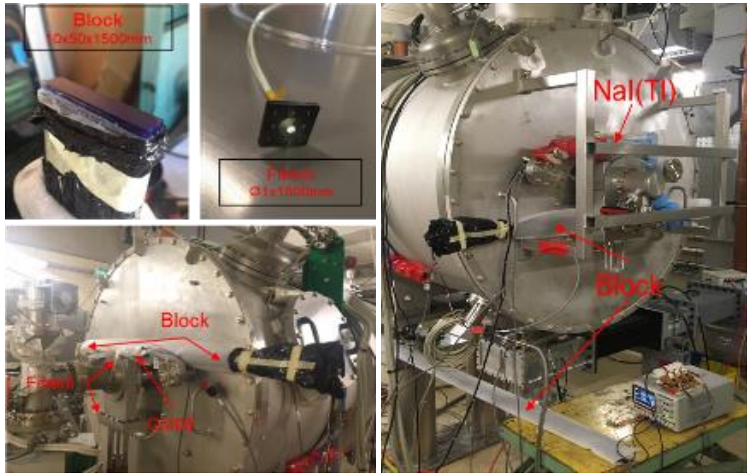
- It is an open source Monte Carlo simulation toolkit
- Allow to calculate particle-matter interaction
- It is a simulation toolkit, hence there are no predefined models, but you can have a lot of examples to learn from
- You can create your application, but you will need to write your code in C++
- Modeling complex geometry can be painful!

```
template <typename T>
struct G4TaskSingletonEvaluator
{
  using key_type  = typename G4Traits::TaskSingletonKey<T>::type;
  using data_type = G4TaskSingletonData<T>;

  template <typename... Args>
  G4TaskSingletonEvaluator(key_type&, Args&&...)
  {
    throw std::runtime_error("Not specialized!");
  }
};

//--------------------------------------------------------------------------------//

template <typename T>
class G4TaskSingletonDelegator
{
public:
  using pointer        = T*;
  using evaluator_type = G4TaskSingletonEvaluator<T>;
  using data_type      = G4TaskSingletonData<T>;
  using key_type       = typename G4Traits::TaskSingletonKey<T>;

  template <typename... Args>
  static void Configure(Args&&... args)
  {
    auto& _data = data_type::GetInstance();
    evaluator_type _eval(std::forward<Args>(args)...);
```

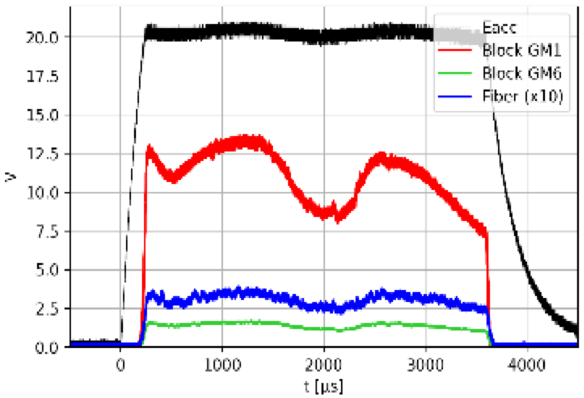


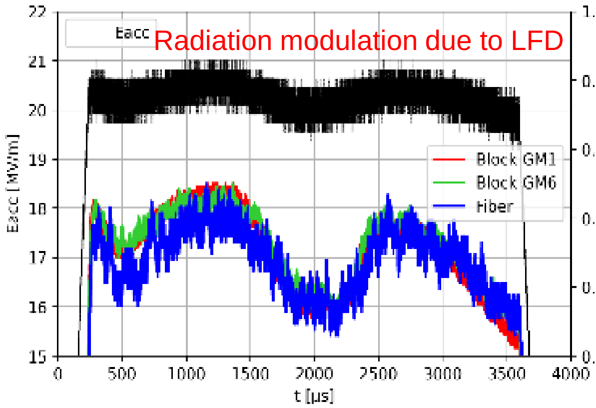
https://geant4.web.cern.ch/

Case 1: Field emission, neutron production and activation

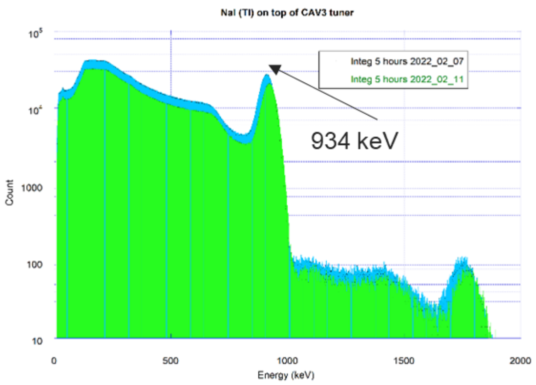


Proof of concept during ESS cryomodule test in CEA and Lund





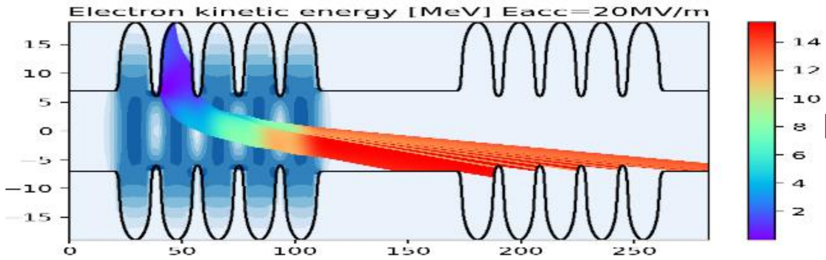
CAV1 excited with **nominal pulse**, the maximum Eacc is about 21.2MV/m (black), radiation detected by block at GM1 position, close to cavity (red), radiation detected by block (green) and from fiber (blue). *Right: zoomed and normalized view of the same pulse where it is possible to appreciate closely the change in the radiation amplitude due to Lorentz force detuning.*



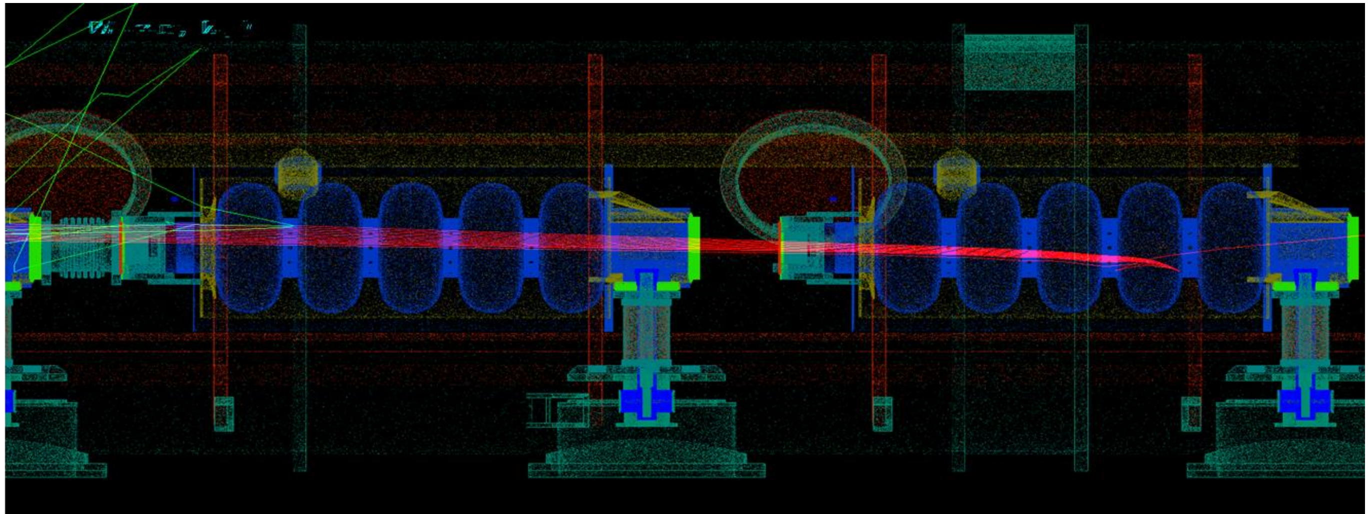
DATA

GEANT4 A SIMULATION TOOLKIT

Particle tracking code



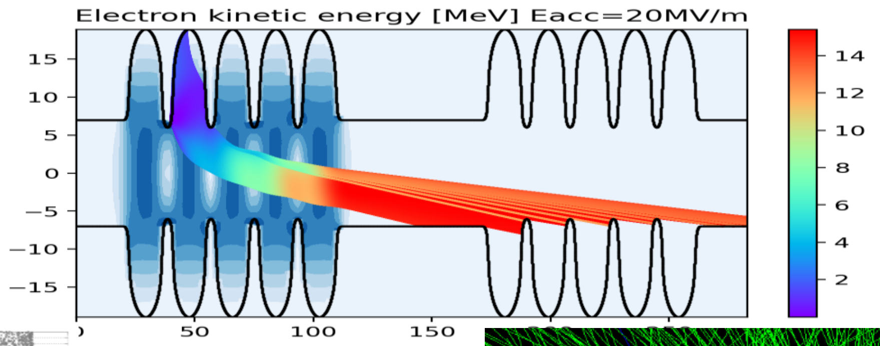
Single emitter trajectories calculation with one cavity powered (CAV4) while the adjacent is off (CAV3). Trajectory colours are determined with respect to the electrons kinetic energy. All the impact on the beam tubes and adjacent cavity have energies between 12 and 15MeV.

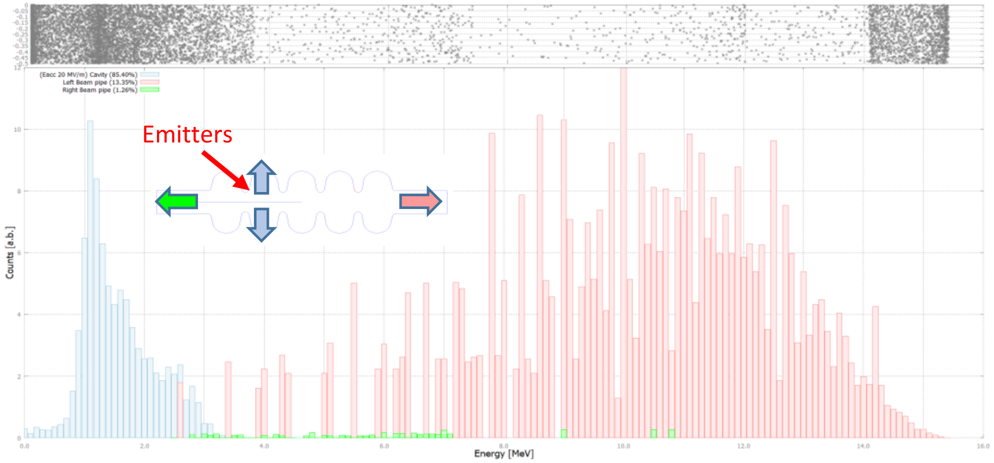


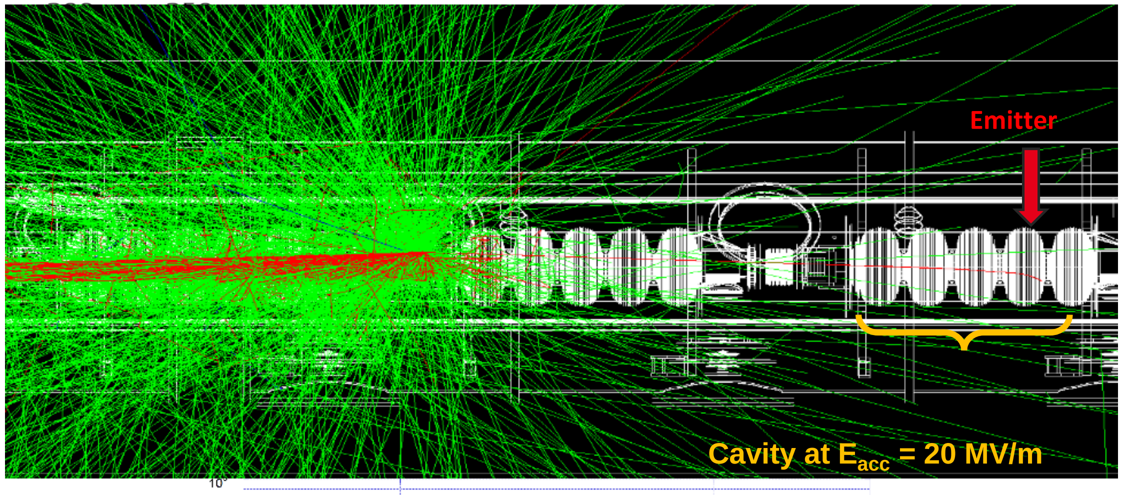
FE on CAV4 iris
Trajectory evolution while varying the phase around the typical 15 MeV, CAV3 impact case

Simulation flow-chart

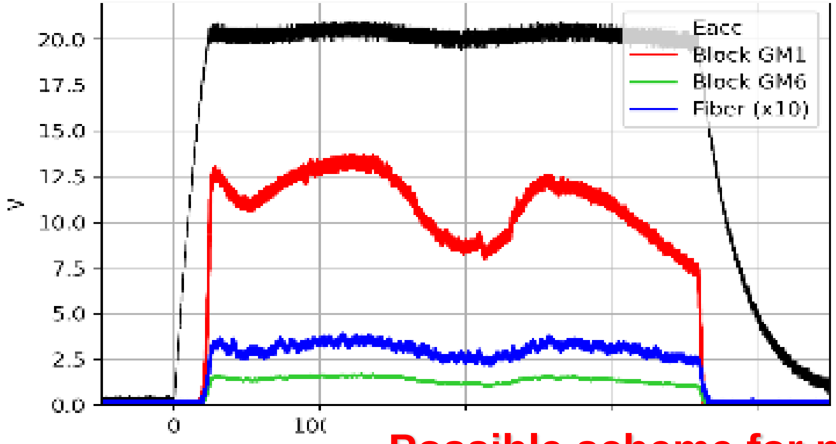
Particle tracking code

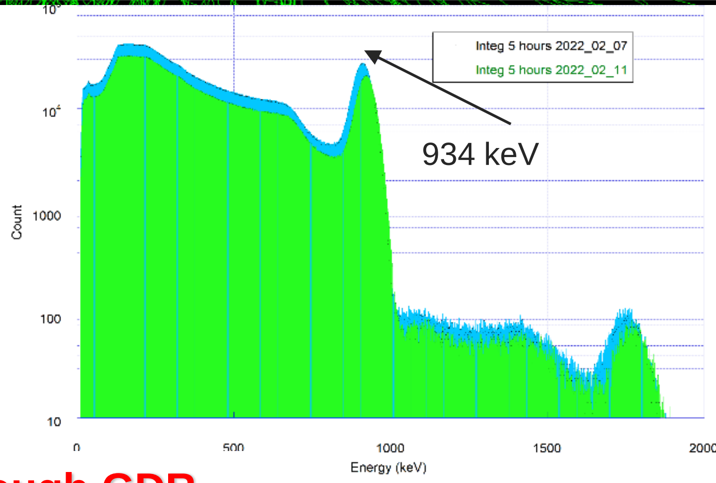






DATA





DATA

Possible scheme for neutron production through GDR

Field emission e^- → Bremsstrahlung → γ → $\gamma + Nb^{93} \rightarrow n + (Nb^{92m})$ → γ@934keV

Half-life 10.15 days

Giant dipole resonance

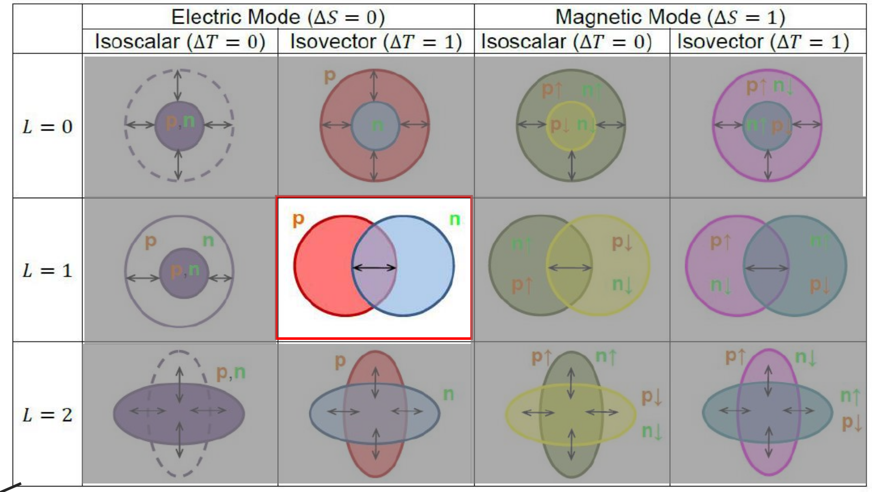
Geant4 calculates all this, once the correct physics processes are used

Possible reaction “steps”:

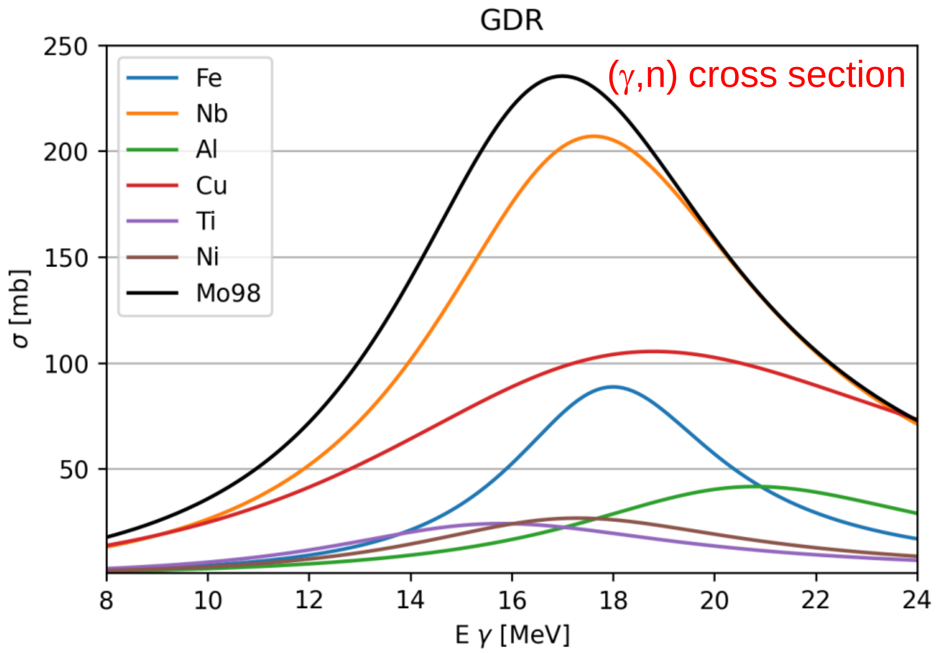
1. γ produced by e- bremsstrahlung
2. $\gamma + Nb^{93} \rightarrow n + Nb^{92m}$

(1) is originated by field emission electrons
(2) is due to the nuclear GDR

Giant Nuclear resonances

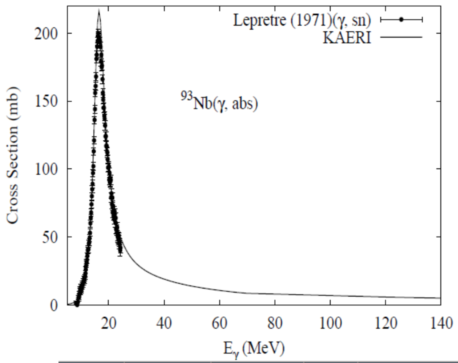


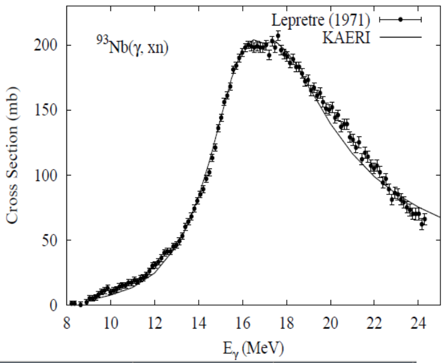
Giant Dipole Resonance



$\gamma + {}^{93}\mathrm{Nb}$

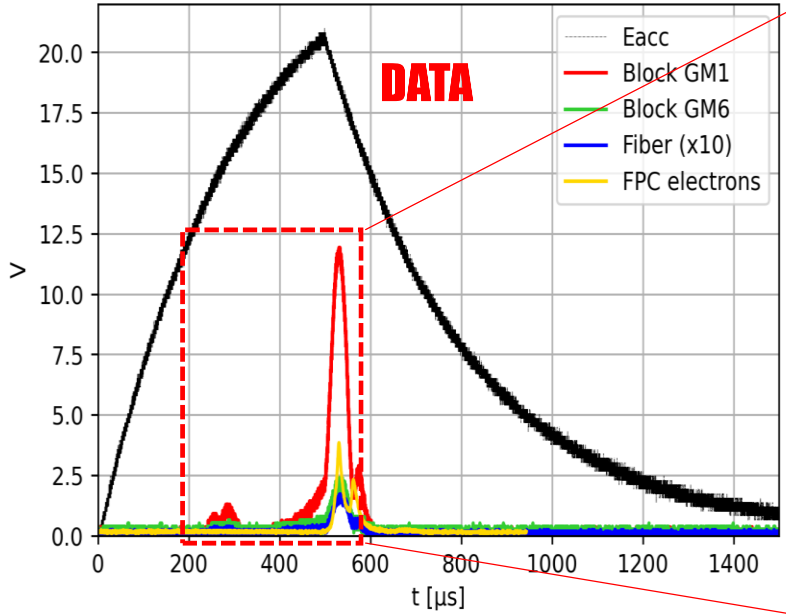
Abundance (%)	Threshold Energies (MeV)								
	γ,n	γ,p	γ,t	γ,He-3	γ,α	γ,2n	γ,np	γ,2p	γ,3n
100.00	8.83	6.04	13.39	15.65	1.93	16.71	14.68	15.44	28.77

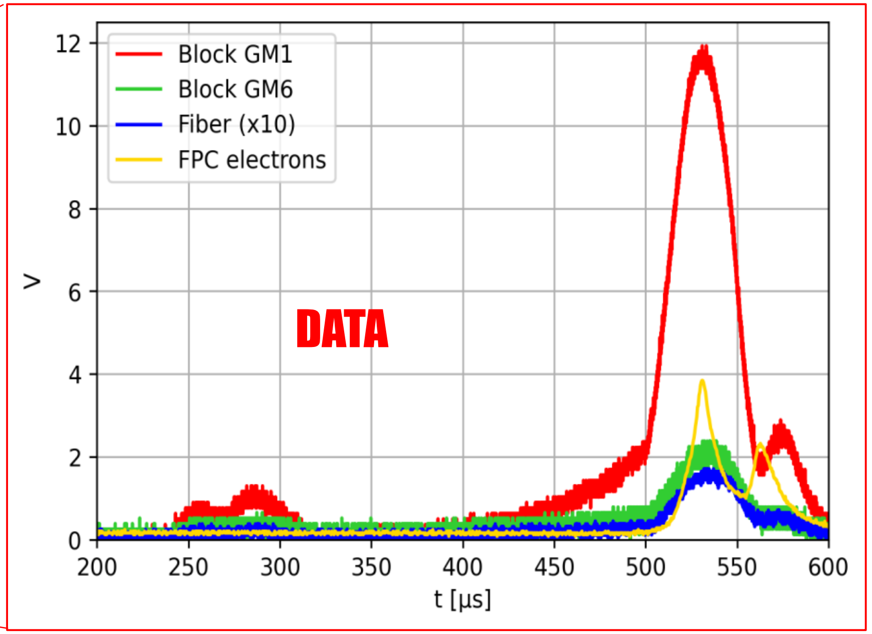




Target A	Reaction	Final Z-Symbol	Final A	Maximum Energy (MeV)	Maximum Cross Section Value (mb)	Full Wight at Half Maximum (MeV)	Integration Energy Limit (MeV)
93	G,XN			17.622	207	8	24.3
93	G,XN			17	195	6.5	23
93	G,N	41-Nb	92	16.26	200	4	24.3

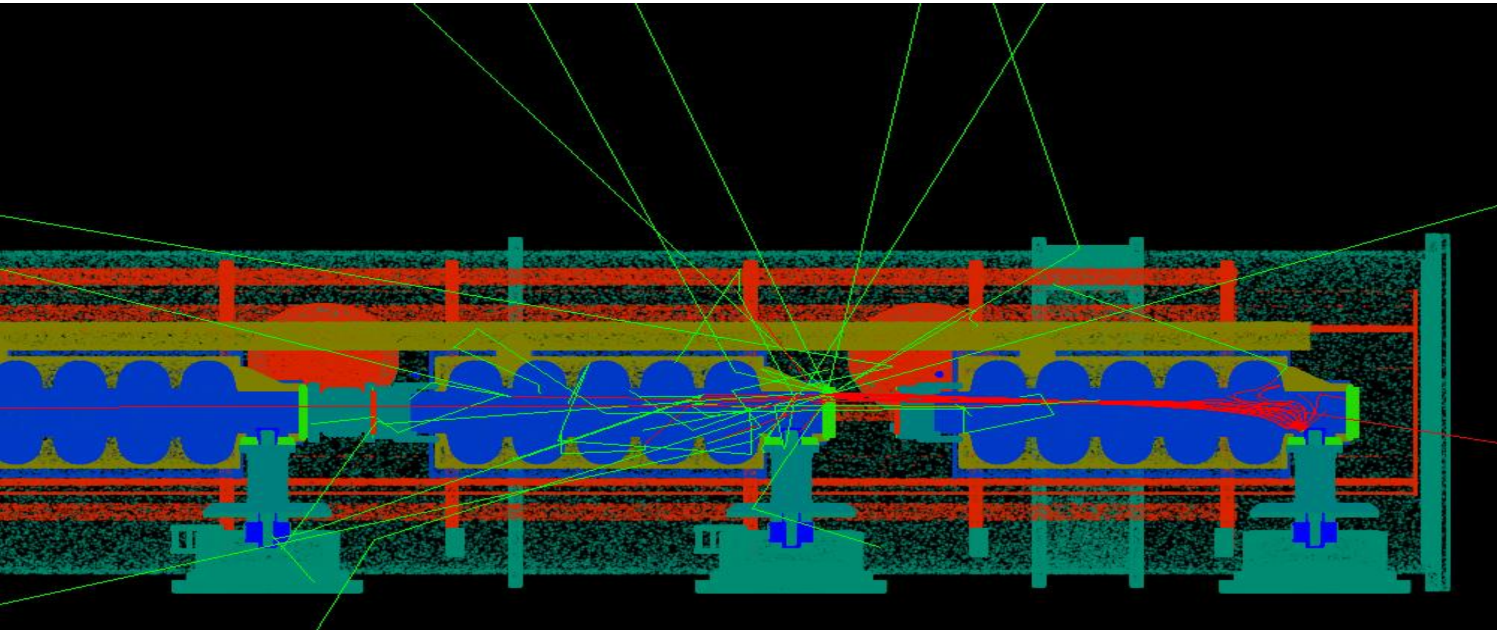
Case 2: FPC electron emission



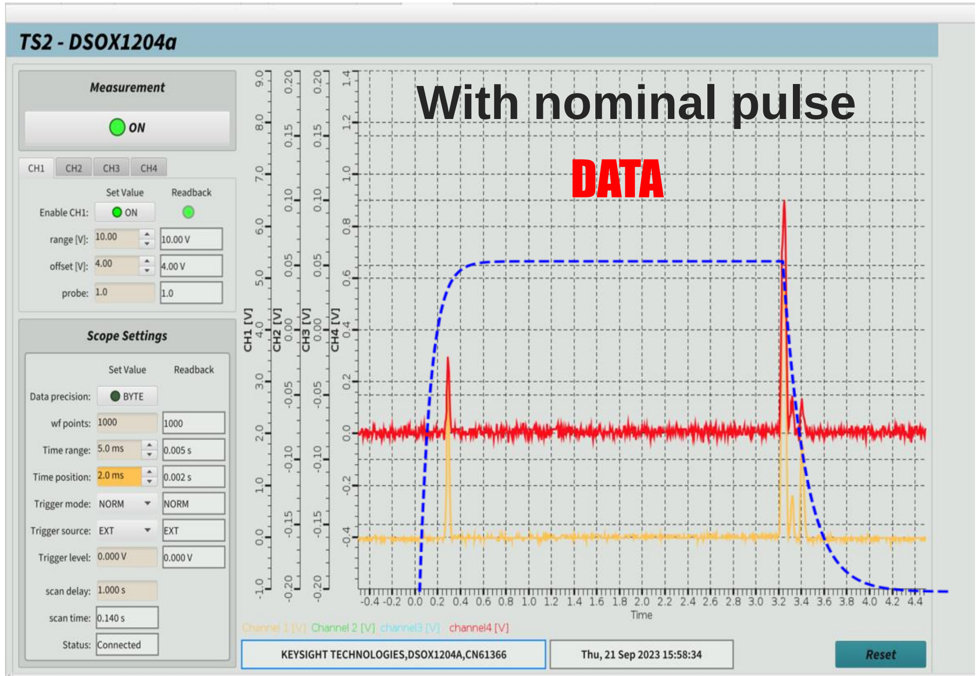


CAV4 excited with **500µs square pulse**, the maximum Eacc is about 20MV/m (black). It is possible to appreciate the **electron current detected by the pick up in the fundamental power coupler (gold)** and the radiation detected by the plastic scintillator at the cryomodule ends, block at GM1 position (red) block at GM6 position (green) and fiber (blue).

"thanks to 10µs time resolution, we are able to distinguish between FE and FPC electron emission"

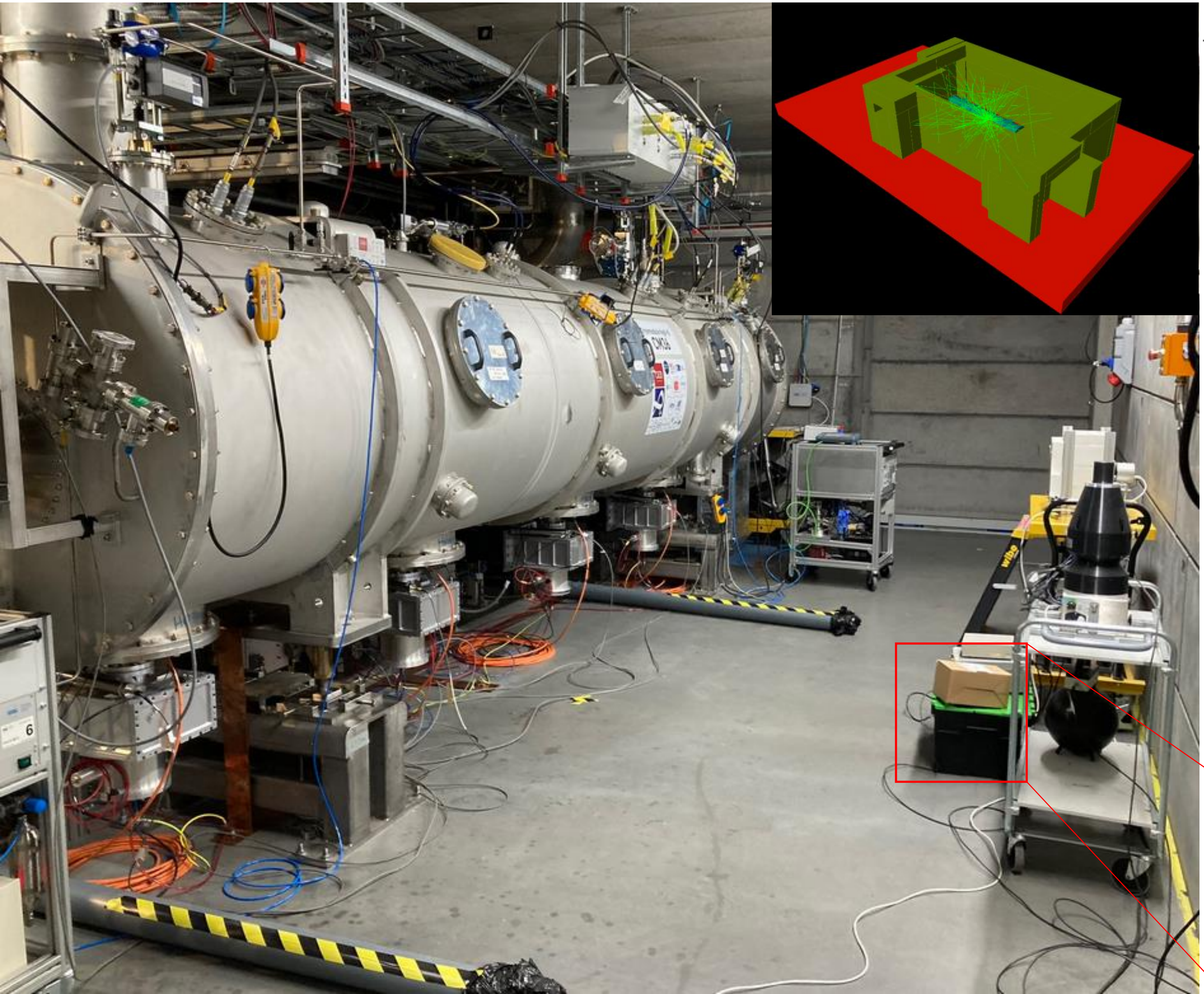


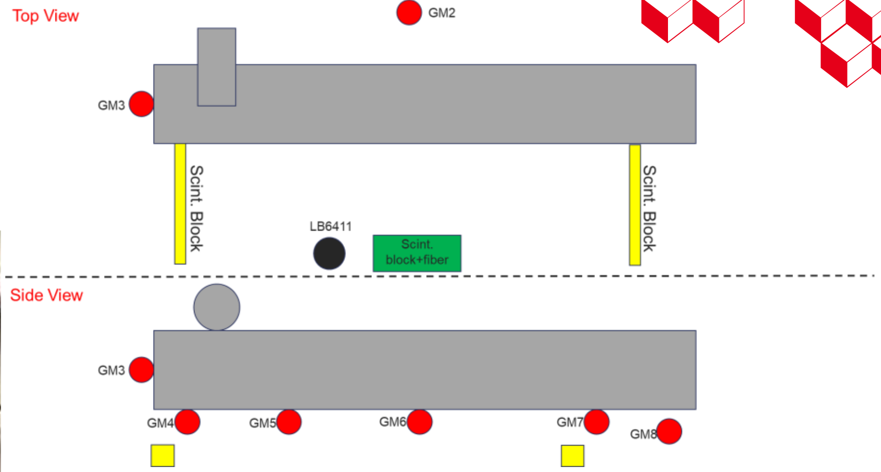
FPC4 low energy electrons (here 100 eV ~ threshold SEY>1) are captured by the cavity field, generate secondary tracks



Outlook

Test Stand 2 @ESS





- We are currently working with the ESS team to develop diagnostics and simulations for cryomodule testing and commisioning
- We are working on detectors and simulations for the vertical test stand in Saclay

Saclay Gen II detector

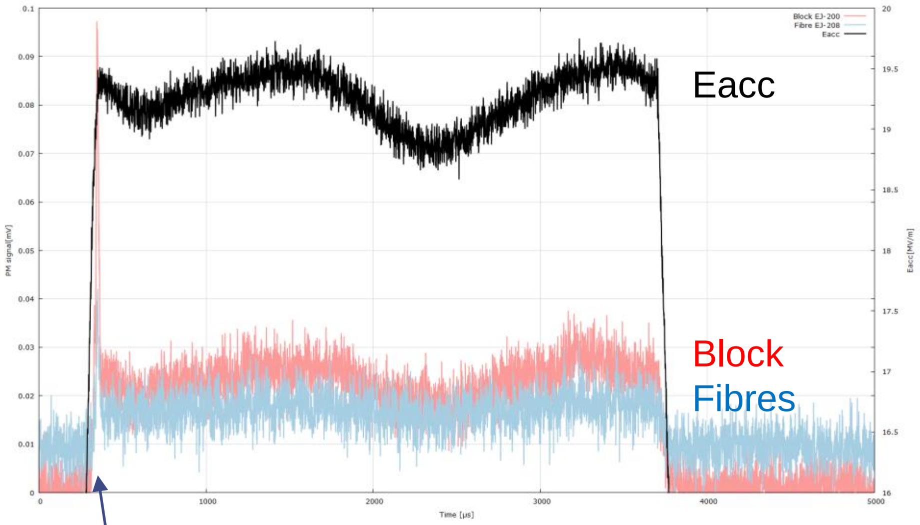
Thank you for your attention

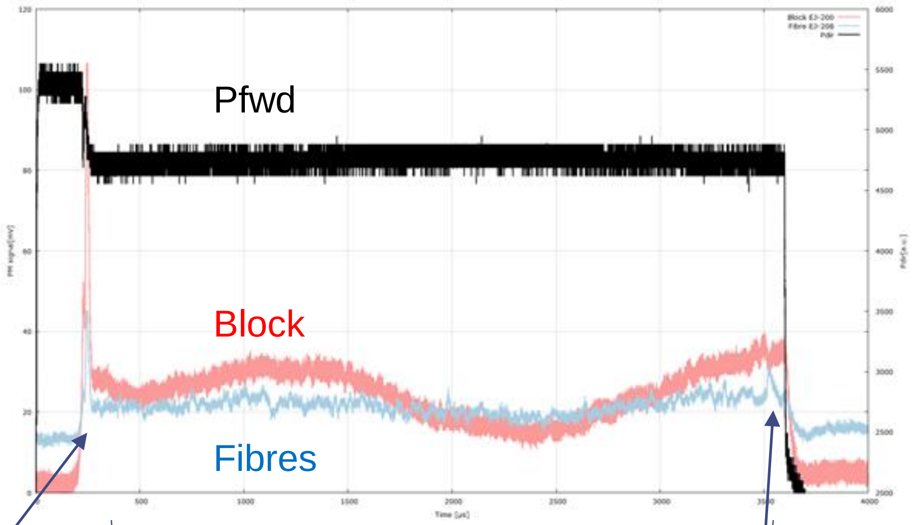
Back up slides

Time-resolved radiation measurements (*details*)

More details within the pulse structure

Using the plastic scintillators with PMTs (Gen I)





radiation from the cavity follows Eacc variations

radiation from the cavity follows Eacc variations

radiation spike at the end of filling time : coincides with e^- detection in the coupler

radiation spike during cavity decay:
coincides with e- detection in the coupler, while crossing a MP band