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Numerical Evaluation of Micro-Pocket Fission Detectors

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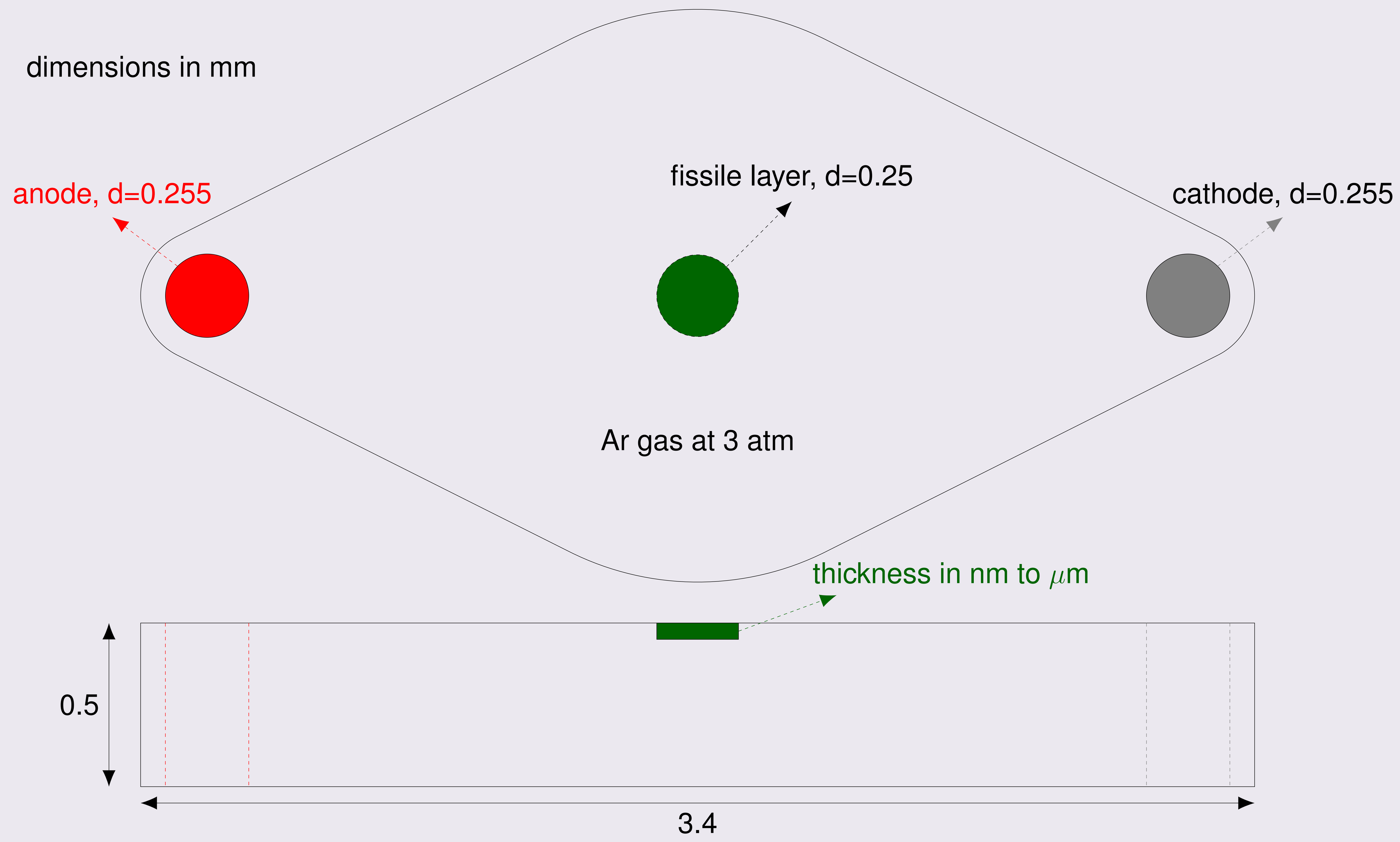
Introduction

Micro-pocket fission detectors (MPFDs) are miniature fission chambers to measure in-core neutrons that have been under development at Kansas State University for over one decade. Current-generation devices have been used at a number of university reactors (Kansas State, Wisconsin, and MIT), and as part of the first experiments performed during the recent restart of the Transient Reactor Test Facility (TREAT) at Idaho National Laboratory (INL). To improve understanding of the existing MPFDs and to optimize designs for future deployment, the dynamic responses of a prototypic MPFD were evaluated using Garfield++, Elmer, Gmsh, and Stopping and Range of Ions in Matter (SRIM), which are presented here.

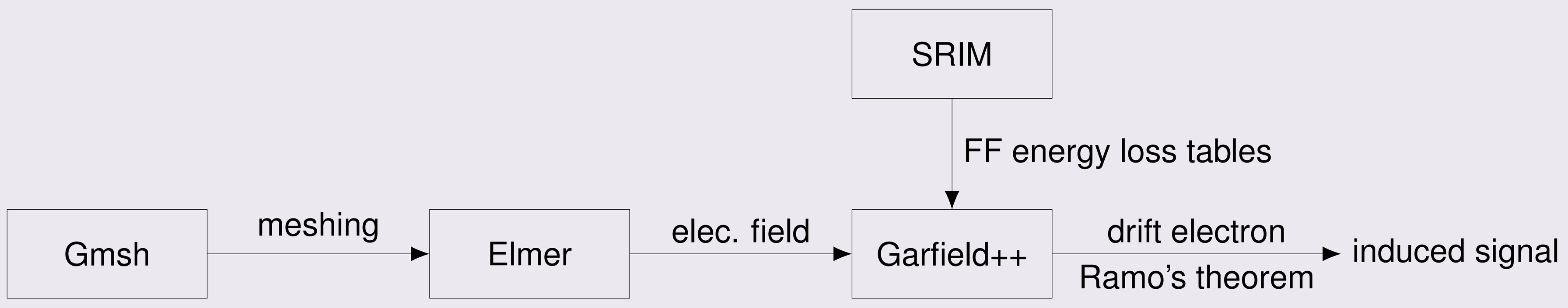
Geometry



Computational Routine

The following computational routine [1, 2] was used to evaluate MPFDs.

- Gmsh: 3-dimensional finite element grid generator with a build-in CAD engine and post-processor.
- Elmer: finite-element software package for the solution of partial differential equations.
- SRIM: Stopping and Range of Ions in Matter.
- Garfield++: C++ toolkit for detailed simulation of gaseous and semiconductor particle detectors. At current stage, its application is limited to simulate the drift of electrons in gas.



To simulate the drift of electron, the equation of

$$\frac{d\boldsymbol{r}}{dt} = \boldsymbol{v}(\boldsymbol{E}(\boldsymbol{r})) \quad (1)$$

is solved using Mont Carlo integration. $\boldsymbol{E}(\boldsymbol{r})$ is the electric field at position $\boldsymbol{r}$, calculated from Elmer results. $\boldsymbol{v}$ is the drift velocity. t is time.

During the drift of electron, the induced signal is computed simultaneously using Ramo's theorem,

$$i(t) = -q\boldsymbol{v} \cdot \boldsymbol{E}_W(\boldsymbol{r}). \quad (2)$$

i is current. q is elementary charge. $\boldsymbol{E}_W$ is the weighting field, which is computed applying 1-V at the anode in Elmer.

Parallel Plate Testing Example

To illustrate the Garfield simulation, a 1-D, parallel plate testing code was developed. Electric field of parallel plate with distance d is

$$E = \frac{V_{\text{anode}}}{d}, \quad (3)$$

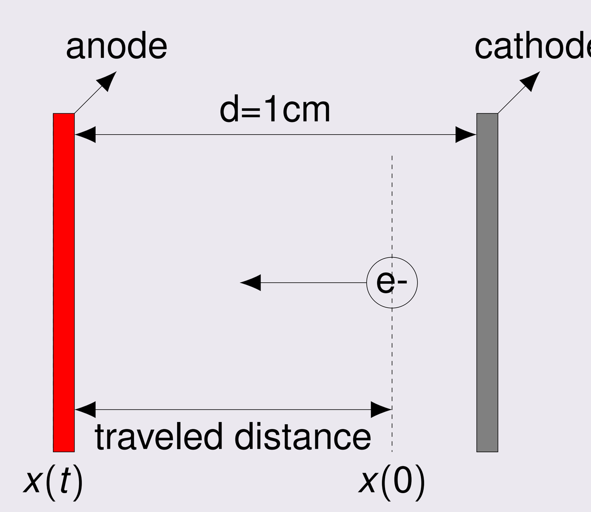
assuming grounded cathode. Apply the Ramo's theorem, the induced charge due to electron drift is

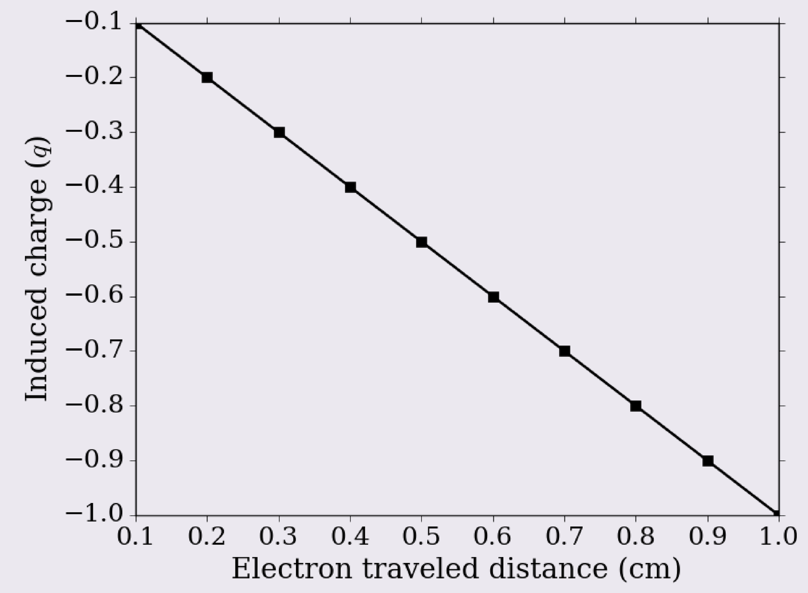
$$\begin{aligned}\Delta Q &= -q\int_0^t \boldsymbol{v} \cdot \boldsymbol{E}_W(\boldsymbol{r})dt \\ &= -q\int_0^t \frac{dx}{dt} \cdot \frac{1}{d}dt \\ &= -q\frac{x(t) - x(0)}{d}.\end{aligned} \quad (4)$$

In the simulation,

- electrons born at different positions in a 1-cm parallel plate were drifted under 10 V/cm electric field;
- the plate was filled with vacuum-like Ar gas to eliminate the collision between electron and gas atom.

The calculated induced charges are shown below, which match the analytical solution.





Garfield Application Parallelized by Hybrid MPI and OpenMP

```
Initialize MPI
▷ MediumMagboltz defines Ar gas; ComponentElmer reads geometry and electric field from Elmer
Initialize MediumMagboltz, ComponentElmer and TrackSrim class objects        ▷ To track fission fragment
#pragma omp parallel
Initialize thread-private MediumMagboltz, ComponentElmer, Sensor, and AvalancheMicroscopic class
objects                                             ▷ To drift electron and to calculate signal
end omp parallel
for ff ← [0, N_fission fragment) do
    if ff % number of nodes == MPI rank then        ▷ Assign fission fragments to MPI nodes
        Determine ff is Sr or Xe
        Randomly sample position and direction of ff
        TrackSrim → track ff and sample electron cluster distribution
        #pragma omp parallel
        Thread-private Sensor → clear signal
        #pragma omp for
        for i ← [0, 1% electrons in each cluster) do
            Thread-private AvalancheMicroscopic → drift electron
        end for
        #pragma omp critical
        Accumulate thread-private Sensor → signal
        end omp critical
        end omp parallel
    end if
end for
Print cluster distribution and signal for post-processing
Finalize MPI
```

Computed Electric Field

100 V is applied to anode. Cathode is grounded.

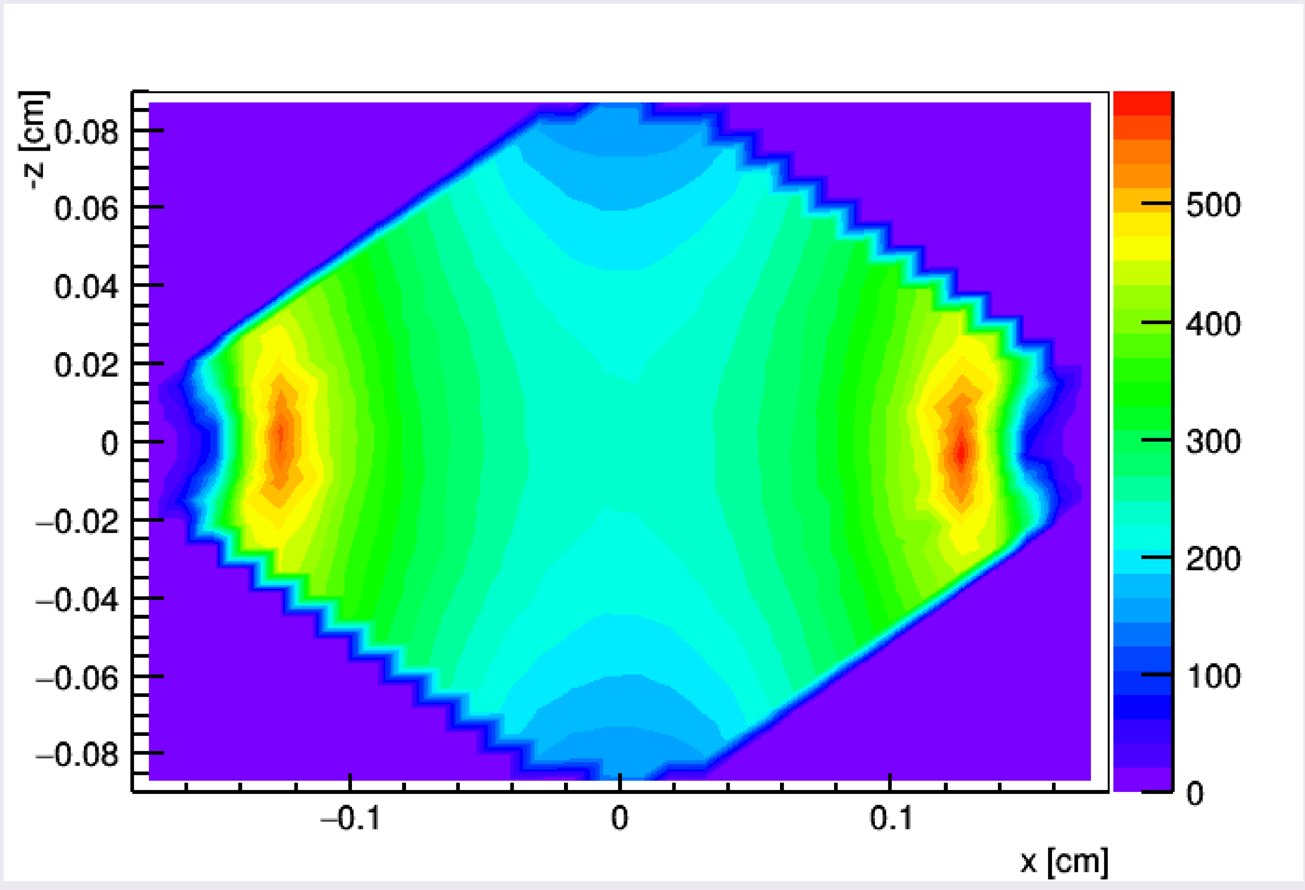


Figure: Elmer-computed electric field (V/mm)

Computed Signal

In each run, 10^3 Sr ions with initial kinetic energy of 101 MeV and 10^3 Xe ions with initial kinetic energy of 69.8 MeV were simulated. These fission fragments were born uniformly in the fissile layer and entered gas isotropically. The energy loss in the fissile layer was neglected. The averaged signal and deposited energy (MeV) to create electrons over these 2×10^3 fission fragments are followed.

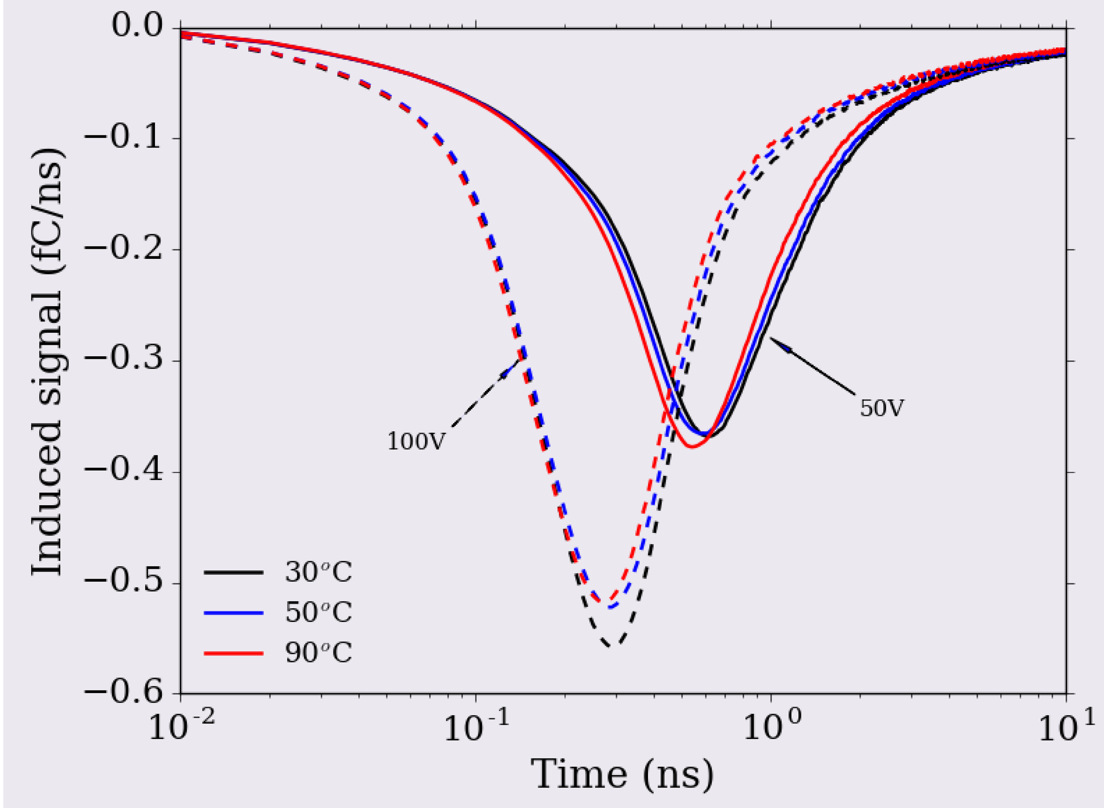


Table: Avg. deposited energy (MeV) to create clusters per fission fragment.

	50V	100V
30°C	8.09±0.15	8.11±0.15
50°C	7.68±0.14	7.40±0.14
90°C	7.01±0.12	6.80±0.13

Conclusion

The dynamic responses of the MPFDs under different temperatures and applied voltages were evaluated.

- Each fission fragment deposits a few MeV of energy in the gas.
- The pulses in the MPFDs can be formed in the nanosecond scale, thus accommodating high count rates and, hence, high neutron-flux levels.

Ongoing work aims to extend this model and validate it against existing and planned experimental data.

References

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