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# COSICAF, a fission chamber simulation tool for academic purposes

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***Abstract*—Since a few years, simulation codes were built at CEA Cadarache to predict the signal of ionisation chambers and taylor detectors for specific applications. It is proposed here to present COSICAF, a tool developed for mainly academic purpose and rapid fission chamber prototyping. This numerical simulation, mostly based on semi-empirical models and Monte-Carlo method will help students to understand how ionisation chambers work. Through the paper, models and their numerical implementation will be discussed. A focus is made on recently implemented features like charge multiplication and correlated source which make the simulation of proportional counter possible. To demonstrate the interest of the code, simulations of a planar fission chamber is proposed.**

## I. Introduction

Ionisation chambers sensitive to neutron flux and more specifically fission chambers play a key role in nuclear industry where they are used mainly for core neutron monitoring. Those detectors are constituted of a gastight body which contains at least two polarised electrodes, a volume of noble gas and an active material such as a fissile deposit. When a neutron travels trough the detector, it has a chance to react with the active material, producing energetic heavy ions. Heavy ions interact with the gas and electron/ion pairs are created. By gathering charged particles thanks to the polarised electrodes, current pulses are generated at the output of the detector.

Depending on the neutron flux and the ionisation chamber design, it is possible to operate such detector in three different modes [1]: pulse mode where pulses doesn't overlap; Campbell mode where pulses pile up but it is possible to link the count rate to signal variance; current mode, where the signal is high enough to produce a current proportional to the count rate[2].

Ionisation chamber simulation is complex since it involves neutron/matter interaction, heavy ion interactions with gases, and electromagnetics. Simulations are of great interest to prototype a detector, estimate their typical response in a given neutron flux, or even correct measurement performed during experiments.

To make simulation accessible, COSICAF [3], an open source software written in Octave/Matlab[4] was developed at the instrumentation, sensor and dosimetry laboratory of CEA Cadarache. This tool is part of the decade effort of our team on fission chamber simulation. Unlike previous softwares like CHESTER [5] and Pyfc [6] which were designed for research purpose only, COSICAF is dedicated mainly to rapid prototyping of detectors and for education purpose. Hence, included models are highly simplified and the core of the software is accessible to make practical work with minimum effort. Originally, the software was only able to simulate current pulses of fission chambers operating in saturation regime with Monte-Carlo method. It was recently enhanced to allow simulation of boron, lithium and helium 3 detectors. charge multiplication was also taken into account to handle proportional counters. At last, correlated sources were added to simulate detectors where more than one heavy ion is able to interact with the gas.

In this paper, the general structure of COSICAF will be presented; the models used during the simulation are summarized and implementation related problems like geometry description, particle tracking, electric potential computation are discussed in detail. In a second part, the new features of the code are described: It is shown how the signal generation procedure is modified to take into account the charge multiplication and how the COSICAF database can be expanded to simulate additional detectors. In the last part of the paper one example of simulation, a planar fission chamber built by the CEA fission chamber workshop is discussed.

## II. General description of COSICAF

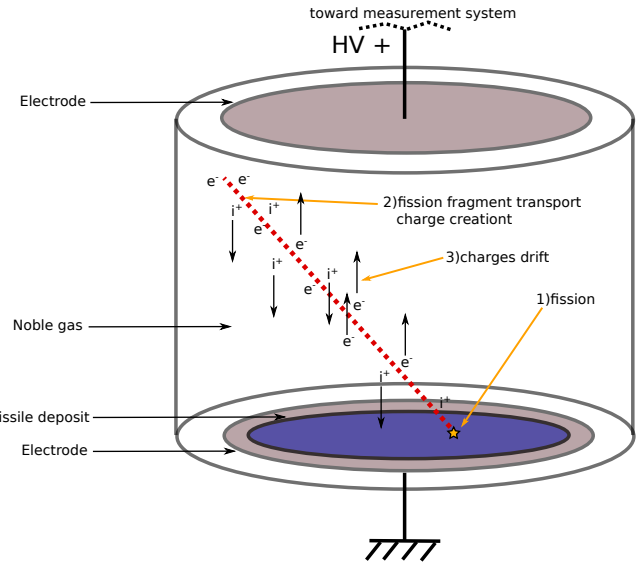


Fig. 1. Working principle of a fission chamber.

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A scheme of ionisation chamber is shown in Fig. 1, it depicts the physical processes involved in a detector simulation which are:

1) Reaction between neutron and active material.
2) Emission of a heavy ion.
3) Transport of a heavy ion in the matter and generation of ion/electron pairs.
4) Transport of charge carriers.
5) Estimation of the signal induced by the charged particles.

For the sake of simplicity, since the simulation is performed in pulse mode, the interaction of neutrons with active material might be simplified into a uniform random generation of heavy ion inside the active material. Because of that hypothesis, the kinetic energy of the neutron is considered as negligible and no effects like flux depression or self shielding can be taken into account.

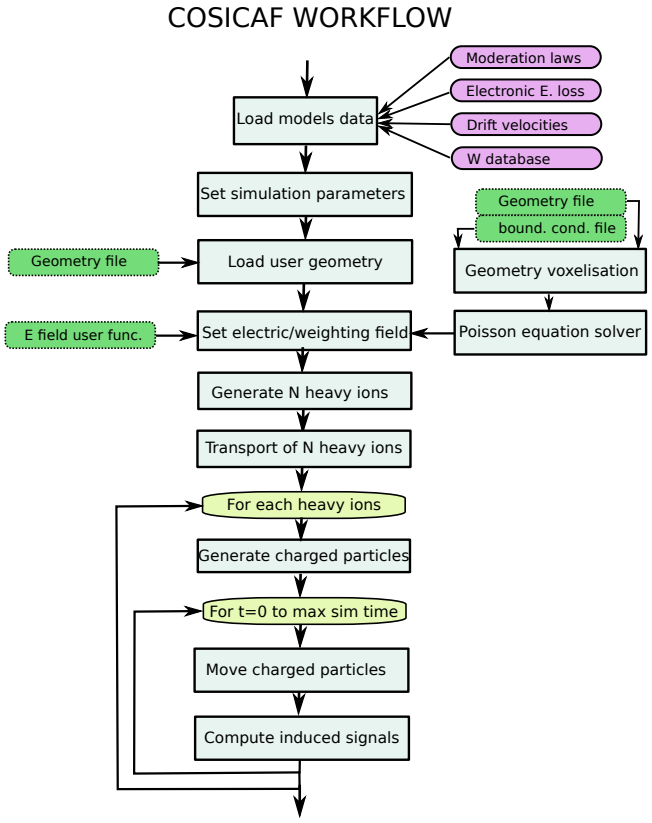


Fig. 2. COSICAF workflow. The core of the software uses a Monte-Carlo method to simulate N detector pulses.

The general structure of COSICAF is depicted in Fig. 2, each part of the software is detailed below.

### A. *Geometry definition*

Source definition and particle tracking are highly dependent of the geometrical description of the problem. Before implementing any physics, it is mandatory to set a proper geometry representation. COSICAF was designed to handle geometry of arbitrary complexity with an undefined amount of heavy ion sources and electrodes. Because of its complexity, Constructive Solid Geometry used in software like MCNP is not applicable. Most of the fission chamber geometries are planar or cylindrical, we chose to reduce the geometry definition to cylinders and cylinder shells parallel to the z axis. All the volume are defined by a height, an outer and an inner radius plus the position of the cylinder base. Only the inclusion relation is implemented, it is handled by associating an inclusion number to each volume: Volumes with the higher inclusion numbers are contained in the volumes of lower inclusion numbers. Each piece of geometry is linked to a material, a volume mass, and an attribute that allows defining boundaries or how heavy ions are interacting with the volume. An example of a geometry is given in Fig.3 for a flat fission chamber.

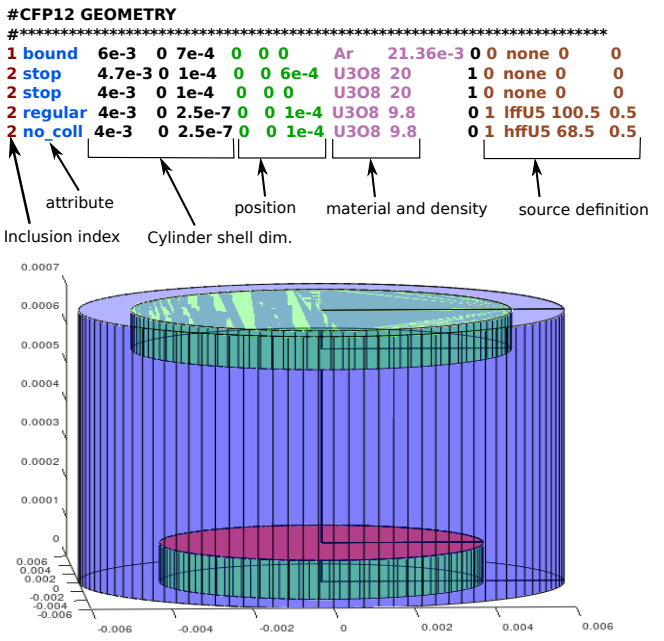


Fig. 3. Geometry description file and the resulting output generated by COSICAF.

### B. *Heavy ion generation and transport*

Heavy ions are generated uniformly in source volume. For fission fragments (f.f.) emission, the use of the fission yield would lead to a large amount of data for heavy ions transport. Chung [7] and Mat'ev [8] showed it is possible to reduce the fission yield to only two mean fission fragments while keeping a rather good quantitative estimation of energy deposited by f.f. in material. From the JEFF 3.1.1 fission yield of U235, two mean fission fragments were estimated, their characteristic is available in Table I. Other fissile deposits might be considered but the original COSICAF code take only into account U235 fission fragments and alpha particles. At each randomly selected emission point, only one heavy ion is generated since it is assumed that one ion is able to exit the fissile deposit. Hence, cases with thin deposits or gaseous active materials could not be simulated until the inclusion of

TABLE I
DEFINITION OF THE TWO MOST PROBABLE FISSION FRAGMENT GENERATED DURING THE FISSION OF URANIUM 235.

| kin. E(MeV) | Light f.f. | | | heavy f.f. | | |
|---|---|---|---|---|---|---|
| | Z | M (uma) | E (MeV) | Z | M (uma) | E (MeV) |
| 169.5 ± 3 | 38 | 95 | 100.5 | 54 | 138.5 | 68.5 |

correlated sources in the software. Then, a random propagation direction is associated to each generated heavy ion.

Many models are available to simulate the transport of heavy ion [9], [10]. Monte Carlo techniques and computation of the collision integral gives exact heavy ion trajectories and energy losses. It is also possible to compute energy losses on the ion projected trajectory toward the direction of propagation with PRAL algorithm [11]:

$$\frac{d\overline{x}}{dE} = \frac{1}{S(E)} - \frac{\mu}{2E}\frac{S_n}{S}\overline{x}, \tag{1}$$

with $S(E)$ and $S_n$ (MeV/(mg.cm$^2$)) respectively the total and the nuclear stopping power, $\overline{x}$ the range and $\mu = M_t/M_p$ the ratio of the target and projectile particle mass. Other quantities might also be obtained with PRAL algorithm like straggling which compute the dispersion of the trajectory from the straight line.

In COSICAF, it is considered that heavy ion trajectories are straight lines. The error induced by this approximation is rather small for f.f. transport in noble gases: for light U5 fission fragment (U5 l.f.f.) in argon, the straggling correspond to 4.5% of the range. This hypothesis greatly simplify particle tracking: from the propagation direction vector it is possible to know all the volumes crossed by the heavy ion by computing only plane/line and cylinder/line intersections. To make the transport problem more tractable, Nguyen and Grossman [12] among others derived an analytical moderation law by solving equation 1 with a Bohr electronic stopping power, it gives:

$$E(x) = E_0\left(1 - \frac{x}{R_{E_0}}\right)^n, \tag{2}$$

where E(x) is the energy of the particle after a travel $x$, $R_{E_0}$ is the range of the particle at the initial energy $E_0$ and n a semi empirical parameter related to the shape of the stopping power. A similar approach was chosen for COSICAF, but instead of the power law of eq.2 and the use of Bohr electronic stopping power, we decided to fit a five order polynomial on $f(1 - x/E_0) = E/E_0$ data computed with PRAL algorithm and total stopping powers provided by SRIM [13].

Considering the total stopping power is accurate to describe the transport of heavy ions, but it brings some errors while considering gas ionisation since only the electronic stopping power is related to charge pair creation. A correction can be estimated by computing the energy lost through electronic collisions as a function of the ion's kinetic energy. Neglecting this correction lead to an overestimation of charge pair creation of 4 % for U5 l.f.f in argon. Taking it into account makes the error below 0.4%. The estimation of charge pair generated along the ion tracks is performed by using $W$, the mean energy needed to generate a electron/ion pair. For noble gases, W is of the order of 30 eV [14].

### C. Charge transport, induced signal

For each heavy ion track, charged particles are generated by using a database of $W$, only volume with a material referenced in the $W$ database will contain ions and electrons. Since $W$ is orders of magnitude smaller than the typical energy losses of heavy ion in gases, millions of charged particles are generated along the fission track. Hence, regarding the needed computing power and the approximations already done, it is vain to track each electron and ion. Instead, charged meta-particles representing thousand of electrons or ions are generated along the heavy ion track to make the simulation run in a reasonable amount of time.

Charged meta-particles are then drifted because of the polarised electrodes at a velocity given by:

$$v_p = \mu_p E \tag{3}$$

Where $v_p$ (m/s) is the group velocity, $\mu_E$ the mobility and $E$ the electric field. Our software relies on drift velocities from Raju [15] for the electrons and on Frost's semi-empirical model for ions[16]. It is assumed there is no charge recombination during the drift. From a practical point of view, COSICAF uses a explicit Euler scheme to move electric charges and to compute the induced signal. For each time step, meta-particles are moved by a $\vec{\Delta l}$ distance given by:

$$\vec{\Delta l} = \mathrm{sgn}(q)\frac{\vec{E}}{E}.v_p(E).\Delta t \tag{4}$$

where $dt$ is the time step, $E$ the electric field and $q$ the charge carried by the meta-particle. According to the Shockley-Ramo theorem [17], charged particles movement induces a current signal on electrode. On the k$_{th}$ electrode, it is computed by:

$$i_k = q_m v_d(E)\frac{\vec{E}}{E}.\vec{E_{0k}}. \tag{5}$$

where $\vec{E_{0k}}$ is the weighting field and $\vec{E}$ is the electric field.

All meta-particles are followed until the maximum computation time is reached or until all the charges are destroyed by hitting walls or electrodes.

### D. Electrostatic computation

Electric field appears in all equations related to charged particles drift, this quantity is rather important since it is, with the weighting field, essential for signal computation. COSICAF has two different methods to describe electric field which will be used in the simulation. The first one allows to define a user function, which is useful for simple geometry since electric field derivation is straightforward. For more complex cases, it is not possible to compute the electric field analytically. COSICAF offers the possibility to solve Poisson

equation with Dirichlet boundary conditions using random walk technique. Let us consider the following equation in a 3 dimensional domain $G$:

$$\nabla.(\epsilon \nabla V(\vec{r})) = 0, \text{ for } \vec{r} \in G, \tag{6}$$

$$V(\vec{r}) = V_p, \text{on the boundary of } G, \tag{7}$$

where $\epsilon$ is the dielectric permittivity. By dividing G into a mesh with constant step $h$, it is possible to estimate the electric potential at $\vec{r}$ by setting particles at this position and starting random walks on the mesh until they reach boundaries. With N particles, the solution of the Dirichlet problem is given by [18], [19]:

$$V(\vec{r}) = \frac{1}{N} \sum_{i=1} N V_p(i) \tag{8}$$

with $V_p$ the electric potential at boundaries reached with random walks. Since we are interested in the electric potential in the whole domain and not only in $\vec{r}$, the computation is speed up by updating all the potential along random walks. In COSICAF, the direction of the random walk is selected with a random number $a$ from an uniform distribution and the probability to move in each direction which is given by:

$$P(x, y, z + h) = \frac{1}{3} \frac{\epsilon(x, y, z + h)}{\epsilon(x, y, z + h) + \epsilon(x, y, z - h)} \tag{9}$$

One of the main problem to use this numerical method is the need of a meshed geometry. COSICAF provides a routine which "voxelize" the surface defined geometry. An example of the voxelisation algorithm output is depicted in Fig.4 for a detector with a complex geometry. Once meshed geometry is available, a C++ routine computes the electric potential. The method is not computationally effective but is quite simple to implement and to understand which is perfect for an educational code. During the simulation, dedicated routine estimates the electric field directly from electric potential matrices, through numerical differentiation.

## III. Advanced features of the simulation code

COSICAF is successful to simulate regular or complex fission chambers but, due to its limited database and the ways to handle sources it fails to describe other detectors like boron lined or helium 3 detector or even fission chambers were the two fission fragments are interacting with the gas. We recently extended the capability of COSICAF in order to make those simulations possible.

### *A. Moderation laws*

New moderation laws were included in COSICAF for Tritium, Lithium and alpha particles in few materials and gases. Some are compared with TRIM computation in Fig.5. Their validity domains, between 5-0 MeV, allow to handle a wide range of reactions. Moderation laws have a fairly good agreement with TRIM computation but some discrepancies are noticeable at low energy.

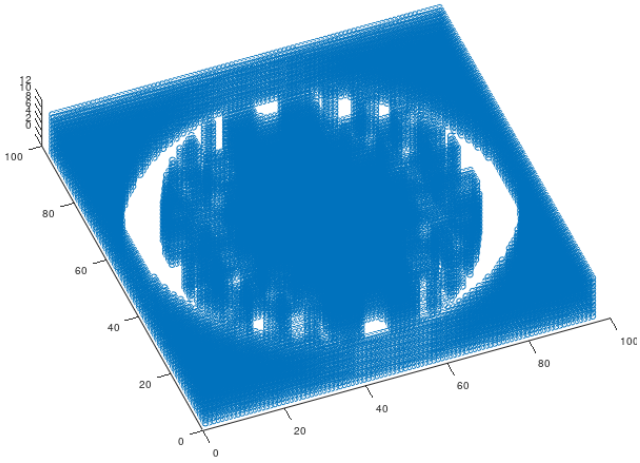

Fig. 4. Voxel representation of alumina dielectric permittivity in a complex detector geometry.

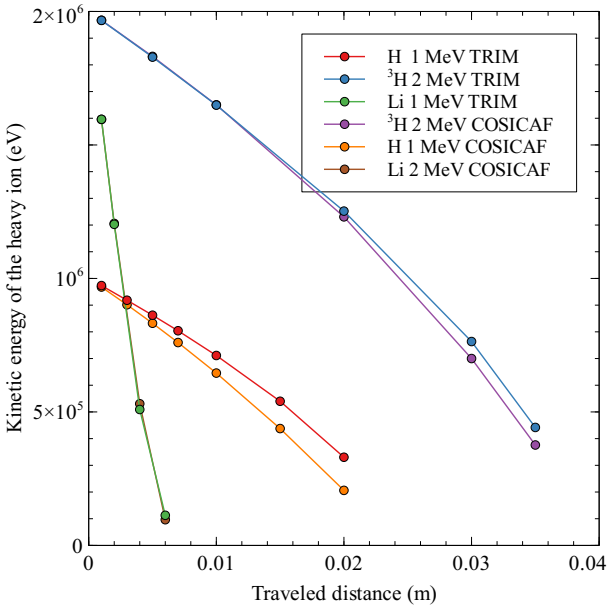


Fig. 5. Comparison of moderation laws with TRIM computations.

Hence results obtained on reactions such as neutron with $^3$He where 0.75 MeV of kinetic energy is produced are not accurate and should be be considered as qualitative.

### *B. Correlated sources*

To simulate the correlated emission of proton and tritium in helium 3 detector, it is necessary to modify the source definition. This was done first by uncoupling the source definition from the geometry definition. COSICAF is now able to load a source definition file with one or two heavy ions per source. The initialisation of heavy ion was modified as well to generate correlated emission of projectiles at the same location with opposite transport directions.

### C. Charge multiplication

Charge multiplication is required to simulate proportional counters where the electric field is structured to make electrons energy large enough to ionise the gas and produce more electron-ion pairs. The electron multiplication is given by:

$$\frac{dn}{n} = \alpha dx \tag{10}$$

where $\alpha$ is the Townsend's first ionisation coefficient and n the electron density. Ionisation coefficient are implemented in COSICAF through experimental data provided by Kruithof [20]. The Euler scheme used to move charges and compute induced signal was a bit modified to take into account the generation of new pairs. Each electronic meta-particle has its charges increased by a factor of:

$$\Delta q = q.\Delta l.\alpha \tag{11}$$

For each time step, new charged meta-particles are generated to keep tracks of the generated ions, thus, the computation of proportional counters is order of magnitude slower than the simulation of detectors in saturation regime.

## IV. Experimental validation

To demonstrate the interest of COSICAF, we simulated the CFTM, a special fission chamber built and designed by the CEA cadarache fission chamber workshop. It consists of a flat fission chamber with a 1.25 cm radius and a $L$=5 mm inter-electrode space. The detector is inflated with a mixture of Ar+20%$N_2$, and contains 10 $\mu$g of U235. The electric field is defined through a user function since for planar geometry, it is only given by:

$$\vec{E_{plan}} = \frac{\Delta V}{L}\vec{e_v} \tag{12}$$

where $\Delta V$ is the polarisation voltage. Alumina spacers are not taken into account in the geometry and it is assumed that boundary effect on electric field is negligible.

A complete set of experiments was performed on the Minerve zero power reactor with the CFTM. Prior to the simulation, various charge spectra were recorded to find to different working regime of the detector. We found that experiments with a 2 bar filling pressure and a 700 V polarisation voltage was perfect since the saturation regime is well established and current pulses measurements with direct (fissile deposit holder is the cathode) and inverse (fissile deposit holder is the anode) polarisation were available. Only absolute measurements were performed thanks to carefully calibrated measurement systems in charge and in current.

Pulses were generated with Cosicaf in both inverse and direct polarisation and charge spectra were computed. Their comparisons with data recorded with a current pre-amplifier designed by CEA are available in Fig. 6 and 7.

For direct polarisation, we note that, even with the various approximations such as straight f.f. trajectories and simplified fission y ield, t he s pectra a re i n g ood a greement: t he mean

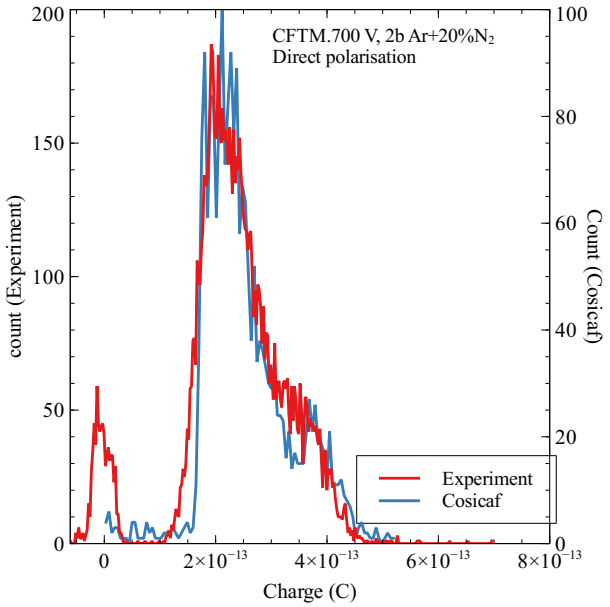


Fig. 6. Comparison between experimental and simulated CFTM charge spectra.

charge for the simulation is 2.51 $10^{-13}$ C while it was measured at 2.53± 0.10 $10^{-13}$ C. The transimpedance of the preamplifier was measured, its uncertainty, mainly due to the non-negligible electronic noise during calibration procedure, was estimated to 4%. The slight difference between the simulation and the experimental result might be explained by the low histogram statistics and by approximations made on fission yield and on straight heavy ions trajectories.

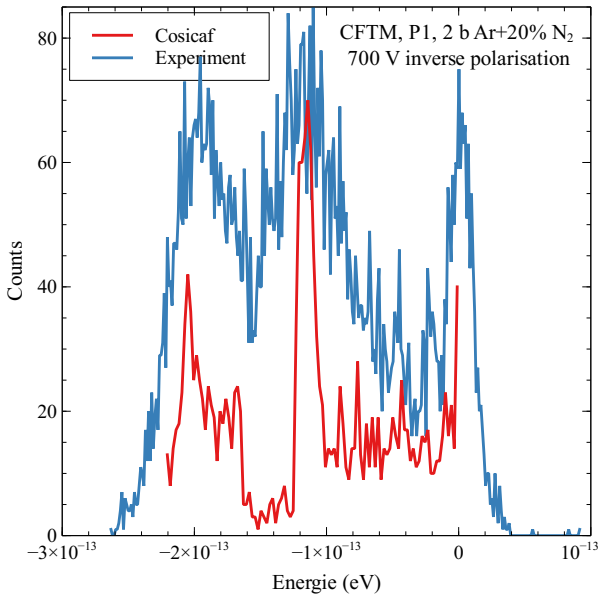


Fig. 7. Comparison between experimental and simulated CFTM charge spectra with inverse polarisation.

For inverse polarisation case, the structure of the spectrum

of both simulation and experiment is similar. In this configuration, the end of fission tracks contributes more to the induced charge. After the initial energy losses, the stopping power become highly dependent to the fission yield, that is why two groups of pulses are noticeable on the experimental data. For COSICAF, two mean fission fragments are considered, which simplify the structure of each group: only the geometric effects spread the two lines corresponding to two fission fragments.

## V. Conclusion

Through the paper, COSICAF, a simulation software for academic purpose was presented. It is useful to simulate current pulses at the output of ionisation chamber in saturation or in proportional regime. Since education is one of its primary goal, all the low levels function are exposed to the user as well as the physical models included in the software. The simulation helps students to understand how signal are generated in an ionisation chamber but also how to perform computational physics. Through the software, Monte-Carlo methods can be studied either as problem like electrostatic computation or particle tracking. There is still room for improvement, the COSICAF database is still reduced but additional materials and heavy ions could be easily integrated. Campbell and current mode could also be simulated from the computed pulses with additional work [1], [21]. Even if the software assumes strong approximations, it was shown that for fission chamber signal, the quantitative results are in rather good agreement with the experimental ones. That might not be the case for other ionisation chambers which rely on low energy reactions: straight trajectory is not accurate anymore and the ion transport model is too simple.

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