Instrumentation for high performance cavities and cryomodule field emission analysis

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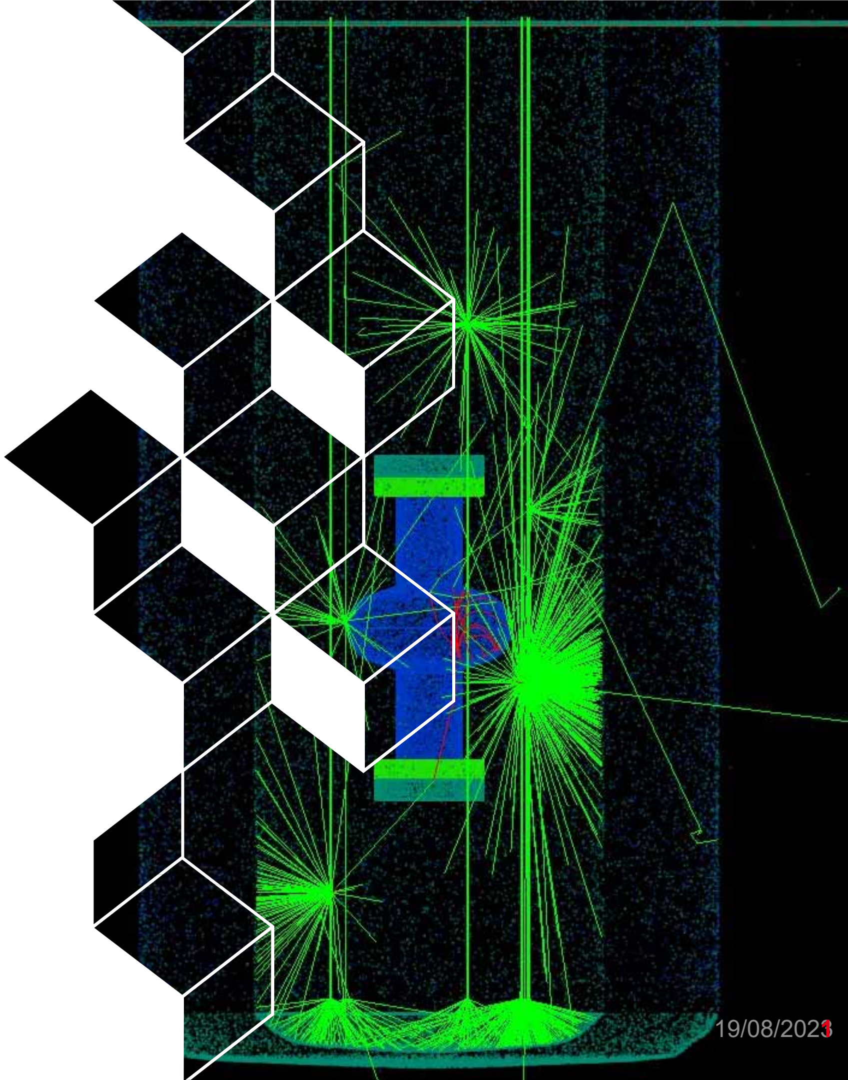


Why investigate radiation induced by FE

Many projects/machines report concerns about FE and degradation with beam operation

Within projects with many contributors, comparison between radiation measurements on a given cavity

- at different test facilities
- at different stage of testing (VT, CM test bunker)

is not straightforward, unless they have the exact same setup

Need for quantitative measurements of the radiation source(s) especially in the development phase of prototypes, to qualify prepartion and assembly tooling and procedures

Characterization has more value (emitter(s) position and electronic current) but probably very challenging

A combination of dedicated instrumentation and simulation models can improve the situation

Some options for radiation measurement

Area monitors:

Our area monitors measure H*(10) equivalent dose rate

- GM tubes
  - are not calibrated above ~1.3 MeV
  - saturate earlier than spec when radiation is pulsed (dead time)
- ionization chambers are more suited
- neutron detector (rem type,...)

cannot be placed close to the cavity, the environment is always interfering.
usable in a cryomodule test environment as long as a set of reproducible placements is defined and applied

Scintillator based detectors:

Scintillating medium coupled to a photodetector

- Inorganic scintillators are widely used i.e. NaI (spectrometry)

- plastic (PS, PVT,...) is a good candidate (low cost, any shape)

  - in the form of fibres, provide the transport of the scintillation photons
  - fast scintillators : extra functionnality based on coincidence can be added

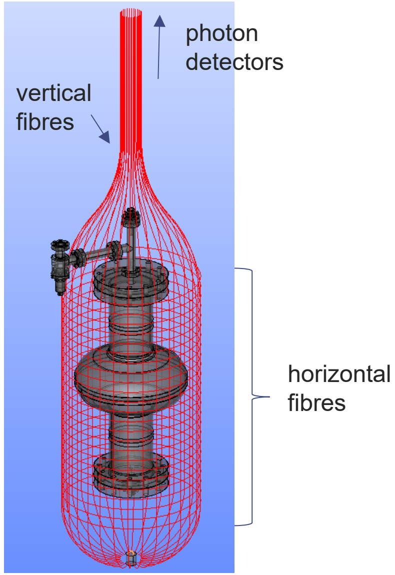
Wishlist for a dedicated detector

Great improvement if radiation is measured:

- closer to the source, i.e independent from the environment
- with a maximized angular coverage
- with the minimal granularity that can describe the angular distribution
- with calibration in the whole energy range of interest

We try to apply this to a single cell cavity :

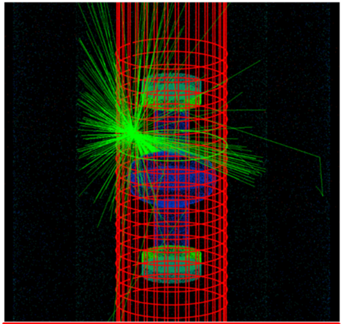
- The cavity is placed inside a scintillating fibre mesh in LHe
- The photodetectors are outside the Dewar or inside GHe

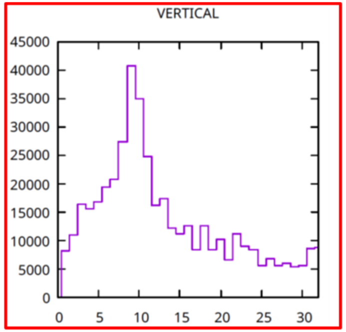


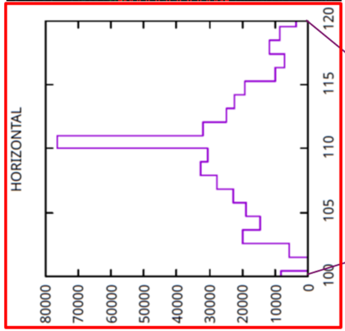
The birdcage detector for single-cell cavities

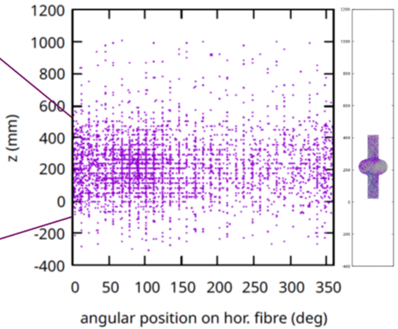
- Geant4 model for the design and optimization of the fibre network
- includes scintillation and transport of optical photons in auxiliary optical fibres
- total of 52 channels for PVT fibres + top&bottom caps
- We are currently evaluating a MPPC for the photodetection of all channels

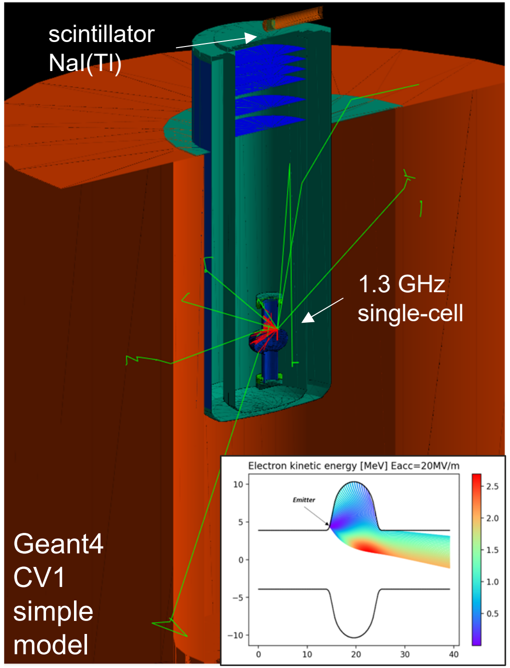
- Example:
  - 1.3 GHz single-cell
  - 1 FE e^- per period emitted at Epk location (equiv 0.2 nA)
  - Eacc = 30 MV/m
  - photon count $10^3 – 10^5$ s^{-1} on individual fibres







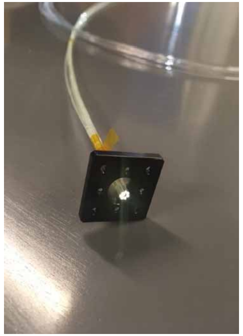




Test of a scintillating fiber channel at 2K

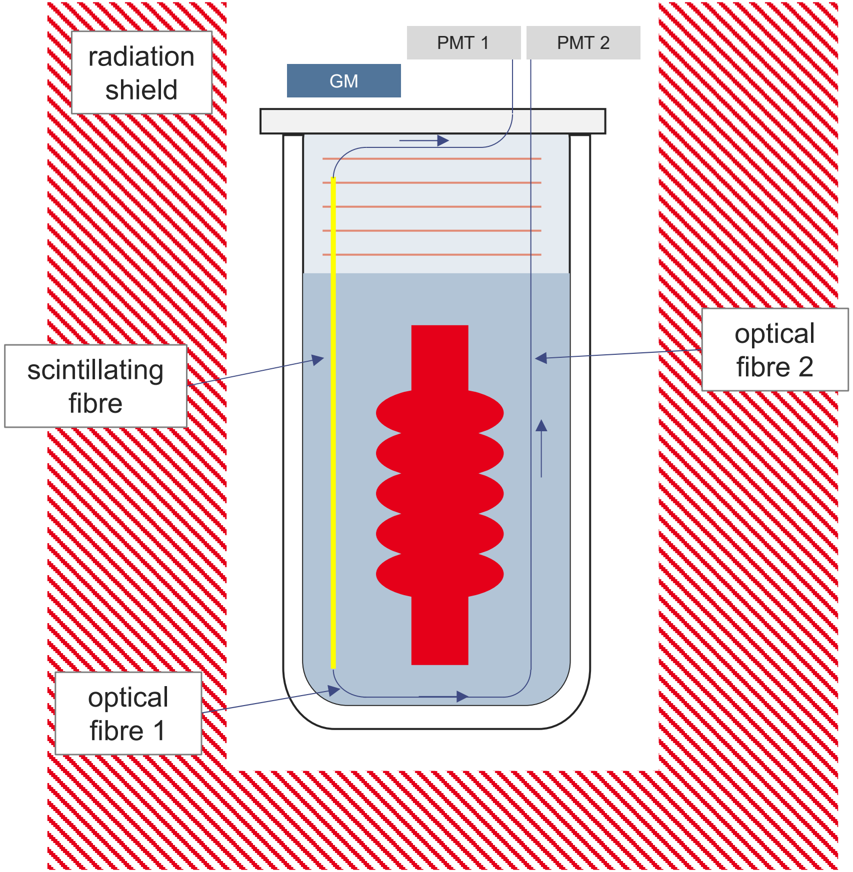
- First test performed with a fibre bundle installed between the helium vessel and magnetic shield of one ESS cavity. The fibers were not damaged

- 4 tests performed inside the CV2 VT representative assembly
  - one scintillating fiber connected at each end to a PMMA fibre to transport the optical photons out of the cryostat to a PMT
  - the three fibres are partially in LHe or GHe

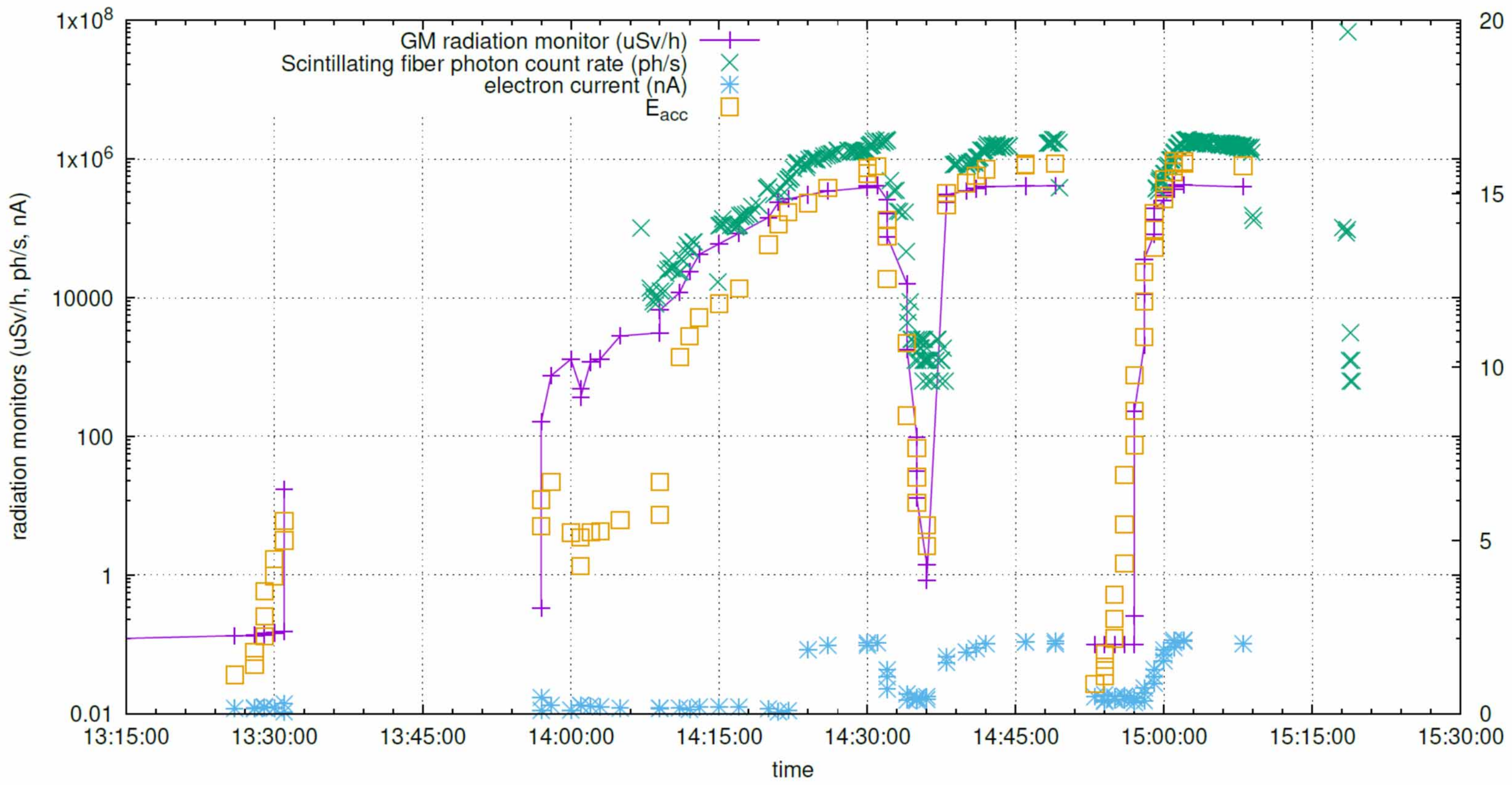


ESS electron impact energies

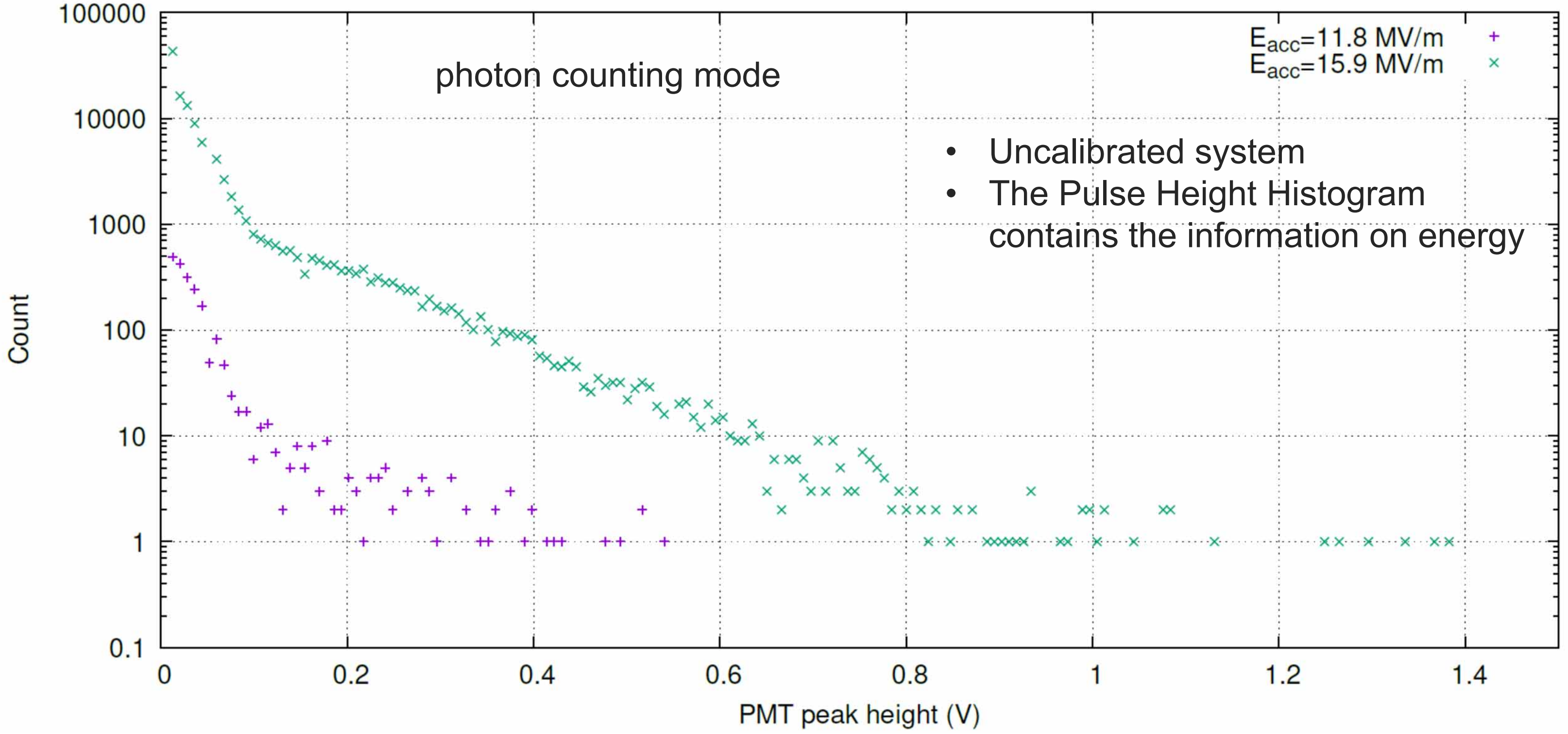
Beta			0.67	0.86
Eacc [MV/m]			16.7	20
Most probable	From	To		
Ei [MeV]	3rd iris	out	7.5	7.3
	3rd iris	same cav.	1.6	1.1
	4th iris	out	6.6	12
	4th iris	same cav.	1.5	1.1
Max. Ei [MeV]			7.7	15.2



Test with a contaminated ESS HB cavity



Test with a contaminated ESS HB cavity

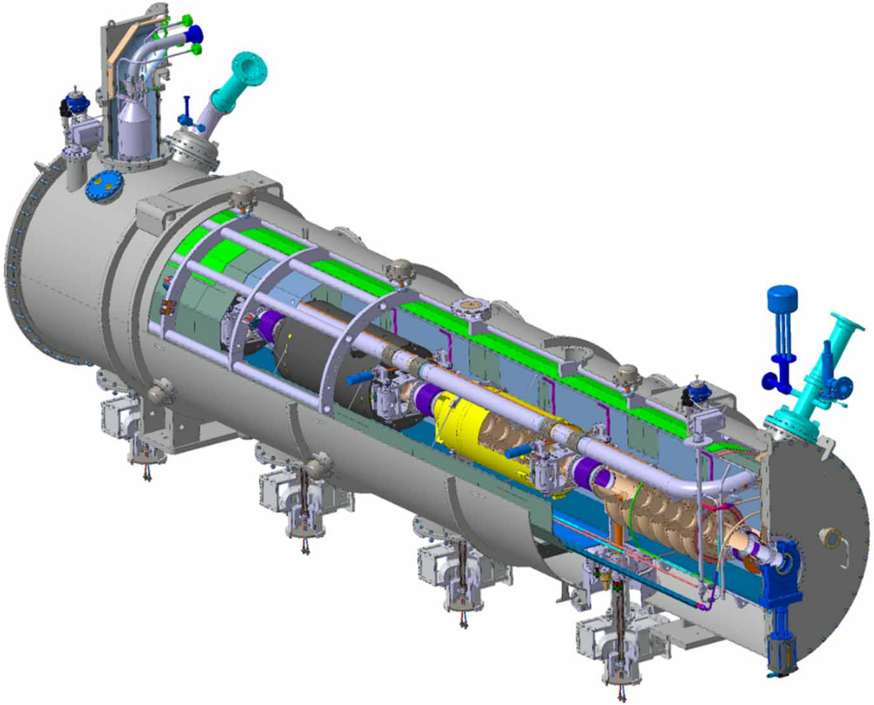


- Uncalibrated system
- The Pulse Height Histogram contains the information on energy

ESS elliptical cavity cryomodules

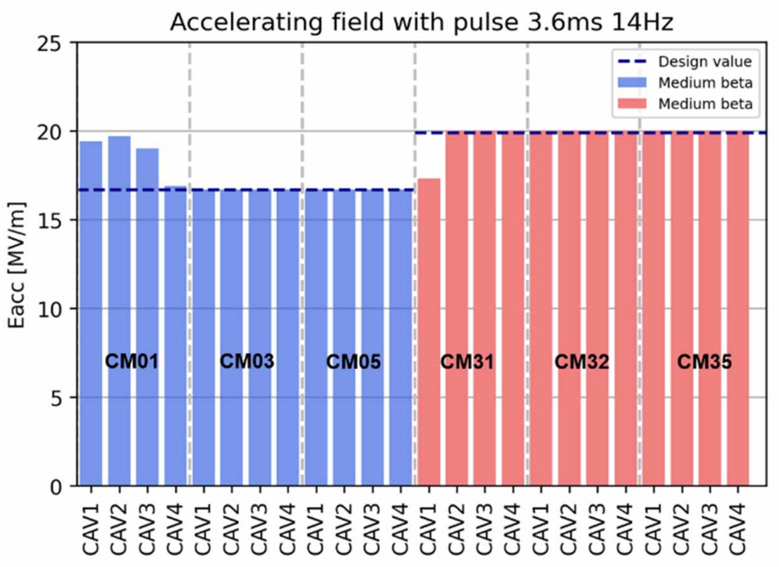
	MB	HB
beta	0.67	0.86
cell number	6	5
Eacc (MV/m)	16.7 + *10%*	19.9 + *10%*
Qo	> 5 10^9	
Rep. rate (Hz)	14	
RF pulse length (ms)	3.2 *3.6*	

(italics = CM test values)



ESS Cryomodule testing at CEA

- all cavities tested one by one
- some tested in pairs (limited power of 1.2MW)
- CM02 rebuild entirely after vaccum accident but not re-tested
- 9 modules tested in total including prototypes

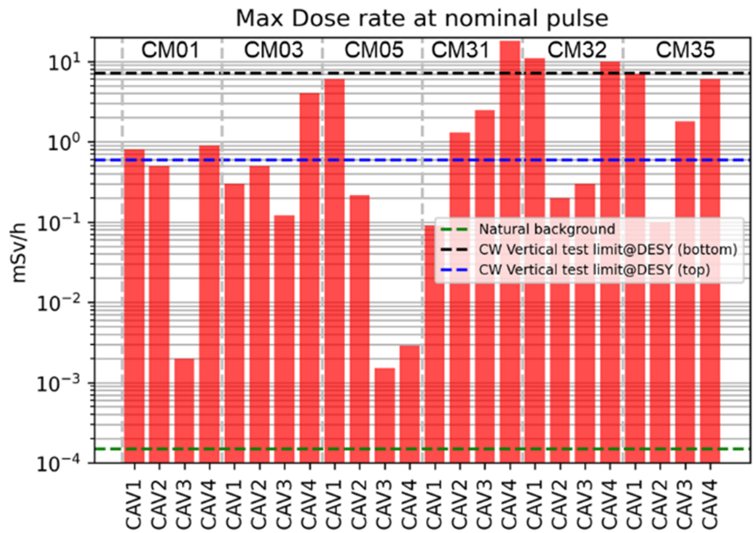


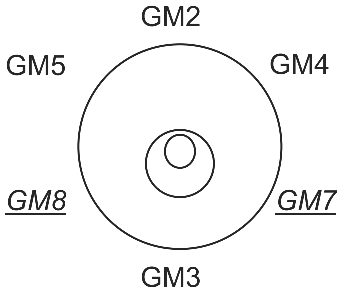
Details in WEPWB064 O.Piquet et al. "Performance Analysis from ESS Cryomodule Testing at CEA"

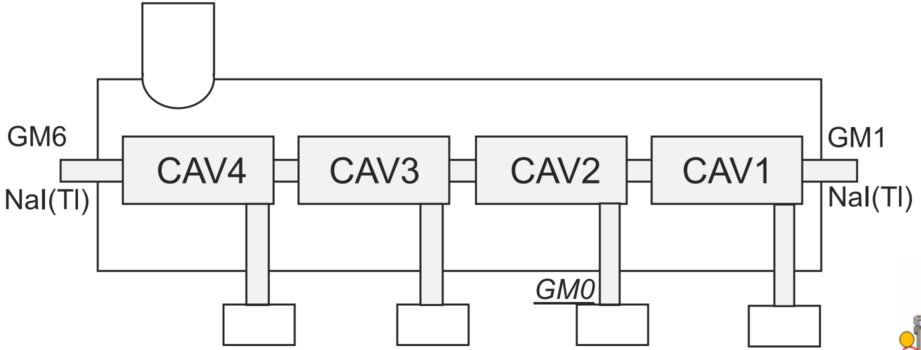
radiation instrumentation

inside the bunker :

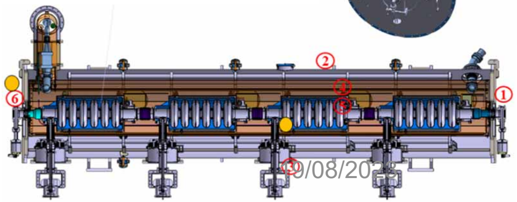
- 3 high dose rate GMs :
  - *GM0* fixed @ FPC2
  - *GM7* and *GM8* moved around the cavity under test
- 6 low dose rate GMs
- plastic scintillators (fiber bundles, blocks) for time resolved measurements
- 2 NaI(Tl) scintillators with MCA (energy spectrum)
  - on gate valves
  - or on carts for lateral radiation
- 1(2) LB6411 neutron detector in the bunker (on cavity 4 side)



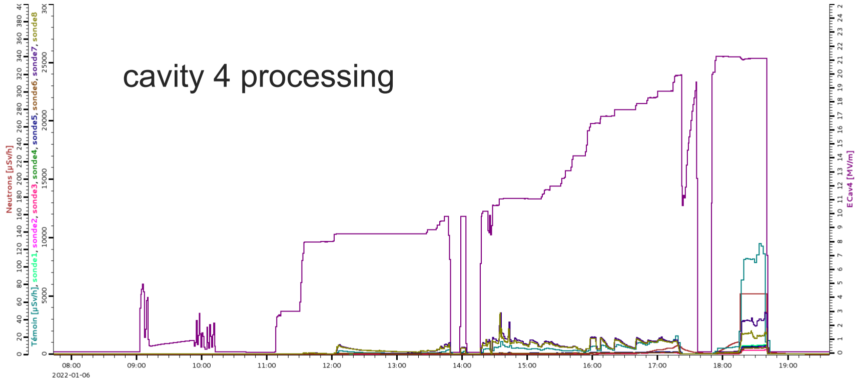


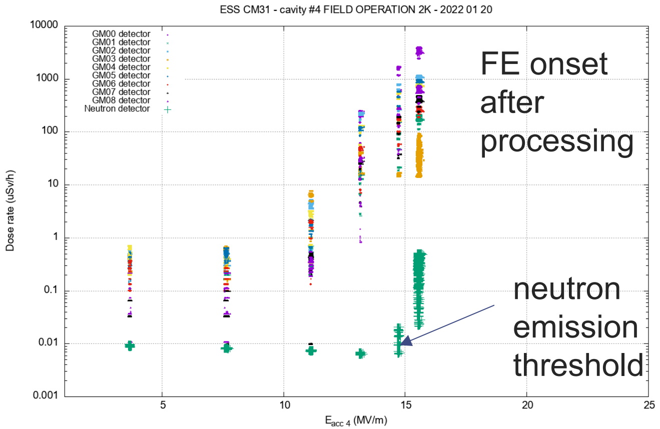


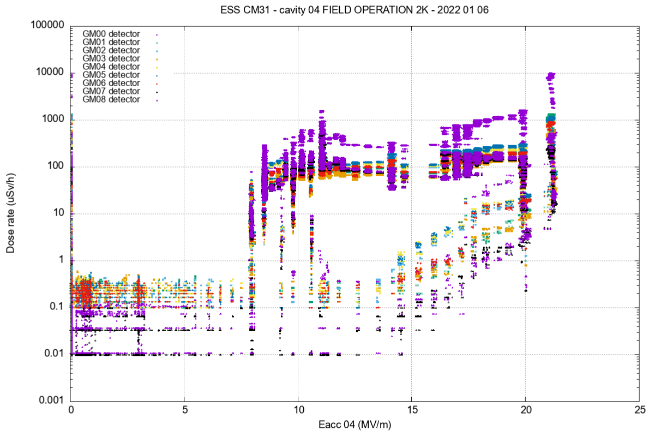
setup for cavity 2

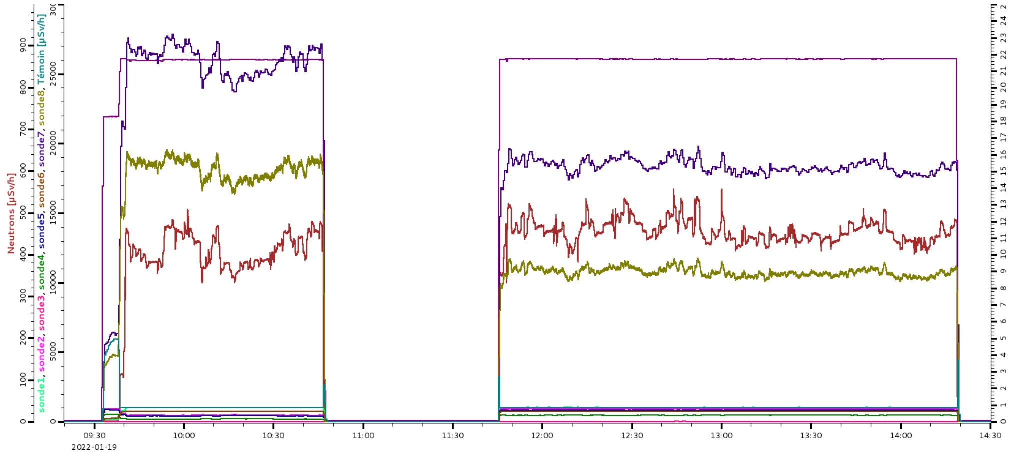


monitoring of FE - cavity 4 CM31 - neutrons





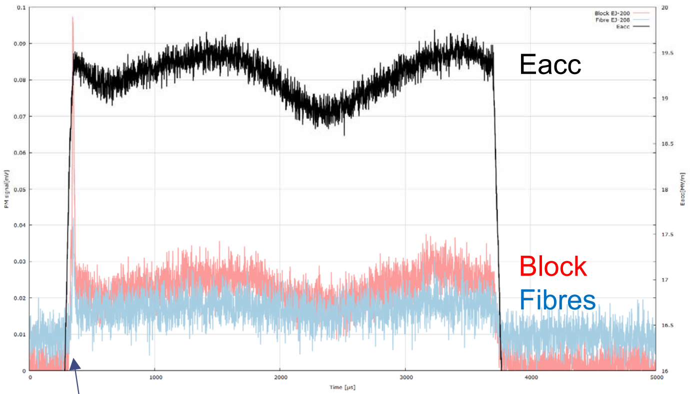


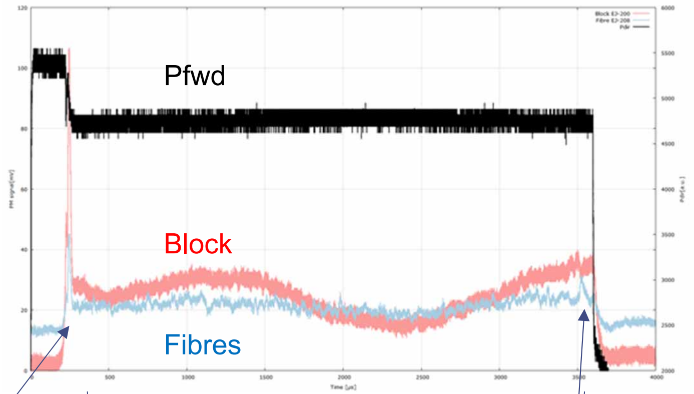


neutron dose rate 400 – 500 μSv/h

Time resolved radiation measurements

using the plastic scintillators with PMTs





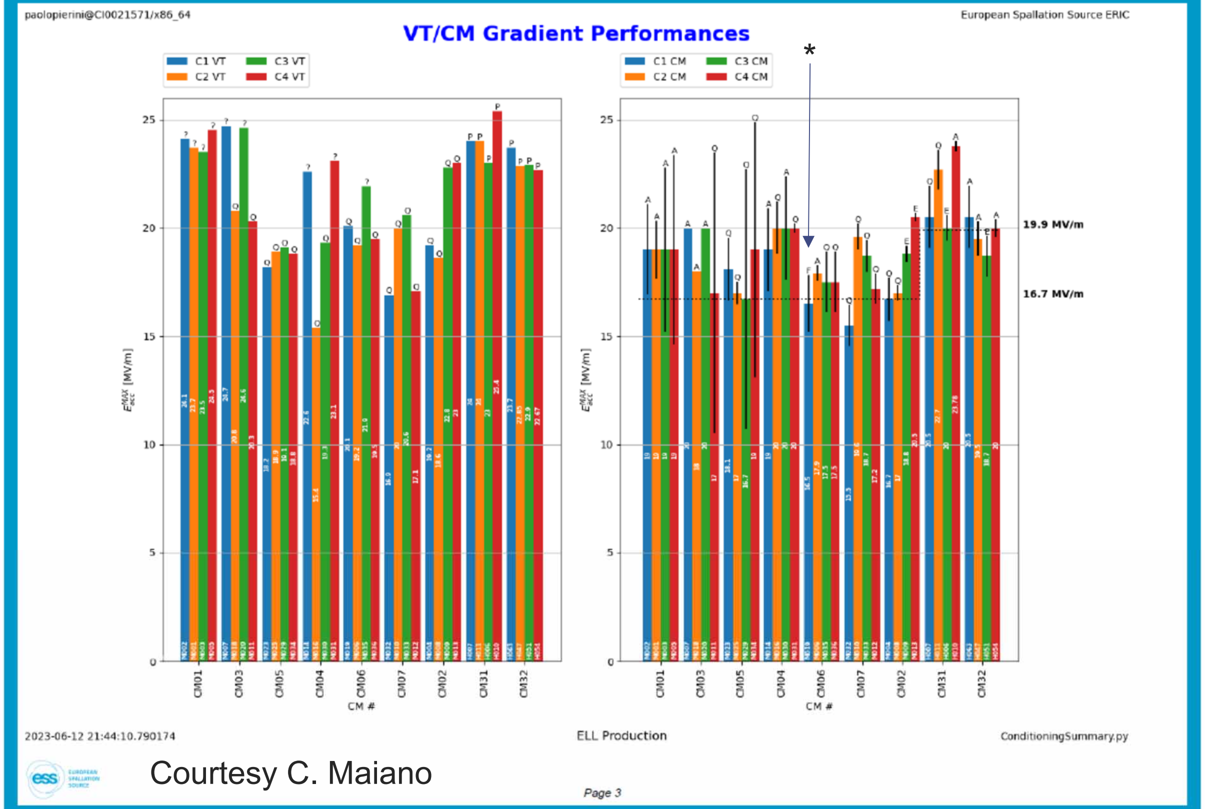
radiation from the cavity follows Eacc variations

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

Testing at ESS Test Stand 2



Courtesy C. Maiano

All modules shipped to ESS are tested at TS2

9 CM passed the test in TS2

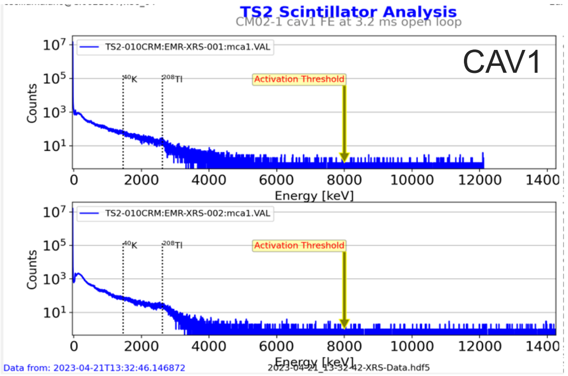
Currently testing CM33

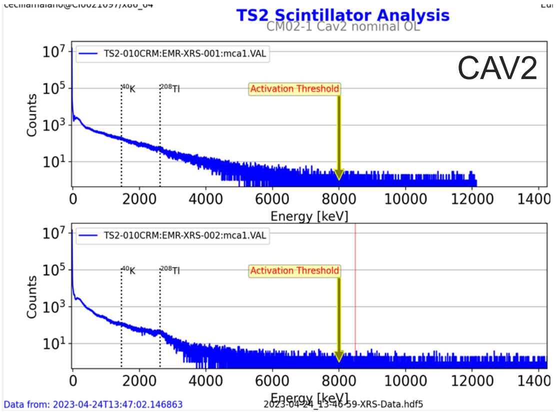
*CM06 cavity 1 : Quench due to FE

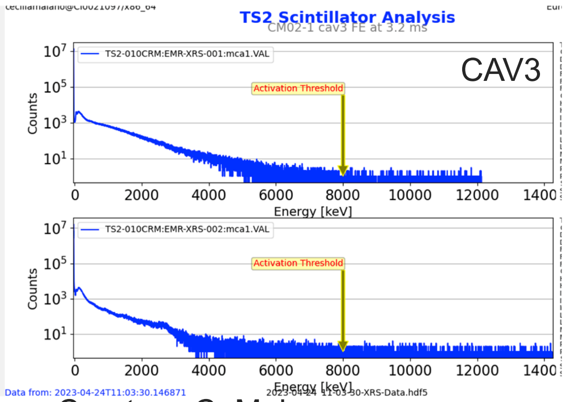
Cavities tested individually

4 cavities can be run simultaneously

Medium beta CM02-1 testing at TS2







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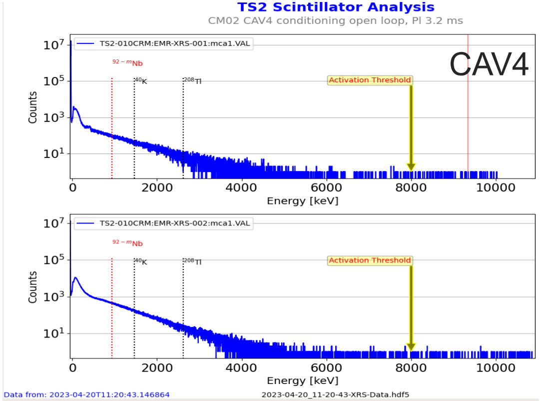
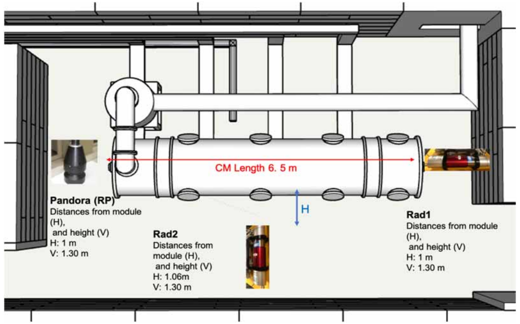




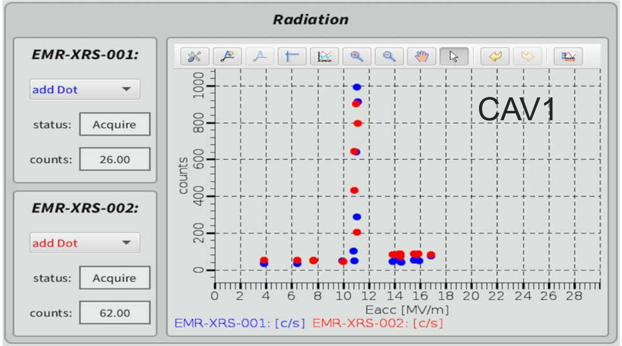
2 x Scintillator-based Spectrometers

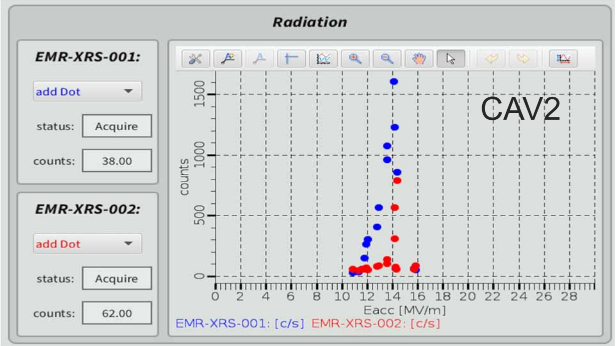
Monitoring of γ energy spectrum : if the activation threshold energy is exceeded, counts above it are recorded

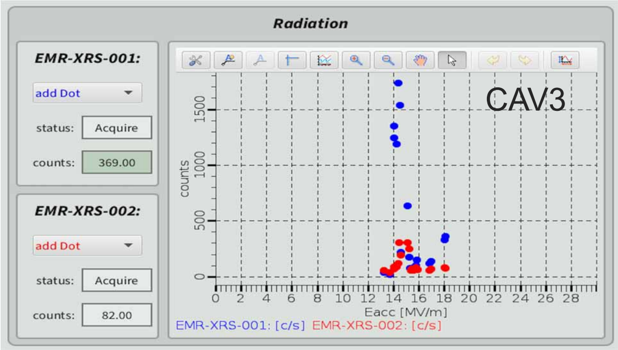
LB6419 monitor for pulsed mode combined γ and neutron

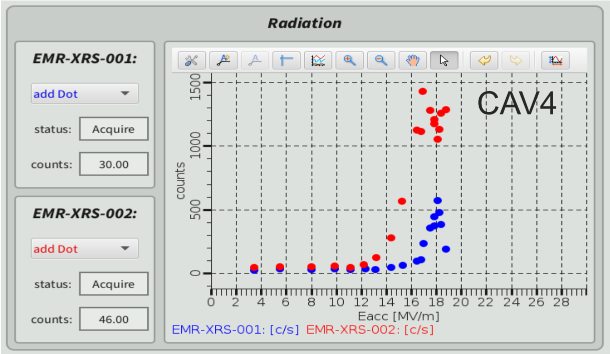
Progressively installing Saclay's bunker instrumentation

Medium beta CM02-1 testing at TS2









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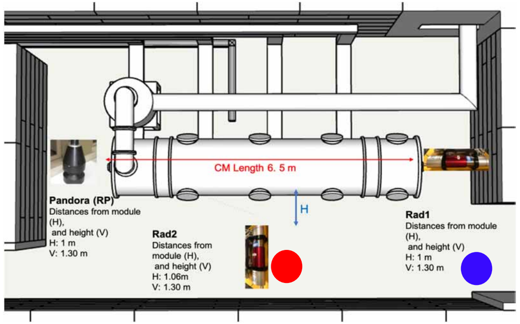


The window of coupler 4 has developped a crack before the test

The window was exchanged in situ in local clean room conditions

Simulation process

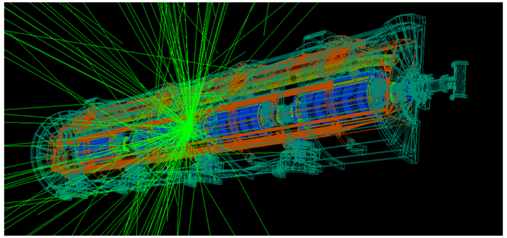
2D Fishpact simulations of FE electron trajectories, scanning:
- E_{acc},
- FE emitter position,
- RF phase

output

distribution of electron impact position & momentum

select a subset of interest, e.g. filtering on starting point E_{pk}, on impact energy, impact position

at this stage, interesting scenarii can be defined

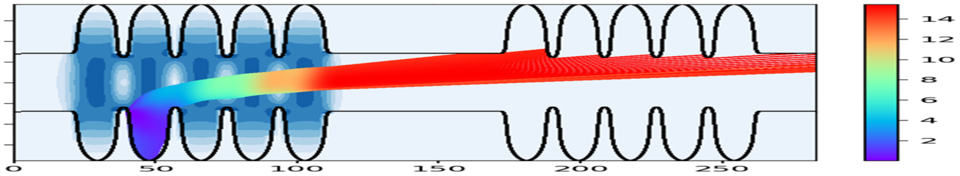


Geant4 MC simulation of the scenario using the impact parameters position and momentum as starting conditions for electrons;
repeated N>>1 times to accumulate statistics

output

all particles generated by the e- interaction.
A selection of data to be recorded has to be provided, e.g.:
- energy spectrum of gammas, neutrons in a given detector or volume
- count of gammas, neutrons produced in a given component
- count and timing of scintillation photons in a photodetector
- entire tracking of an event
- ...

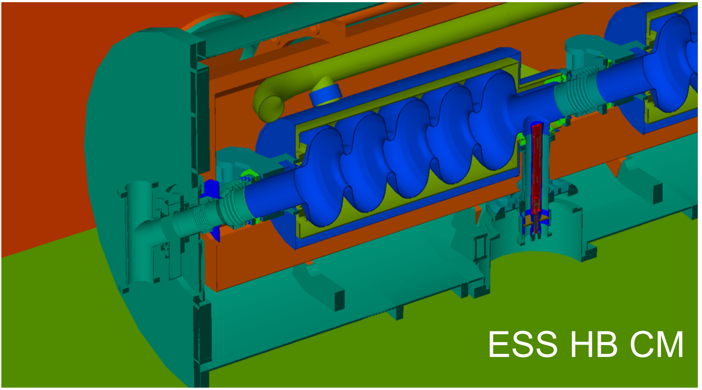
e- impact energy > 14 MeV in Cavity 3 downstream tube must start from iris1 of Cavity 4 when E_{acc4} =20 MV/m in a narrow phase range

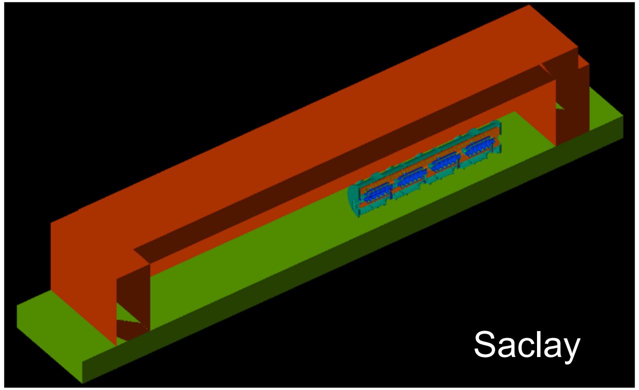


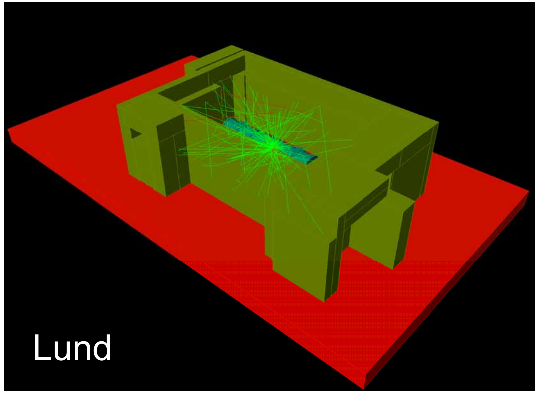
Geant 4 models

Graded realism approach for geometry:

- very detailed geometry around the beam vaccum
- use material compositions as provided by manufacting material certificates as much as possible
- cryomodule components modelling is simplified or skipped if their volume or density is small
- exception for parts containing elements prone to activation

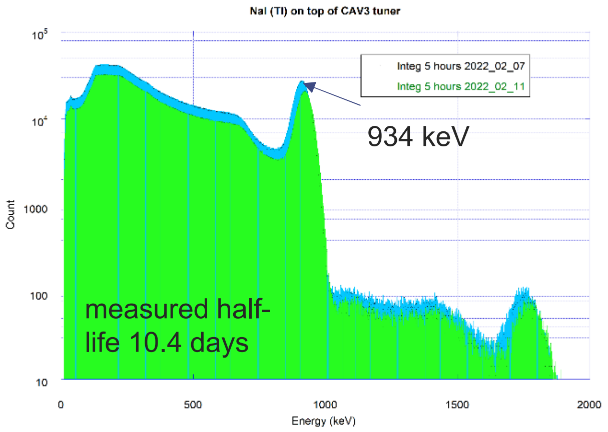






CM31 neutron emission

- During test of cavity 4 at nominal gradient the LB6411 in the bunker records H*(10) ~ 400 uSV/h
- Several weeks later the CM is opened, the activated area is identified as the downstream beam pipe of neighbour cavity 3
- A 2" NaI(TI) spectrometer is installed at this spot in order to identify the possible activated material



- Among the produced radio-isotopes, only one with half-life > 1 day has been positively identified :
- ^{92m}Nb through its main gamma decay line at 934 keV and its half-life of 10.2 days matching measurements

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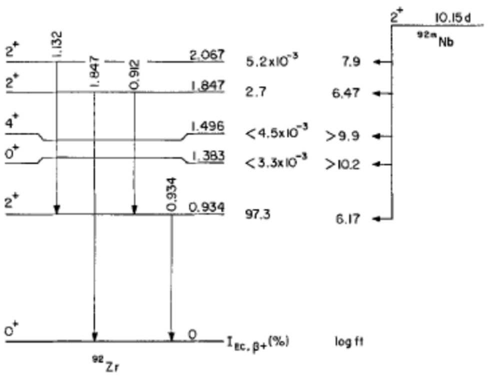


Fig. 2. Decay scheme of ^{92m}Nb

Z. Phys. A – Atoms and Nuclei 322, 331–332 (1985)

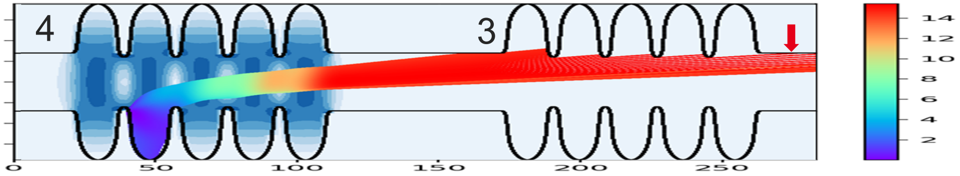
Decay Scheme of ^{92m}Nb

O. Helene and I.D. Goldman
Instituto de Fisica da Universidade de Sao Paulo, Sao Paulo, Brazil

The ^{92m}Nb was obtained by (γ, n) reaction on a metallic niobium target ($\sim$1 g/cm^2), using the bremsstrahlung produced in a tantalum foil by the electron beam from the linear accelerator of the Instituto de Física of the Universidade de São Paulo. Three irradiations were performed for 6.5 to 8.0 h, using electron beam energies between 14.0 and 16.5 MeV and intensities of about 10 μA. The residual gamma-ray activities were measured with two Ortec Ge(Li) detectors of 27 cm^3 and 53 cm^3 for periods up to 95 d. Energy and efficiency calibrations were obtained using gamma-ray lines from ^{60}Co and ^{154}Eu.

CM31 neutron emission scenario analysis

- Field emission from cavity 4 is initiated on first inner iris (coupler side)
- FE electrons are accelerated across cavity 4. At nominal Eacc, trajectory calculations show:
  - electrons are able to exit cavity 4 and hit all irises of cavity 3 (unpowered) and reach cavity 2
  - the escaping electrons have an energy spectrum extending up to 15 MeV



Fishpact simulations E. Cenni

- Induced Bremsstrahlung in cavity 3 and cavity 2 mainly on Nb

Mechanism:

- ~15 MeV $e^- \rightarrow e^- + \gamma$ (Bremsstrahlung in Nb)
- $\gamma + {}^{93}Nb \rightarrow {}^{92m}Nb + n$
- ${}^{92m}Nb \rightarrow {}^{92}Zr + \gamma_{934\ keV}$

GIANT DIPOLE STATES 613

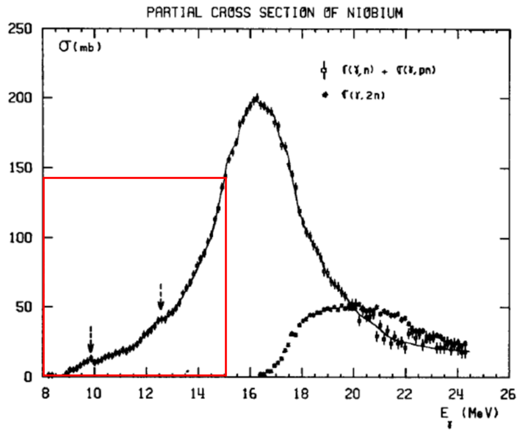
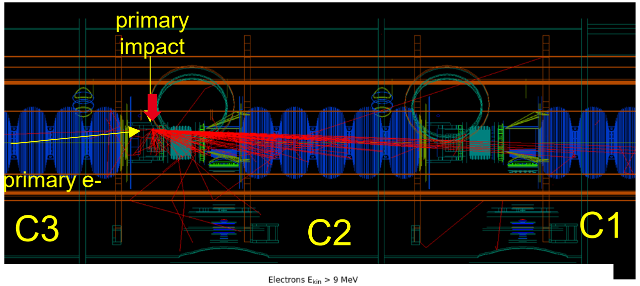
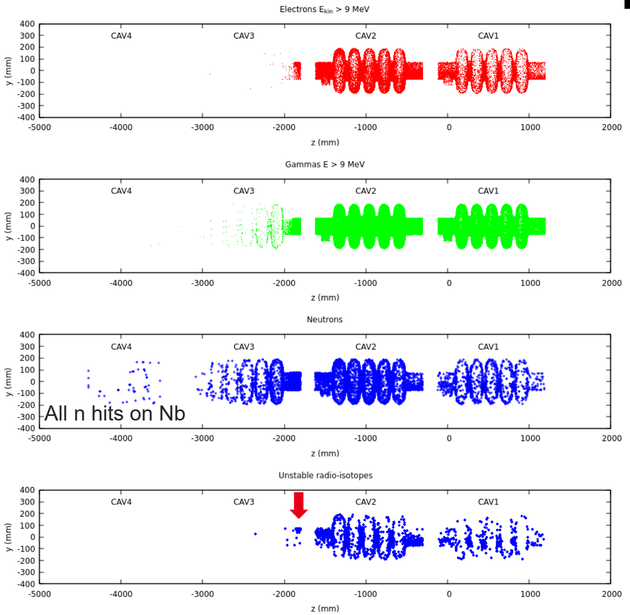


Fig. 5. Partial photoneutron cross sections $\sigma(\gamma, n)$ and $\sigma(\gamma, 2n)$ of ^{93}Nb.

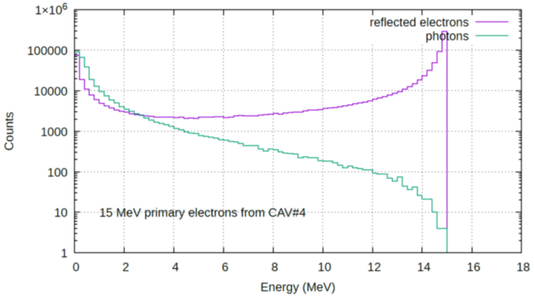
A. Leprêtre et al. Nuclear Physics A175 (1971) 609-628

CM31 neutron emission simulation





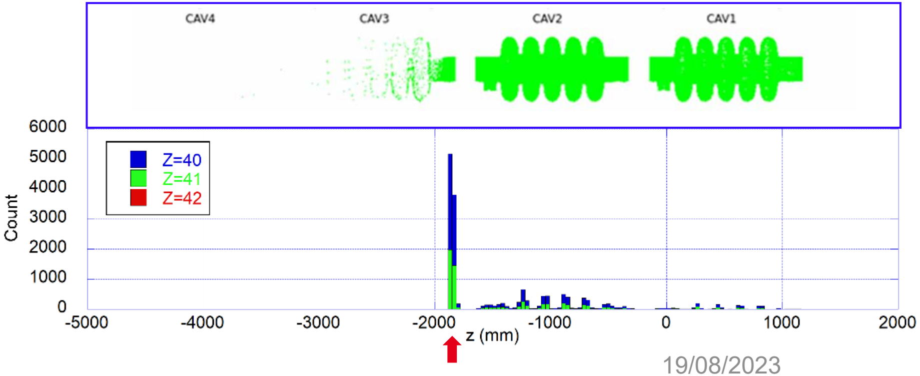
simple model with monoenergetic 15 MeV electrons



Observed in the simulation: scattering of impinging primary e- due to the low angle of incidence of 2° on Cavity 3 beam pipe

only e^- and γ potentially involved in GDR shown (E > 9 MeV)

Unstable isotopes are distributed
~1/2 in Cavity 3 beam pipe
~1/2 in Cavity 2 and Cavity 1



Upgraded simulation process

Improved Geant simulation:

Track charged particles in the RF field

- not natively implemented in Geant4, but the toolkit includes all the necessary building blocks
- implemented a RF field map import, dynamic interpolation

Generate primary electrons

- at the FE emitter site
- using a Monte-Carlo generator to have the phase distribution follow the Fowler-Nordheim law

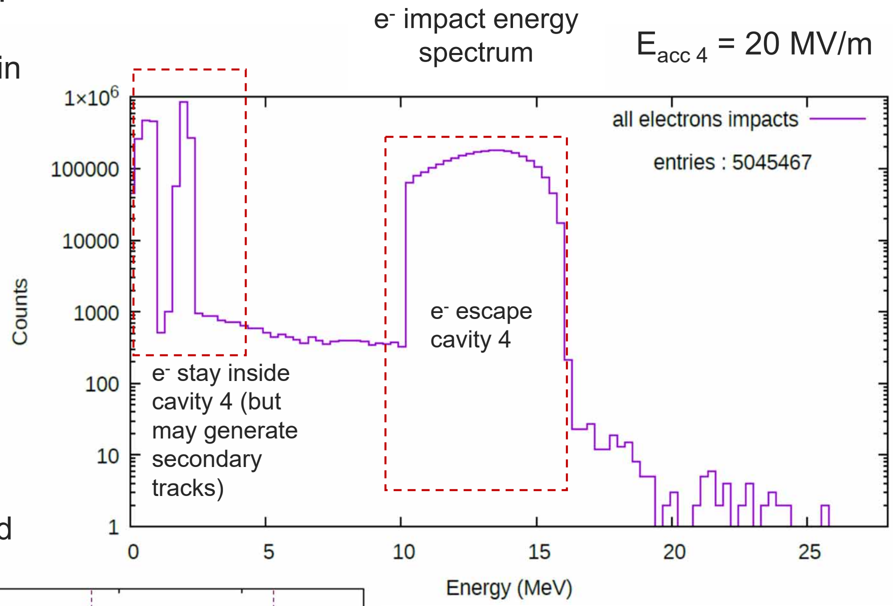
Enabled:

- multiple cavity operation
- emission from the FPC can be tracked

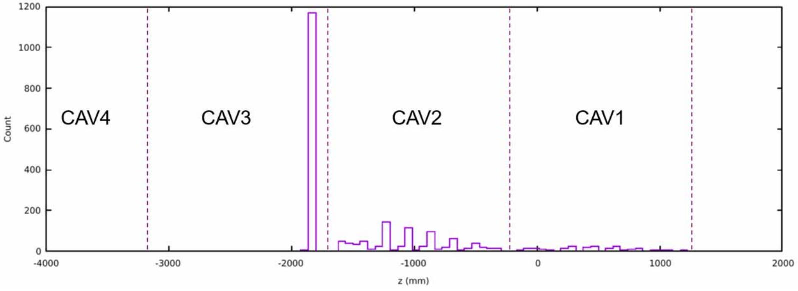
CM31 neutron scenario - upgraded G4 simulation

How does the introduction of F-N statistics affect the results?

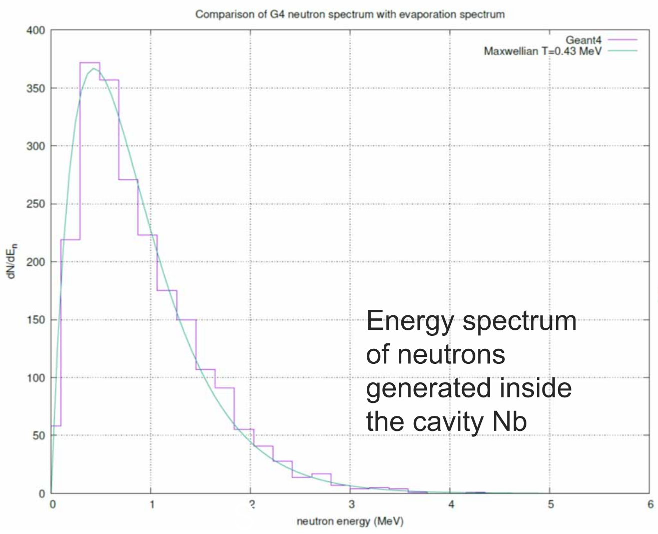
- e^- launched at other phases will get a different energy gain
- scattered e- are accelerated
- The electron population will spread in the cavity string
- For the same number of initial electrons, less will reach cavity 3 with an energy above threshold for subsequent photoneutron production
- The resulting spatial distribution of generated neutron and activation is unchanged

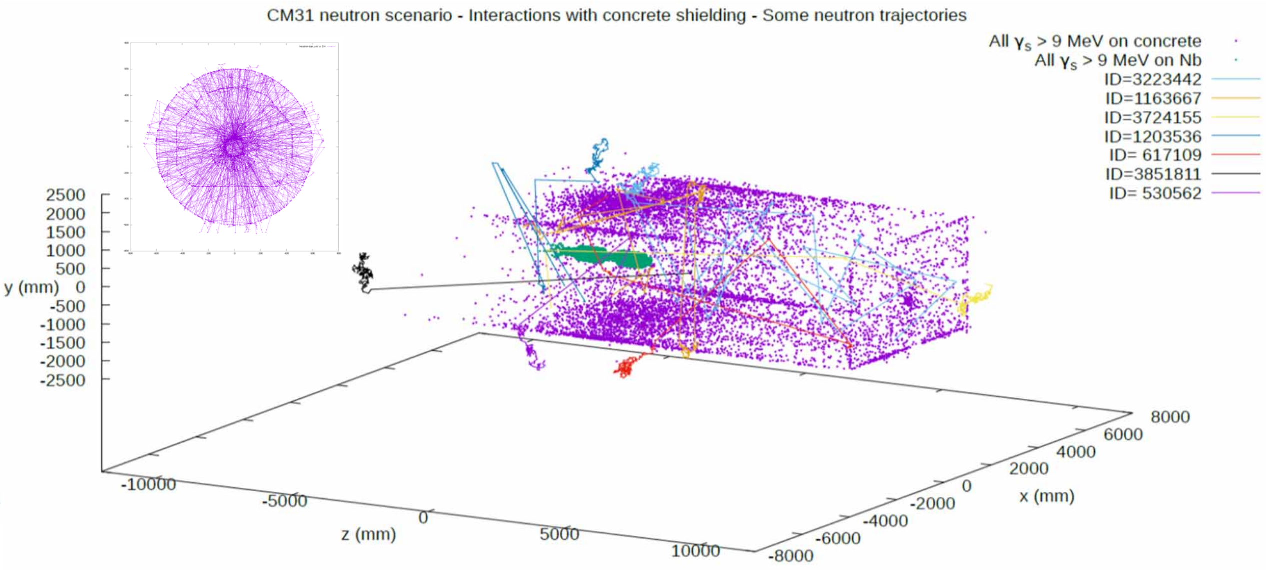


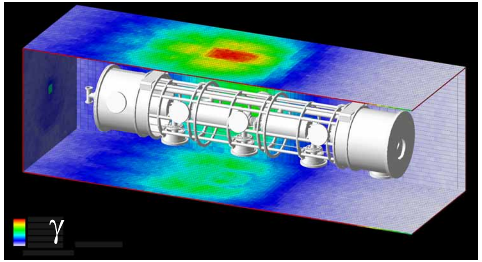
position of generated neutrons

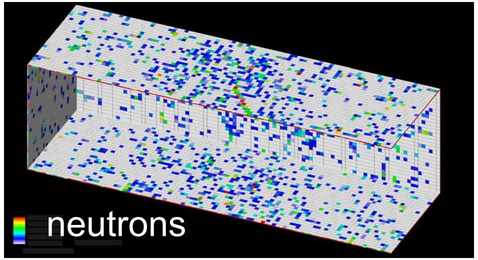


CM31 neutron emission upgraded simulation



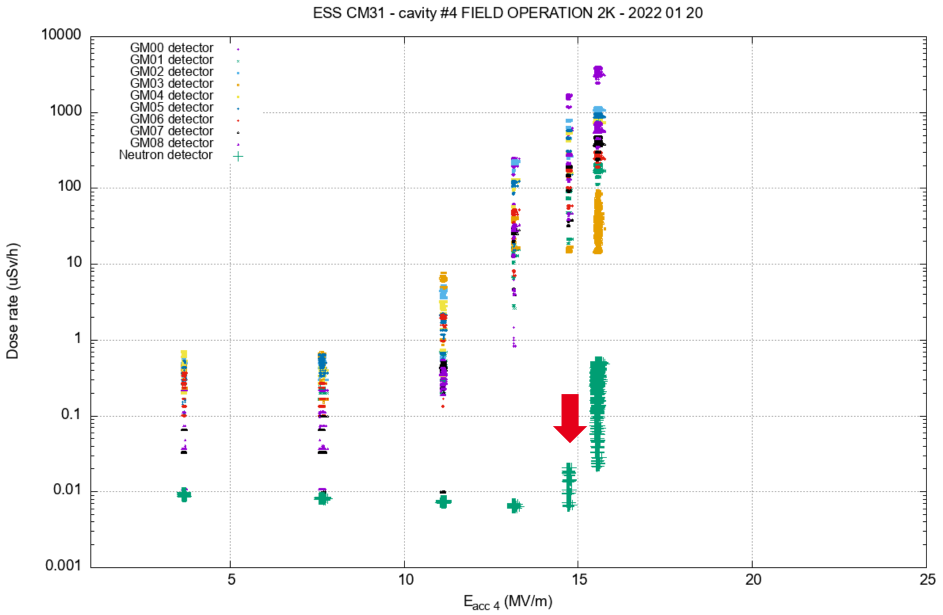


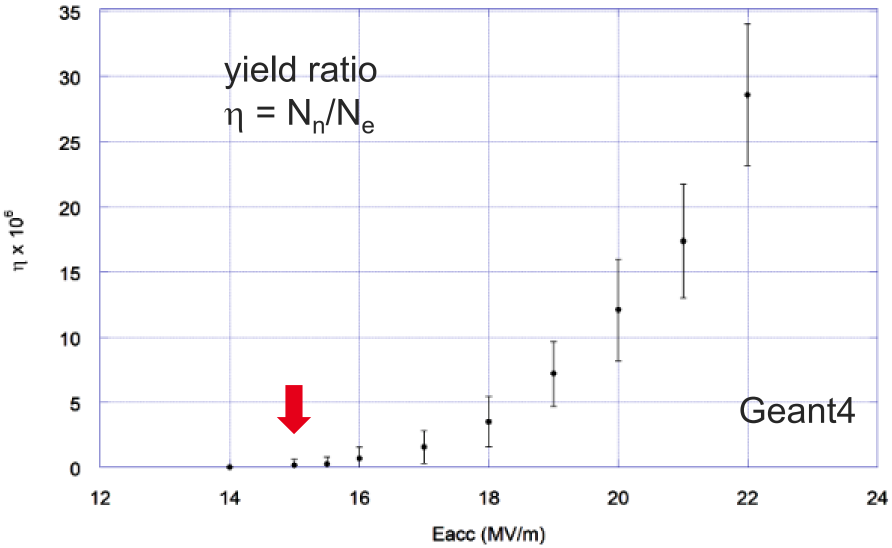




No moderating material in the bunker
→ neutrons experience several scattering events before they are absorbed
→ their distribution is randomized

CM31 neutron emission threshold





Experimental threshold of neutron emission at 14.7 MV/m

Geant4 threshold for neutron production at $E_{acc\ 4}$ = 15 MV/m

yield ratio = 1.2 10^{-5} at 20 MV/m

Estimates for the FE current for CM31

2 measurements available

N_e number of primary electrons
I_{FE} average FE current during flat top

number of ^{92m}Nb decays = number of neutrons

decay measurement

simulation of ^{92m}Nb decay measurement on Cavity 3

→ estimate of total number of ^{92m}Nb decays = estimate of number of generated neutrons N_n x η = N_e → $I_{FE} \approx 10\ \mu A$

simulation of $\eta = N_n/N_e$

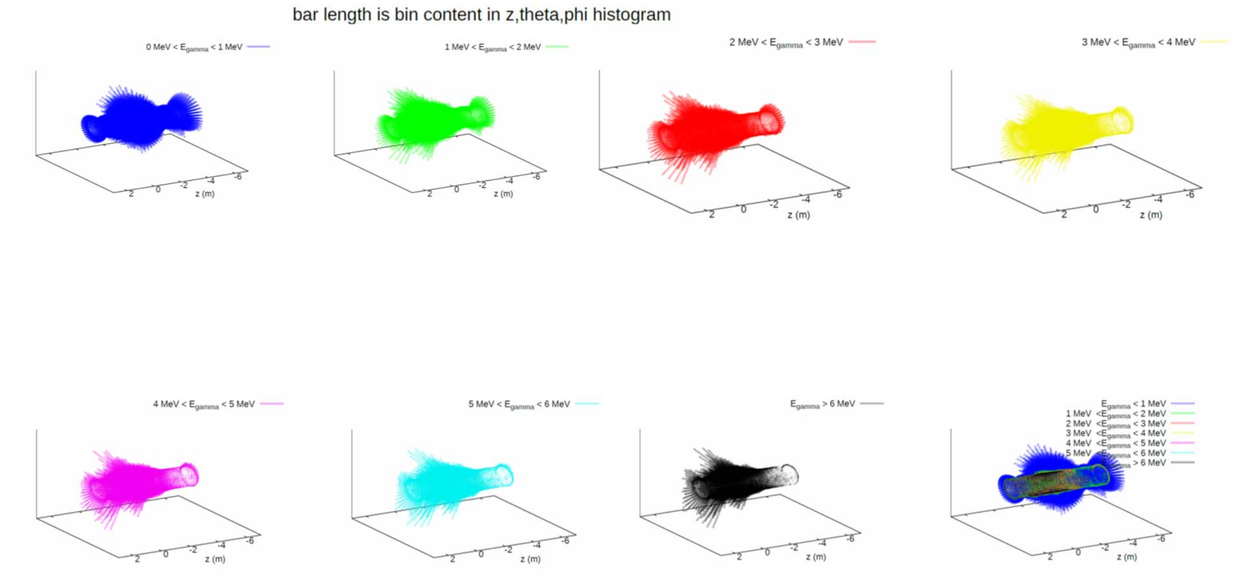
integ. dose neutrons measurement (LB6411)

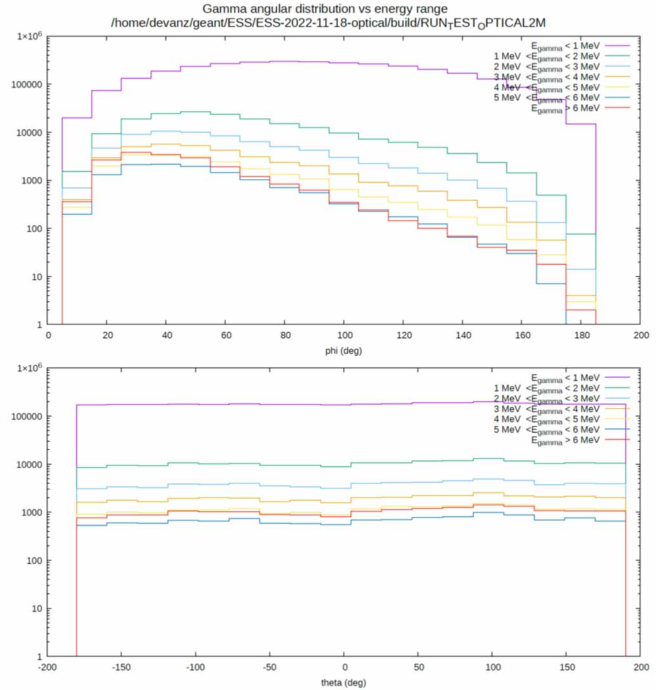
simulation of neutron detection in the bunker → ratio of measured/ generated neutrons

→ estimate of number of generated neutrons N'_n x η = N'_e → $I_{FE} \approx 44\ \mu A$

Angular distribution vs energy

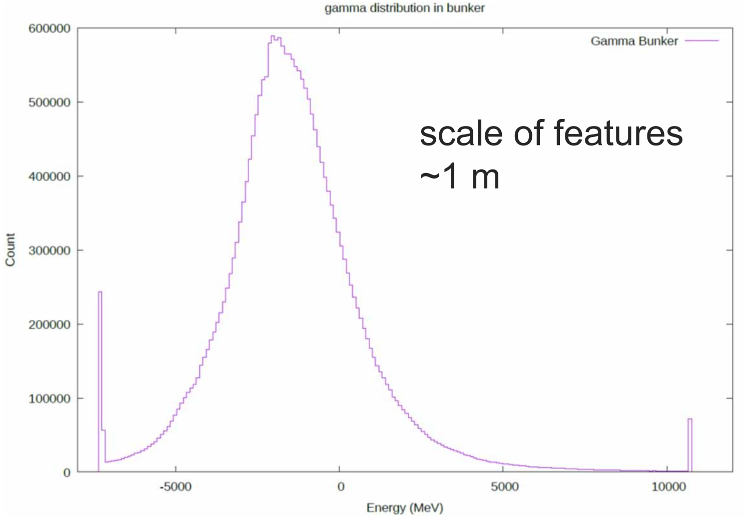
angular distribution of γs for energy slices, at the vacuum vessel

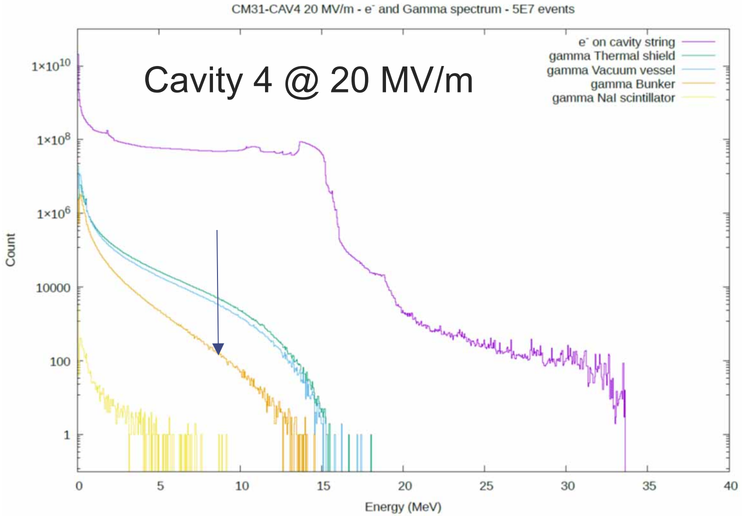


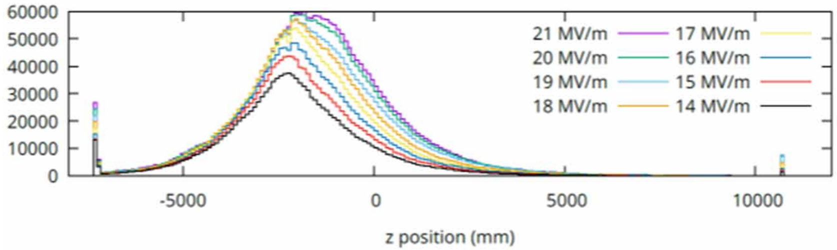


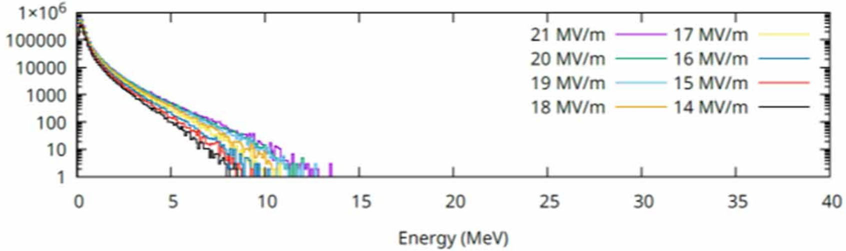
low energy γ dominates and smear the angular distribution: detection inside the module should be beneficial

γ distribution at the bunker level







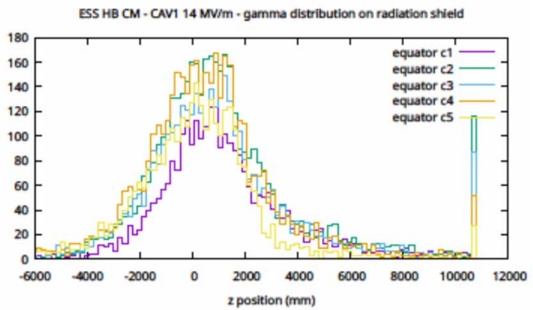


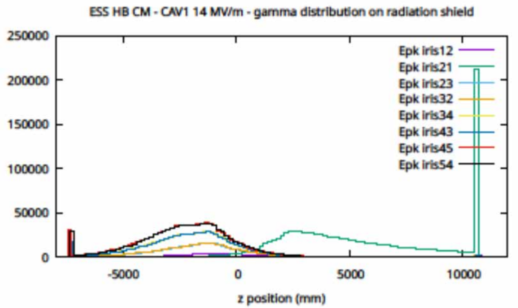
the objective of the simulation is to help position the detectors in the bunker

Discrimination between cavity MP & FE

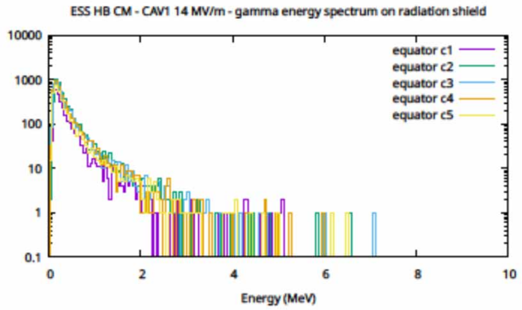
MP e⁻ from CAV1 equators
Eacc = 14 MV/m

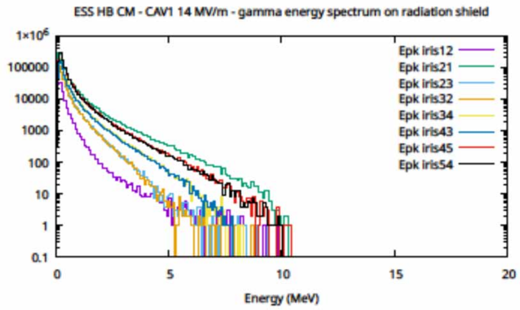
FE e⁻ from CAV1 irises
Eacc = 14 MV/m





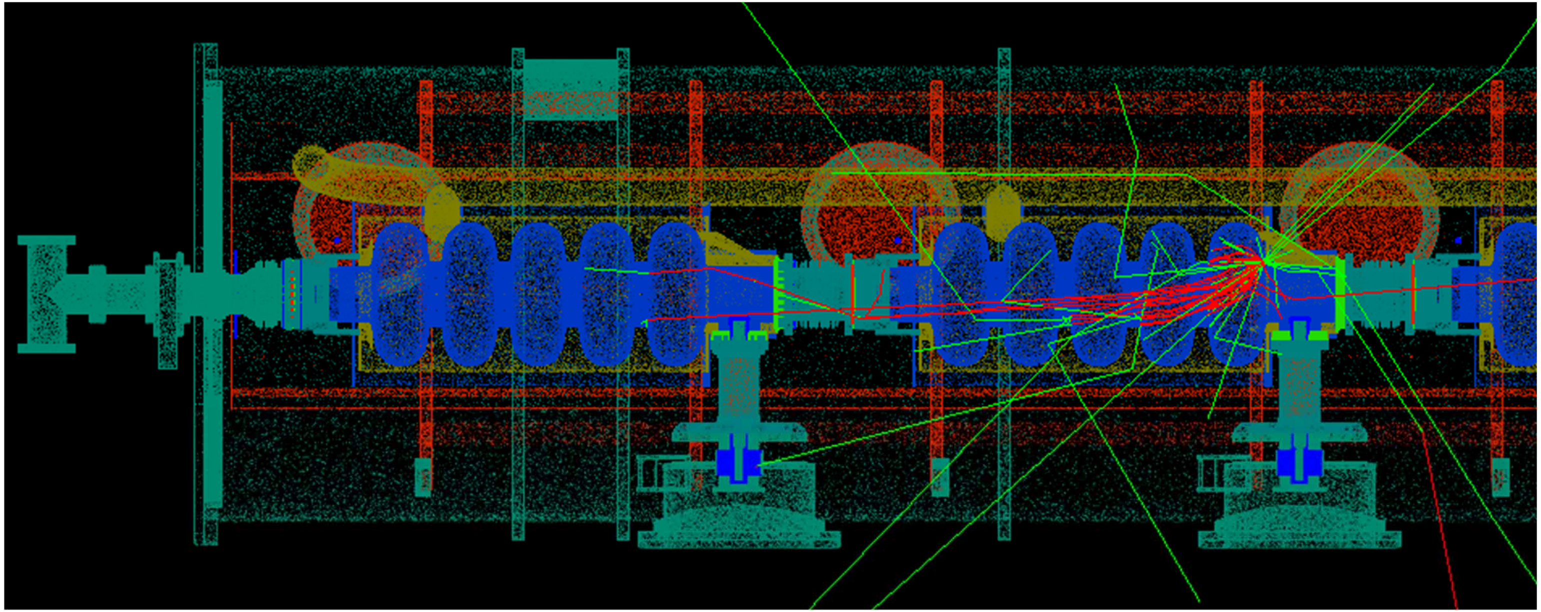
Distribution of γ radiation along z in the bunker





Spectrum of γ radiation in the bunker

FPC electron acceleration

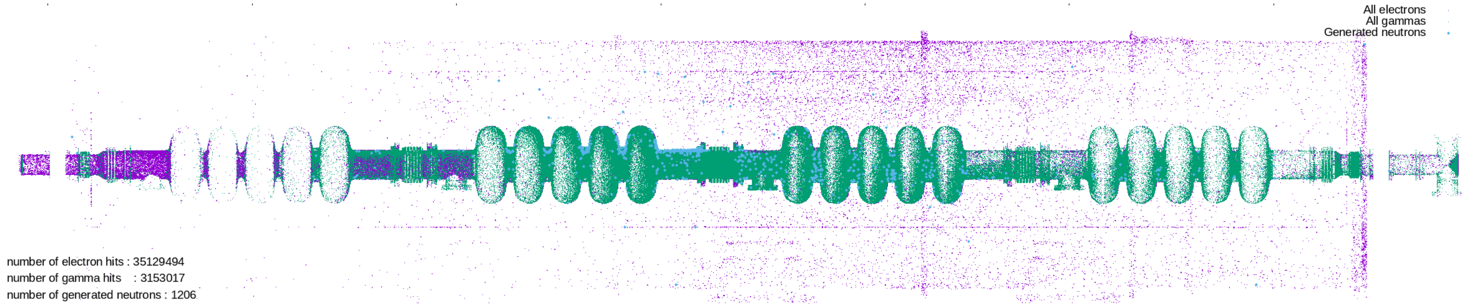


- 100 eV e^- launched from coupler during cavity decay (Eacc ~ 14 MV/m)
- captured e^- hit cell 1
- part of the scattered e^- are accelerated in 1 – 5 cells

Conclusion

A detailed simulation model provides
- a way to interpret measurements even if only area monitors are available
- data to improve the layout of radiation sensors in a cryomodule test bunker
- a description of the nature (energy, distribution) of what we are trying to measure
- predictions for other CM test conditions (i.e. multiple cavities)
- predictions of the interaction with other devices (i.e. arc detectors, protection systems)

We are developing scintillator based instrumentation to measure cavity radiation closer to the source
- first tests of plastic scintillators at cryogenic temperatures are positive
- we are currently building the birdcage detector for the single-cell cavity
- we plan to further expand the concept to cryomodule testing environment



THANK YOU FOR YOUR ATTENTION

Many thanks to the SRF/TS2 team at ESS-Lund