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A Fast Simulator for VTX, a microTPC for STAR

Documentation and User's Guide

1 Abstract

The STAR VTX(Microstrip Vertex detector) Fast Simulator program(VFS), a TAS analysis module in STAR software simulation chain, is designed to simulate the signal response of the VTX detector and the performance of the hit reconstruction algorithm. The input of VFS program is the hits banks generated by GEANT Monte-Carlo package(mct) [1]. VFS assigns each Monte-Carlo hit a spatial width and a spatial resolution according to a parameterization which is depend on the track trajectory, detector characteristics and geometry. The hits are then smeared about the known track according to the calculated spatial resolution. Those hits whose are close enough in space and time are merged to form larger single clusters. The output of VFS forms the input of the VTX grouper program which will perform the task of track reconstruction and pattern recognition.

2 VTX detector

Since their ability to produce 3-dimensional space points and good two tracks resolution, TPC (Time Projection Chamber)detectors have been used in a large nubmer of high energy experiments and is suitable for vertex reconstruction and particle identification. The main element of TPC is the position-sensitive multiwire proportional counter(MWPC) which consists of a great number of thin anode wires assembled in a plane and mounted between two cathode plates. The MWPC is not only the most widely used detector type in high-energy experiments, but it also plays a significant role in several other fields of research. Nevertheless, the MWPC has two major limitations:

- The spatial resolution perpendicular to the wires is limited by the wire spacing(1mm).
- The rate capability is limited by the long positive-ion collection time.

To overcome these two limitations, one can try to reduce the anode wire spacing to improve the accuracy and reduce the incoming particle flux per wire and one can also try to reduce the anode-cathode gap to speed the ion-collection rate. However, for wire spacing small than 1 mm and anode-cathode gap smaller than 1 mm, the MWPC becomes very difficult to operate because of the electrostatic instabilities arising from mechanical tolerances. A new type of position-sensitive detector, microstrip gas chamber(MSGC), has been proposed and developed by Oed [2]. This detector consists of an insulating substrate on which an anode-cathode structure is etched in a metal film on a few μm thick. Small strip(anode) are located between two larger strips(cathode). The electrical field near the anodes are large enough to cause gas multiplication of electrons. An cathode plate placed several mm above the microstrip ensures that an electron produced anywhere in the gas volume will drift towards to anode strip where it will experience an avalanche amplification to produce an observable signal.

Compared with MWPC and others gas counters this new detector has the following advantages:

- Uniform gas amplification over the entire surface and a good energy resolution of the incident radiation [2] [3]
- High limiting counting rate. [3] [5]
- High position resolution transverse to the strip structure. [4] [5]
- Low operating voltage.

In this report, we plan to simulate the performance of a proposed MSGC detector, the VTX(Microstrip Vertex detector) and study its hits reconstruction efficiencies. The VTX is composed of four layers of cylindrical microstrip anode chamber with length 20 cm and anode pitch 200 μm. The filling gas of VTX is DME and the active gas volume of the VTX is bounded by coaxial field cage cylinders with microstrip anode plane end-cap at both ends. A high voltage membrane at the center divides the VTX into two drift regions and create an **E** field , such that ionizing electrons will drift towards to the end-caps. The end-caps consists of thin gap, microstrip anode-cathode plate in which the primary signal electrons are detected by avalanche multiplication the anode pad. For each particle track, the drift time provides on coordinate(z), while the signals on the anode provide the coordinates in the plane of the MSGC. The basic parameters of the VTX are summarized in Table 1.

3 VFS program

Basically, the VFS simulation program seeks to provide a hit-finder model for STAR VTX detector. The is achieved by formulating the pad response function and pad resolution as function of the transverse diffusion and track crossing angle along the pad direction. In the drift direction the spatial width of signal pulse is determined by the track dip angle and by the longitudinal diffusion of the primary ionization as it is drifted to the pad plane. The effect of the electronics shaping time, an additional factor contributing to the spatial width of the signal pulse along the drift direction, has also been included into the parameterization.

The main structure and functionality of VFS program contains the following five parts:

1. Initialization.

   It consists of the following tasks:

   - Check the input vfs parameters,
   - read in VTX detector parameters.(characteristics geometry, drift time,shaping time,resolution....)

2. Read in Monte-Carlo hits data and copy to VFS `vtxpoints` table.

3. Sorting the hits according to row information and set-up pointer index

4. Assign each hit a pad response function [6] and a spatial resolutions [7] then the hits are smeared about the known track position

5. Merge hits that are close in space(xy) and time(z). Merge criterion see Eqs.(4C-3) and (4C-4) in STAR CDR [8] .

The VFS approach is summarized below:

- Pad direction(rϕ)

  1. smeard position=highest pad $\pm$ random(100 μm)
     $\Rightarrow$ RMS $\equiv$ 200 μm $/\sqrt{12} \cong$ `60` μ`m`
  2. `Alternative:` $\sigma^2 = \sigma_0^2 + \sigma_D^2 \lambda (1 + \tan^2 \alpha) + \sigma_\alpha^2 \tan^2 \alpha$

- Drift/time direction(z)

  $\sigma^2 = \sigma_A^2 + \sigma_B^2 \lambda \sec \alpha + \sigma_C^2 \cos \alpha \tan^2 \alpha$

  where,

  $\sigma_A^2 \rightarrow$ signal-to-noise term

  $\sigma_B^2 \rightarrow$ diffusion term $= \sigma_B^2 = \frac{\sigma_D^2}{N_0}$, $N_0 \approx 200\ e/cm$

  $\sigma_C^2 \rightarrow$ angular track term $= \sigma_C^2 = \frac{h^2}{12 N_{eff}}$, $N_{eff} \approx 60\ e$

  h=pad length

  $\Rightarrow$ σ_C=`110` μ`m` for h=3 mm, but we use σ_C=`200` μ`m`

- Merging criteria

  Hits are merged if they are close enough in time and space:

  1. $\Delta_{pad} < \sigma_1 + \sigma_2 +$ `1 pad width`
  2. $\Delta_z < \sigma_1 + \sigma_2 +$ `2 time bins`

- <u>Merged position and resolution</u>

  1. Same as Larger one if the smaller one is totally absorbed.
  2. Mean value of merged hits if they are not completely absorbed by each other.
  3. Reject large merged hits
     (a) $\Delta_{pad} + \sigma_1 + \sigma_2 >$ `10 pad width`
     (b) $\Delta_z + \sigma_1 + \sigma_2 >$ `20 time bins`

In the following chapter, we first briefly describe the parameterizations of pad response function and resolution in VFS and its merging criteria. Then the VFS users guide and documentation are presented and the result of simulation are discussed.

4 Pad response function – Parameterization

The pad response function describes the signal observed on a pad as a function of the position of the variance. Two points from different tracks are indistinguishable if they are very close in both rϕ and z-direction. The resolution in the rϕ direction is determined by the width of signal along the anode pad. Its variance depends on the anode-cathode geometry an, the transverse diffusion of a single electron suffers and the crossing angle of the track. The parameterization of pad response function have been s tudied [6] and was implemented int oour VFS program.

Two models are adopted in VFS. The first one is a simple square response function which is totally determined by the anode-cathode geometry. Due to its good two track resolution(250μm (rms)), the characteristic width of pad response is about the order of magnitude of anode pitch(100 μm for VTX).

For the second model, the pad response function is approximately an Gaussian in shape $e^{\frac{-(x-x_0)^2}{2\sigma^2}}$ with a characteristic width given by

$$\sigma^2 = \sigma_0^2 + \sigma_D^2 \lambda (1 + \tan^2 \alpha) + \sigma_\alpha^2 \tan^2 \alpha \tag{1}$$

where,
λ-is the drift length in meters
D-is the anode pitch for VTX
α-is the track crossing angle in radians

There three terms correspond to an intrinsic pad response σ_0^2, determined by the anode-cathode geometry in the amplification region, a diffusion term σ_D^2, and a σ_α^2 term which accounts for the effect of crossing angle of the track relative to the normal of the anode.

- `The intrinsic pad response,`σ_0

  This is determined by the measurement. Since the data is not available for DME gas, for the time being we assume that it is the half pitch of anode pad ($\sim 200\mu$m for VTX)

- `The diffusion term,` σ_D

  The coefficient of the diffusion term may be written as,

$$\sigma_D^2 = \frac{\sigma_D^2(0)}{(C + \omega^2\tau^2)} \tag{2}$$

  where $\sigma_D^2(0)$ is the free field single electron diffusion, ω is the electron cycltron frequency, τ is the mean collision time and C is a constant.

  For STAR TPC this has been measured and a value of σ_D=185 μm/$\sqrt{cm}$ was obtained, while for VTX it is not available yet.

- `The angular track term,`σ_α

  This is based on the fact that the signal is broadened for inclined tracks due to the effect of adding displayed Gaussian distributions from the neighbor anodes. We expect that the value of this term will be very small.

  The hits are smeared in our simulation using a Gaussian distribution whose width σ is given by the parameterization.

5 Pad resolution function – Parameterization

The pad resolution function which represents for the uncertainty on coordinate measurement have been studied [7] and given by,

$$\sigma^2 = \sigma_A^2 + \sigma_B^2\lambda \sec\alpha + \sigma_C^2 e^{\gamma\lambda}\cos\alpha\tan^2\alpha \tag{3}$$

where,
λ - is the drift length in meters
$e^{\gamma\lambda}$-is the inverse of an attenuation factor appearing in the denominator
α -is the track crossing angle in radians

The three terms correspond to an intrinsic resolution σ_A, determined by the signal-to-noise ratio on the pads, a diffusion term σ_B, and a term which accounts for the effect of angular track. It has been shown that the effect of attenuation, due to electron capture, is negligible, thus $\gamma \to 0$ and $e^{\gamma\lambda} \to 1$.

- `The signal-to-noise term,`σ_A

  This item has not been measured yet. In our simulation we assumed the worst case for it as 200 μm.

- `The diffusion term,`σ_B

  The coefficient of the diffusion term may be written as [9]

$$\sigma_B^2 = \frac{\sigma_D^2}{N_0} \tag{4}$$

  where σ_D is the coefficient of the diffusion from the pad response function [6] and N_0 is the total number of electrons liberated along the pad length. For DME gas this has been calculated and a value of 200 electrons/cm was obtained.

- `The angular track term,`σ_C

  ALEPH reported this term as the angular pad effect [10] and a formulation was given by

$$\sigma_C^2 = \frac{h^2}{12N_{eff}} \tag{5}$$

  where h is the pad length and N_{eff} is the effective number of electrons per unit length. The value of N_{eff} depends on diffusion which provides a declustering effect for ionization fluctuation along the track. For STAR TPC, a suitable number for N_{eff} is 12.

6 Hit merging and merging criteria

In our simulation, hits are merged according to their seperation and calculated spatial width in both the pad plane(r,ϕ) and the drift direction(z). First the hits are sorted row-by-row according to their drift time,i.e their position in the drift direction. A maximum cut-off is imposed on the spatial width of the charge distribution in the drift direction (also in the pad plane), in order to minimize the time spent looping over neighboring hits in any given pad. With this method, when neighboring hits are seperated by greater than twice the cutoff, no more hits can merge with the hit in question.

The merging criteria for hits in the same row are given by,

$$\Delta_{pad} < \sigma_1 + \sigma_2 + pad\ width \tag{6}$$

and

$$\Delta_z < \sigma_1 + \sigma_2 + 2\ time\ bins \tag{7}$$

where σ is the calculated width of the charge distribution for each hit. The criteria for Eq. (4.1) is based on the fact that double hits are considered

clearly resolved provided the signal peaks along the pads are seperated by at least the sum of the width of their respective pad response functions,σ, plus the width of one pad. Two signal pulses cannot be seperated in time if their centroids are less than Δ_z, and this value is determined by three factors: electron diffusion, shaping time and the projected track segment along the drift axis. The later is calculated from the pad length(h) and dip angle(θ). In the initial design of VTX, the drift length is 10 cm and 512 time samples was used, therefore one time bin is equal to 200 μm.

7 The Fast Simulator (VFS) Users Guide

Welcome to VFS, the TAS version of the Fast Simulator for the central STAR VTX. VFS is a package that contains modules for simulating the signal response of VTX detector and the performance of hits reconstruction algorithm. For details, please see the following VFS Topics.

- *Module specifications*
- *Module usage*
- *Code documentation*
- *Data structure model*

7.1 Module specifications

- Module specifications for VFS

  The requirement of the fast simulator is to take the known Monte-Carlo pad row crossings from GEANT and apply known resolution effects of the detector. In VFS, this is achieved by using a parameterization of the pad response and pad resolution. The precise form of these parameterizations has been described in STAR notes #33 and #34. The pad response and pad resolution are modeled by a gaussian distribution whose width σ is given by these parameterizations. In the drift direction the response of the detector is calculated from the projected path length across each pad row; the longitudinal diffusion and the shaping time of the readout electronics.

- Input/Output specifications

  - *Input tables:*

    `vfspar` - (vfs library) vfs parameters

    `vfsctrl` - (vfs library) control parameters

    `mhits_mwc` - (mct library) Monte-Carlo hits for the VTX
  - *Output tables:*

    `vtxpoints` - (vfs library) reconstructed VTX hits

7.2 Module usage

- Getting started

  VFS exists in the **sim** branch of the STAR library. All the files you need to build a VAS executable image are contained in the *vfs* branch of the **sim** directory. The code is arranged according to the STAR library convention. After checking out VFS into your own working directory, a VAS executable image can be made either by sourcing **vfsx.bld** in the **vfs/wrk** sub-directory or by **Makefile** in the **bin** directory. To check out VFS modules, type the following command at your working directory:

  % `sl_retrieve_pkg vfs -c`

Then either type the following command in the **bin** subu-directory:

/vfs/bin% `make tas`

or the following one in the **wrk** subu-directory:

/vfs/wrk% `source vfsx.bld`

This builds TAS along with VFS and MCT, the Monte-Carlo to Tables conversion module written by Richard Morse. Input to VFS are the table representations of the GEANT HITS banks produced by MCT.

An example kumac file, showing how to run an event through MCT and VFS is provided in the **vfs/wrk** directory. This file (filename = **vfsx.kumac**) reads in the parameters needed by VFS; turns on the modules in TAS; defines filters and ntuples for the output and shows how to specify input and output files.

- VFS parameters

  The parameters required by VFS are described below.

  - **vfspar table**

    It contains basic parameters such as the coefficients of the pad response function and pad resolution function. This table also contains information of the pad sizes and other VTX geometry constants which at some later date will be gotten from the STAR geometry package. This file contains the default values of the fspar table.

  - **vfsctrl table**

    most important - it contains control information for VFS. These are given below.

    vfsctrl.nevent : 1 number of output events required

    vfsctrl.init : 0 switch (set by VFS) after initialization

    vfsctrl.evmerg : 0 event merging mode (0 = off)

    vfsctrl.print : -100 controls diagnostic prints (0 = off)

    vfsctrl.mccopy : 0 switch for MCT data copy

    `fsctrl.evmerg` allows the user to overlap events - but beware of table-size limitations.

- VFS Output

  VFS fills the VFS hit table **vtxpoints**. The hit quality flag `vtxpoints.flag` is used by VFS to mark merged hits. The following convention has been used.

`vtxpoints.flag` = 0 is an unperturbed hit

= < 0 is a merged hit

= 2 discarded - protection from arithmetic overflow

= 3 discarded - protection from arithmetic overflow

= 4 discarded - protection from arithmetic overflow

= 6 discarded - hit within central HV membrane

= 8 discarded - merged with another hit

= 11 discarded - merged hit too large to keep

= 12 discarded - single hit too large to keep

Usable hits are defined as those with `vtxpoints.flag` $\leq$ `0`. A filter routine (a COMIS subroutine) is provided in **vfs/wrk** called **vfs_filt.f**. It tests the value of `vtxpoints.flag` and deletes all rows with `vtxpoints.flag` >`0` in the **vtxpoints** table. This feature is necessary for preparing an output file for the VTX tracking module EGR. Deletion of rows also means that any ntuple definition that uses the **vtxpoints** table will not contain information about the discarded hits.

The number of required output events is set using the **vfsctrl.nevent** switch. VFS decides internally how many events to read-in.

If the evmerg switch is set then input is taken from both a saved output file (usually the background event) and MCT (the additional tracks to be added to the event). The only way I found to add this type of functionality was by requiring that the background event be stored in the vtxpoints table but WITHOUT any hit merging applied.

7.3 Code documentation

- Code documentation for the VFS module

  What follows is a subroutine-by-subroutine description of the VFS module.

  - Integer function **vfs_main**

    The entry point into the VFS module. The following routines are called either directly or indirectly from vfs_main.

  - Subroutine **vfs_init**

    Initialization routine for VFS. Takes values in the VFS parameter tables to calculate the derived values of parameters needed by the module. These derived quantities are passed to other subroutines via common blocks.

  - Subroutine **vfs_mcthit_rd**

    Loads the reconstructed **vtxpoints** table from the Monte-Carlo mhits_mwc table. The **vtxpoints** table is then sorted directly according to the `row` field in that table. This field contains the row, coordinate , momentum and energy loss for each hit. Sorting is performed by the QIKS utility subroutine in the **uti** sub-directory of the **sys** branch of the library. This routine requires two external routines **rcomp** and **rmove** .

- Integer function **rcomp** A utility routine for QIKS which decides which elements to move by `row`.
- Subroutine **rmove**

  A utility routine for QIKS which moves **vtxpoints** table elements by `row`.
- Subroutine **vfs_gen_padres**

  Generates the pad response and pad resolutions for each Monte-Carlo pad crossing. This is accomplished according to the parameterizations described in STAR note #33 and #34. Hits are the smeared according to the calculated pad resolution.
- Subroutine **vfs_vtxpoints_merge**

  Merges hits that are close in both the pad and drift directions. Hits in each row are first sorted according to their z-coord. Routines **zcomp** and **zmove** are supplied to do the job. Within each row each hit is compared with each other hit within a certain z-range of each other (determined by the maximum allowed z-response - an artifical cut-off in the generation to speed up the merging process). If any two hits merge, the hit with the largest row number in the table is made to point to the lower order hit, using the flag field in the **vtxpoints** table as a foreign key. If the lower order hit is already merged, the higher order hit is made to point to the lowest order hit (common to both hits in question). This is an iterative procedure, as not all connections to the lowest order merged hits are necessarily determined in the first pass. My tests have shown that fewer than three passes are typically needed even for a typical central FRITIOF Au+Au event. A final pass through the data then does the merger of all connected hits. Merged hits are flagged as such. (See the definition of `vtxpoints.flag` in VFS Output section .)
- Subroutine **zcomp**

  A utility routine for QIKS which decides which elements to move by `z`.
- Subroutine **zmove**

  A utility routine for QIKS which moves vtxpoints table elements by `z`.
- Subroutine **vfs_rotate**

  Rotates hits into the local coordinate system of the row.
- Subroutine **vfs_hit_smear**

  Calculates the smearing of the Monte-Carlo space-points due to the detector resolution. This is given by the pad resolution function in the x-y plane or a fixed value of 200 μm, and is taken to be a fixed number or pad resolution in z-plane in the drift direction.
- Subroutine **vfs_hits_killers**

  This routine will try to reject hits which are outside the VTX detector.

7.4 Data structure model

- Data structure model for VFS

  Three parameter tables are defined by the VFS library.

  Library: **vfs**

  Owner: `star`

  Description:`This is fast simulator for VTX detector`

  - Table: vfsctrl(1) Zebra code: `VFSC` Type: `Static`

    Owner: `jawluen`

    Description:`VFS control table`

Variable	*Type*	*Dimension*	*Comment*
`evmerg`	I	1	number of events to merge
`init`	I	1	flag to initialize VFS (0=initialize)
`nevent`	I	1	number of output events required
`print`	I	1	controls diagnostic prints(0 = off)

  - Table: vfspar(1) Zebra code: `VFSR` Type:`Static`

    Owner: `jawluen`

    Description: `VFS parameter table`

Variable	*Type*	*Dimension*	Comment
`nrow`	I	1	total number of VTX pad rows(Max=4)
`dbase`	R	1	radius(cm) of the first row
`drivel`	R	1	drift velocity(cm/us) in VTX detector
`drmin`	R	1	merge criterion in radial direction(pad)
`dzmin`	R	1	merge criterion in drift dir.(time bins)
`merge_r`	R	1	max. merged size radial(# of pads)
`merge_z`	R	1	max. merged size in drift dir.(bins)
`padlen`	R	1	padrow length(cm)
`padsep`	R	1	pad pitch(cm)
`padwidth`	R	1	pad width(cm)
`reslim`	R	1	maximum cluster size (cm)
`rowsep`	R	1	row pitch (cm)
`sigma0`	R	1	pad resolution : intrinsic term
`sigmad`	R	1	pad resolution : drift term
`sigmal`	R	1	pad resolution : longitudinal diffusion
`sigmat`	R	1	pad resolution : tan-alpha term
`sldiff`	R	1	longitudinal diffusion
`sprf_0`	R	1	pad response fun.(prf): intrinsic term

sprf_dr	R	1	pad response fun.(prf) : drift term
sprf_ta	R	1	pad response fun.(prf) : tan-alpha term
tshape	R	1	shaping time(nsec) in VTX detector
vtxlen	R	1	total drift length(cm) in VTX detector
zbmax	R	1	total time bins

– Table: vtxpoints(20000) Zebra code:VFSS Type: Dynamic

Owner: jawluen

Description: space points output from VTX fast simulator for VTX detector

Variable	*Type*	*Dimension*	*Comment*
flag	I	1	Hits quality(=0 good; >0 bad;<0 merged)
id	I	1	an unique (foreign)key to this point
id_track	I	1	id of reconst. track this point belongs
row	I	1	VTX row number (=1,2,3,4,)
alpha	R	1	reconstructed crossing angle in xy(rad)
dde	R	1	Error on the dE(energy loss in Gev)
de	R	1	dE associated with this space point
dx	R	3	Error on space points vtxpoints.x (cm)
lambda	R	1	track dip angle(radian)
prf	R	1	value of pad response function (cm)
x	R	3	reconstructed space point coordinate(cm)
zrf	R	1	value of drift response (cm)

8 Results and Discussion

In order to study the reconstruction efficiency of VTX fast simulator a FRITIOF Au+Au have been generated and tested. The input VFS parameters are listed below:

- vfsctrl.print -100
- vfsctrl.evmerg 0
- vfsctrl.init 0
- vfsctrl.nevent 0
- vfsctrl.mccopy 0
- vfspar.nrow 4
- vfspar.dbase 5.
- vfspar.drivel 0.275

- vfspar.drmin 1.
- vfspar.dzmin 2.
- vfspar.merge_r 10.
- vfspar.merge_z 20.
- vfspar.rowsep 1.0
- vfspar.padlen .3
- vfspar.padsep 0.02
- vfspar.padwidth 0.02
- vfspar.reslim 1.
- vfspar.sigma0 0.02
- vfspar.sigmad 0.02
- vfspar.sigmal 0.0
- vfspar.sigmat 0.02
- vfspar.sldiff 0.016
- vfspar.sprf_0 0.02
- vfspar.sprf_dr 0.02
- vfspar.sprf_ta 0.02
- vfspar.vtxlen 10.
- vfspar.tshape 140.
- vfspar.zbmax 500

In [11] the hits pattern from Monte-Carlo simulation and those from VFS are shown, as well as t he total multiplicity for a central Au+Au event as a function of the VTX row number and z. The three distributions show the number of GEANT pad crossings, the number of hits from VFS and the number of merged hits. This indicates that only 14 % of the pad crossings are lost due to hit merging , which is substantial improvement than normal TPC. Further analysis on the influence of geometry is underway. Nevertheless we expect that two track resolution and reconstruction efficiency of VTX is better than the existing vertex detector.

References

[1] The MCT package was written by R.J. Morse.

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[8] STAR Conceptual Design Report, PUB-5347.

[9] R. Sauerwein, TPC-LBL-83-18

[10] ALEPH handbook, ALEPH 89-77.

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