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Parallelization of Garfield++ and neBEM to simulate space charge effects in RPCs



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Outline

- **1** Goal or Motivation
- **2** Space charge effect
- **3** Uncorrelated and parallel random number generation using TRandom3 and OpenMP
- Calculation of space charge electric field with line charge model
- **5** Example of space charge effect in an RPC using Garfield++
- **6** Test a timing RPC with space charge effect
- **7** Summary
- **8** Future Outlook

Goal or Motivation

Goal or Motivation

Space charge effect

Uncorrelated and parallel random number generation using TRandom3 and OpenMP

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Test a timing RPC with space charge effect

Summary

Future Outlook

 Generate 3D Avalanche with Space charge effect in any gaseous detectors.

Precise calculation of dynamic space charge field while an avalanche is generating.

3 Parallelize the avalanche process with space charge effect to reduce the computation time.

Study device physics of RPC and other gaseous detectors.

5 Do all calculations within the Garfield++ framework.

Configuration of an RPC

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Future Outlook

Gaseous detector

- **2** Resistive electrodes: 10^{10} 10^{12} Ω -cm
- 3 Made of Glass , Bakelite etc.
- Spacers are made of polycarbonate material.
- **5** Gap width: 2 mm.
- 6 Operating pressure: atmospheric pressure.
- 7 Gas : Ar, R134a, Isobuten, SF6.
- ⁽³⁾ Read-out strip: Al/Cu.
- 9 High Voltage contacts: graphite paint (1 MΩ/□)



Space charge effect inside the RPC

Goal or Motivatior

Space charge effect

- Uncorrelated and parallel random number generation using TRandom3 and OpenMP
- Calculation of space charge electric field with line charge model
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What is Space Charge Effect?

- Field inside the RPC distorted due to large number of space charge.
- Effective field is higher than applied field at the tip and tail, lesser at center of the electron and ion cloud.



Why Study Space charge effect?

- The performance of RPC, like dead time, rate capability, efficiency etc are highly dependent on the space charge effect when the number of space charge is too large.
- To simulate detector physics we must take care about the time varying electric fields due to rapidly growing of space charge.

Garfield++

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Introduction :

- 1 A C++ based software.
- 2 Used to study the detector physics of particle detectors like RPC,GEM etc..

3 Basic Methods to generate Avalanche

- () Microscopic tracking. Class Name: AvalancheMicroscopic.
- (1) Monte Carlo tracking. Class Name: AvalancheMC
- 4 Built-in field solver : neBEM

Our contribution :

- **()** Added a new class pAvalancheMC to generate avalanche with space charge effect.
- Applied Multithreading technique OpenMP to speed up avalanche process.
- pAvalancheMC is based on Monte Carlo tracking.
- Use of OpenMP version of neBEM.

Correlated random numbers using TRandom3 and OpenMP

Goal or Motivatior

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Summary

Future Outlook



Figure 1: Correlation between random numbers generated by individual threads when 3 threads are used.

- All threads generate random number from same TRandom3 object and same seed.
- 2 Random number generated by three thread are correlated and lies on plane.

Agorithm to generate uncorrelated parallel random number

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Summary

Future Outlook

vector < TRandom3 *>rnd; void SetNumberOfThreads(int number_of_Thread)

```
rnd. resize (number_of_Thread);
for (int ThreadId=0; ThreadId<number_of_Thread; ThreadId++)
rnd [ThreadId]= new Trandom3(0);</pre>
```



Uncorrelated random numbers using Trandom3 and OpenMP

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Summary

Future Outlook



Figure 2: Correlation between random numbers generated by individual threads when 3 threads are used

- All threads generate random number from different TRandom3 object and different seed.
- 2 Random number generated by three thread are un-correlated.

Example of the electron & ion cluster [1]

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Summary

Future Outlook



Figure 3: (a) Left electron distribution. (b) Right side ion distribution [1]

Steps of modeling of space charge region as charged rings and lines

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Summary

Future Outlook

Step1: Dividing Z space into several δz element.



Step2: $\delta z \rightarrow 0$ & radial space divided into several co-centric rings of increasing radius r & thickness δr .



Step3: Divide rings into several curved segments.



Step4: Small $\delta \phi$ so that curved segment becomes a line.



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Charge distribution over a disc at a z position

charge density at z=0.0000

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Summary

Future Outlook

charge density at z=0.0000 from 0 to 360 degree



Figure 4

Field of uniformly charged line[2]

Goal or Motivatio

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Test a timing RPC with space charge effect

Summary

Future Outlook

$$\begin{split} E_x^B &= \frac{\bar{\lambda}(x-\bar{r})}{4\pi\epsilon_0 P^2} \left[\frac{(y+\frac{S}{2})}{\sqrt{(y+\frac{S}{2})^2 + P^2}} - \frac{(y-\frac{S}{2})}{\sqrt{(y-\frac{S}{2})^2 + P^2}} \right] \\ E_y^B &= -\frac{\bar{\lambda}}{4\pi\epsilon_0} \left[\frac{1}{\sqrt{(y+\frac{S}{2})^2 + P^2}} - \frac{1}{\sqrt{(y-\frac{S}{2})^2 + P^2}} \right] \\ E_z^B &= \frac{\bar{\lambda}(z-\bar{z})}{4\pi\epsilon_0 P^2} \left[\frac{(y+\frac{S}{2})}{\sqrt{(y+\frac{S}{2})^2 + P^2}} - \frac{(y-\frac{S}{2})}{\sqrt{(y-\frac{S}{2})^2 + P^2}} \right] \end{split}$$

where, S=length of the line.

 $P = \sqrt{(z - \bar{z})^2 + (x - \bar{r})^2}$, and if Q_{st} is the total charge of this straight line then, $\bar{\lambda} = \frac{Q_{st}}{S}$.

Comparison of neBEM and line approximation [1]

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Summary

Future Outlook



Figure 5: Comparision of total z-directional field (source+image) with neBEM. [1]

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Setup to calculate electron gain with space charge effect

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Summary

Future Outlook

1 Electrode thickness = 2mm.

2 Gas-gap = 2mm.

3 Electrode material = bakelite.

4 Gas-Mixture = Ar (70%),CO2 (30%).

5 Constant Electric Field = 23.5kV/cm.

6 The step size of time has been taken as 0.1 ns.

Example of Avalanche Saturation

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Summary

Future Outlook



Figure 6: Variation of electron gain with and without space charge effect and signal with space charge effect We will analyse the gain in following three different regions:

 a R-1: Non space charge region:
 0 ns to 7.46 ns
 b R-2: Space charge region started:
 10.46 ns to 13.46 ns
 c R-3: Near the peak value to saturated region:

15.46 ns to 23.46 ns

Propagation of electron cloud from 0 ns to 7.46 ns

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Summary

Future Outlook





 At 0 ns 58 primary electrons distributed in 7 cluster.

- 2 As time grows clusters size are increasing.
- 3 Clusters are gradualy merging with time.
- At center yellow region is max charge density.

Propagation of electron cloud from 10.46 ns to 13.46 ns

Example of space charge effect in an RPC using Garfield++



1000

800

600 400

200

1005 8.01 0.015 0.02 0.025

- 2 At 10.46ns max charge density shifted from the r=0 because of space charge field.
- 3 Max charge location shifted again to r=0due to the radial component of ion field.

0.01 0.02 0.03 0.04 0.05 radius r in cm

Figure 8

0.08

-0.08

-0.

Changing of shape of electron cloud from 10.46 ns to 13.46 ns

V/cm

30000

27500

25000

22500

20000

V/cm

x-position in cm

35000

8-0.025

-0.050

-0.075

-0.100

-0.045 -0.060

-0.075

9-0.090

-0.105

-0.04

-0.025

0.000

0.025

P.posini

Example of space charge effect in an RPC using Garfield++





 During propagation the shape of electron cloud is changing an forming a spherical shape.

30000 2 At tip and tail the total electric field is 25000 more than applied 20000 field.

Figure 9

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Changing of shape of electron cloud from 15.46 ns to 23.46 ns

-0.075

-0.090

Example of space charge effect in an RPC using Garfield++





Figure 10

 The shape of electron cloud changing form spherical to cone.

- 2 At 23.46 ns the cone become some co-centric cylinder.
- 3 At 23.46 ns the gain of the avalanche is saturated because the rate of ionisation compensate rate of recombination process.

Setup to test timing RPC with space charge effect

Goal or Motivation

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Test a timing RPC with space charge effect

Summary

Future Outlook

1 Electrode thickness =2mm.

2 Gas-gap =0.3mm.

3 Electrode material = bakelite.

4 Gas-Mixture = R134a (85%),ISOBUTANE (5%),SF6 (10%).

5 neBEM field solver used to calculate applied field.

O Avg Electric Field inside the gas gap = 43 kV/cm (1720 V), 43.25kV/cm (1730 V), 43.38 kV/cm (1735 V).

7 The step size of time has been taken as 0.01 ns.

Electron gain distribution



Figure 11: Electron gain distribution (a)without space charge effect (left) (b) with space charge effect (right)

- A set of 10K avalanche generated from a single electron placed near the negative electrode (z=0.02 cm).
- **2** The shape of the electron gain distribution is modified.
- **3** The avarage value of the gain is reduced by a factor 10.

Test a timing RPC with space

charge effect

Induced charge distribution

Voltage 1730 V

Voltage 1735 V Entries 887 Mean 0.9013

Std Dev 0.7003

0.580

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Test a timing RPC with space charge effect

Summary

Future Outlook



10²

Counts



with space charge effect at voltages ± 1720 V, ± 1730 V and ± 1735 V

 $q_i = \sum_{i}^{N} N_i(t) e_0 \,\delta z \, \frac{E_w}{V_w}$

- E_w = Weighting field calculated by neBEM.
- *V_w* = Weighting potential calculated by neBEM
- **3** $q_i =$ Induced charge
- **4** $N_i(t)$ = number of electron
- **5** e_0 = electronic charge
- **6** $\delta z = distance in one step$
- a,b=electrode thickness in cm,
- 8 g=gas-gap in cm,
- **9** ϵ_r = Relative permittivity

Timing Performance

Test a timing **RPC** with space charge effect







No of thread (N)

8 10 12 14 16

No of thread (N)

1 Time to complete 10K avalanche is reducing with increament of thread number.

- 2 Maximum 5 times speed up is observed for 20 thread without space charge effect.
- 3 Maximum 6 times speed up is observed for 20 thread with space charge effect.

Figure 13

Summary

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Test a timing RPC with space charge effect

Summary

Future Outlook

Proposed a numerical line charge model to calculate the field of space charge inside the RPC.

Ocmpared the results of line model with the field solver neBEM and ring models available in the literature and shows a good agreement.

3 Implemented the line model in the Garfield++ software.

 Implemented the multithreading technique to parallelize Garfield++ and neBEM.

 Performed a realistic avalanche with space charge effect inside an RPC and with realistic field map generated by neBEM.

• Calculate the induced charge distribution with space charge effect.

FUTURE OUTLOOK

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Summary

Future Outlook

Implement photon transport model in Monte Carlo simulation.
 Simulate avalanche to streamer transition.
 Simulate rate effect in an RPC.

4 Test the line model with other gaseous detectors.

Collaborators

Goal or Motivation

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Test a timing RPC with space charge effect

Summary

Future Outlook

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Bibliography I

Goal or Motivation

Space charg effect

Uncorrelated and parallel random number generation using TRandom3 and OpenMP

Calculation of space charge electric field wit line charge model

Example of space charge effect in an RPC using Garfield++

Test a timing RPC with space charge effect

Summary

Future Outlook

 T. Dey, S. Mukhopadhyay and S. Chattopadhyay, Numerical study of effects of electrode parameters and image charge on the electric field configuration of RPCs, Journal of Instrumentation 17 (apr, 2022) P04015.

[2] T. Dey, S. Mukhopadhyay, S. Chattopadhyay and J. Sadukhan, Numerical study of space charge electric field inside resistive plate chamber, Journal of Instrumentation 15 (nov, 2020) C11005–C11005.

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Future Outlook

Thanks For Your Attention! Email: tanay.ino@gmail.com

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back ups

Er kV/cm

-0.5

-0.02

-0.04 -0.06 -0. z position in cm

-0.08



Figure 14: (a) Z- component of space charge field at 10.46 ns, (b) Radial- component of space charge field at 10.46 ns, (c) ϕ component of space charge field at 10.46 ns

0.01 0.02 0.03

radius in cm

-0.4

^{-0.02} -0.04 -0.06 -0.08 Z position in cm

0.01 0.02 0.03

radius in cm

back ups

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Summary

Future Outlook



Figure 15: (a) Z- component of space charge field at 12.46 ns, (b) Radialcomponent of space charge field at 12.46 ns, (c) ϕ - component of space charge field at 12.46 ns

Back ups



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Summary

Future Outlook





Figure 16: Induced charge distribution with space charge effect at voltages $\pm 1720 \text{ V}, \pm 1730 \text{ V}$ and $\pm 1735 \text{ V}$

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