Recent results from pellet tracking

SFAIR annual meeting

Andrzej Pyszniak

12.11.2012
Uppsala Pellet Test Station

Pellet generation conditions:

- nozzle $\Phi = 12.9 \mu m$
- $T_n = 14.1 K$
- $f_{\text{droplet}} \approx 63 kHz$
- $p_{H_2} \approx 400 mbar$
- $p_{\text{Drop Chamber}} \approx 21 mbar$
- $v_{\text{droplet}} \approx 22 m/s$

- $d_{\text{droplet}} = 0.34 mm$
- $\text{pellet} \Phi = 25 - 30 \mu m$ (guess)
- $v_{\text{pellet}} = 77.9 m/s$
- $\sigma_v / v_{\text{pellet}} = 0.42\%$

Above skimmer:

- PR $\approx 57 k/s$
- FWHM $= 2.1 mm$, FW $\approx 3.7 mm$

PTR chamber:

- PR $\approx 22.5 k/s$
- FW $\approx 2.5 mm$
Goal: improving the accuracy of data analysis by precise determination of the interaction vertex (helping in charged particle track reconstruction and background suppression)

Method: measuring positions and velocities of the pellets in a few planes along the pellet stream

Means: lasers and line scan CCD cameras
Pellet tracking for Panda

At Panda two sections of the target pipe, one at the generator and one at the dump are planned for tracking equipment. The sections are 40 cm long.

Tracking section design idea
Four levels for measurement, each with two lasers and two LS-cameras. Level spacing: 60 mm.

Simulations are used to determine the optimal use of the tracking sections and they are also needed in development of tracking algorithms.

Some main points of the design simulations concern:
- **Camera** and **laser configuration** within each level
- **Number of levels** and the **distance between** the levels
Time difference spectrum

Skmr – PTRlow (427 mm)

PTRupp – PTRlow (80 mm)

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Experiment:

Slice at nominal VIC exit position (experiment):

- extrapolated track position $\sigma \approx 100\mu m$
- a position accuracy $\sigma \approx 20\mu m$ at the measurement levels
Pellet stream simulation (1)

- Pellets are generated at position $Y=3000$ mm, where $Y=0$ mm is the position of the accelerator beam crossing.
- The number of initially generated pellets is 100 000. Pellets are generated with a frequency of 40 kHz.
- The XZ position of the generation point is smeared with Gaussian distribution with sigma equal to 20 $\mu m$. The distribution has a cut-off at $3\sigma$. For each of X and Z directions the value is generated independently from the mentioned distribution.
- The stream divergence, measured as sigma of the pellet radial angular distribution, is set to 1 mrad. The distribution has a cut-off at $3\sigma$. For each of X and Z directions the value is generated independently from the mentioned distribution.
The **skimmer** has 1 mm opening diameter and is placed just above the first measurement point.

Pellet **loss** due to, e.g., pellet-pellet collisions was different for different simulations. The whole pellet loss is realized before the first measurement point and is adjusted to give the desired effective pellet rate at the measurement points, in these studies 5 k/s and 14 k/s.

Pellets are generated with mean **velocity** 70 m/s (in direction of the movement), according to a Gaussian distribution with sigma (**velocity spread**) equal to 1% of the mean value. The distribution has a cut-off at $3\sigma$. 

### Pellet stream simulation (2)

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Gravity is not used in simulating the pellet behavior nor in their tracking. (Gravity only influences the time-of-passage/y-coordinate and can easily be taken into account).

The measurement points are located at the following Y positions:

- **First** measurement point is at position Y=2300 mm, 700 mm below generation point.
- **Second** measurement point is located 60 mm below the first one, at Y=2240 mm.
- **Third** measurement point, is located 140 mm below the previous one, at Y=2100 mm.
- The last, **fourth**, measurement point is located at Y=2040mm, 60 mm below the third one.
Pellet detection (1)

- Pellet and camera physical properties
  - Pellet shape and size
  - Camera shape and cycle structure
- Illumination
  - Pellet brightness (the amount of light reflected/refracted by the pellet in an amount of time)

- Real pellet size: 25 $\mu m$
- Pixel size: 37 $\mu m$
- Camera cycle:
  - period: 2.0 $\mu s$
  - exposure: 2.0 $\mu s$
- Pellet brightness smearing: Landau distribution
  - position parameter: 1.0 a.u.
  - sigma: 0.5 a.u.
  - range: from 0.0 to 20.0 a.u.
Pellet detection (2)

- Optics
  - Pellet visible size - physical size multiplied by a random value
  - Position of the center of brightness in respect to the center of mass - a random value multiplied by visible pellet size is added to position of the center of mass

- Pellet visible size smearing: Gaussian distribution
  - center: 4.0
  - sigma: 0.5
  - range: from -3 sigma to 3 sigma

- Brightness center position smearing: Gaussian distribution
  - center: 0.0
  - sigma: 0.2
  - range: from -3 sigma to 3 sigma
Detection

- Maximum possible amount of collected light (theoretical light integral)
- Amount of collected light taking into account camera cycle (corrected light integral)
- Amount of light collected in single pixels along the sensor line
- Signal noise for pixels- amount of collected light in pixel is multiplied by a random value
- Measured light integral

Noise in pixels: Gaussian distribution

- center: 1.0
- sigma: 0.02
- range: from -3 sigma to 3 sigma
Detection
- Maximum possible amount of collected light (theoretical light integral)
- Amount of collected light taking into account camera cycle (corrected light integral)
- Amount of light collected in single pixels along the sensor line
- Signal noise for pixels
- Measured light integral

Noise in pixels: Gaussian distribution
- center: 1.0
- sigma: 0.02
- range: from -3 sigma to 3 sigma
Pellet detection (4)

- Determination of pellet position and time
  - XZ position
  - Time
- Detection threshold
  - Threshold on amount of light collected in single pixel
  - Threshold on amount of light collected in whole cluster (detected pellet)
    - Threshold on light integral from the whole pellet (cluster): 0.01 a.u.
    - Threshold on light integral from single pixel: 0. a.u. (i.e. not used)
Pellet tracking details (1)

Processing stage

- **merge** measurements from all cameras into one sorted measurement stream;

- **take first** pellet recorded at uppermost camera. It will be a beginning point of a **new track**;

- based on **mean** pellet **velocity** in the stream and distance to the next measurement point, calculate **expected time** of arrival of the processed pellet to the next measurement point;

- set a certain size of a **time window** around the expected time, in which the pellets will be looked for. Size of the window may be related to velocity spread;

- **go through** measurement stream for 2nd camera. When window opens, start **saving measurements** found in the window, until the window closes;

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Recent results from pellet tracking
look for a measurement which is the closest to the expected time. Assume this is a measurement of the tracked pellet;

use information of time of flight from previous measurement point to calculate more accurate velocity of the pellet. Use it for looking for the pellet at the next measurement point;

repeat until last measurement point is reached;

apply the described procedure to all pellets recorded in first camera

After processing stage

- go through the tracks doing refined tracking - e.g. calculate directions and velocity by fitting to many points;
- calculate tracking efficiencies and resolutions
Cut on Chi square

- Chi square of fitted tracks describes their quality
- Cut on $\chi^2$ allows to reject most of incorrect tracks without loosing the correct ones
Pellet tracking parameters

- All **meas. points** are used for **pellet identification** and **tracking** in the **Y direction**. Tracking in **X and Z direction** is done using different measurement points. Their order was varied in simulations, as described below.
- Pellet position at the **VIC exit** may be used as an additional point in **XZ tracking**. This was toggled for different simulations.
- Half width of the **search window** at the measurement points is a time corresponding to 2 velocity sigmas.
- **X and Y dimensions of the accelerator beam** (width and height) were varied in the simulations.
- **Cut on** $\chi^2$ of fitting X and Z was set to accept only tracks for which $\chi^2 < 15$ for both X and Z.
Resolution at the interaction region

**Z resolution**

- **All tracks**
  - Counts vs. Meas. Z position - true Z position (mm)

- **Case A**
  - Counts vs. Meas. Z position - true Z position (mm)

- **Chi2 Cut**
  - Counts vs. Meas. Z position - true Z position (mm)

**Y resolution**

- **All tracks**
  - Counts vs. Meas. Y position - true Y position (mm)

- **Case A**
  - Counts vs. Meas. Y position - true Y position (mm)

- **Chi2 Cut**
  - Counts vs. Meas. Y position - true Y position (mm)

Correct tracks
- the same pellet was measured at all measurement points

Tracks after cut on $\chi^2$

Recent results from pellet tracking
**Resolution summary**

**Table:** Resolution of Y position and time reconstruction, for different camera cycles

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Y resolution [mm]</th>
<th>Time resolution [µs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/4µs</td>
<td>0.85</td>
<td>12.0</td>
</tr>
<tr>
<td>2/2µs</td>
<td>0.45</td>
<td>6.5</td>
</tr>
</tbody>
</table>

**Table:** Resolution of X and Z reconstruction, for different measurement setups

<table>
<thead>
<tr>
<th>Setup</th>
<th>X resolution [µm]</th>
<th>Z resolution [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>XZZX with VIC</td>
<td>75</td>
<td>65</td>
</tr>
<tr>
<td>XZZX without VIC</td>
<td>245</td>
<td>240</td>
</tr>
<tr>
<td>ZXXZ with VIC</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>ZXXZ without VIC</td>
<td>265</td>
<td>215</td>
</tr>
</tbody>
</table>

A position resolution $\sigma(x, y, z) < 0.2 \text{ mm}$ is desirable for event reconstruction.
The accelerator beam:

- The model allows to simulate which pellets and tracks occupy the accelerator beam region at a given time.
- The accelerator beam is directed along the Z axis. The beam region is defined as a solid similar to a cuboid, infinitely long along the Z axis and with certain X and Y dimensions.
- First, for each pellet and track we calculate time, when it entered the beam region (passing the top boundary), and the time when it left the beam region (passing the bottom boundary).
- In the next step, we check, if the pellet or track fits within the beam region boundaries in X direction. The pellets and tracks, which fulfill this condition, are used in further analysis.

...
... All acts of pellets and tracks entering to or exiting from the beam region are stored together and sorted chronologically. Based on this, a new set of information is prepared: a chronological list of records containing indexes of pellets and tracks currently occupying the beam region. Each record contains a time stamp, marking its beginning, and information about its duration. Each time the occupancy of the beam region changes, a new record is created and added to the list.

- PR: 5 k/s,
- beam region size: 5mm
- There are pellets in the beam region 70% of the time only

In the pellet tracking mode it is important to have a high fraction of pellets with useful tracking information.
## Tracking efficiency summary (1)

**Table:** Summary of pellet tracking efficiency with no track/pellet in the beam, for 5 mm beam size

<table>
<thead>
<tr>
<th></th>
<th>Probability of no track in the beam (time fraction)</th>
<th>Probability of no pellet in the beam (time fraction)</th>
<th>Probability of no pellet in the beam when no track is in the beam</th>
<th>Probability of no track in the beam when no pellet is in the beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle 2/2µs</td>
<td>0.780</td>
<td>0.70</td>
<td>0.878</td>
<td>0.979</td>
</tr>
<tr>
<td>Pellet rate 5 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cycle 4/4µs</strong></td>
<td><strong>0.778</strong></td>
<td><strong>0.7</strong></td>
<td><strong>0.865</strong></td>
<td><strong>0.964</strong></td>
</tr>
<tr>
<td>Pellet rate 5 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 6.25/5µs</td>
<td>0.826</td>
<td>0.7</td>
<td>0.818</td>
<td>0.960</td>
</tr>
<tr>
<td>Pellet rate 5 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 6.25/5µs</td>
<td>0.622</td>
<td>0.36</td>
<td>0.524</td>
<td>0.896</td>
</tr>
<tr>
<td>Pellet rate 14 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 6.25/5µs</td>
<td>0.531</td>
<td>0.36</td>
<td>0.642</td>
<td>0.942</td>
</tr>
<tr>
<td>Pellet rate 14 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cycle 4/4µs</strong></td>
<td><strong>0.537</strong></td>
<td><strong>0.36</strong></td>
<td><strong>0.613</strong></td>
<td><strong>0.909</strong></td>
</tr>
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Cycle 6.25/5µs ⇒ 20 % inefficiency
## Tracking efficiency summary (2)

**Table:** Summary of pellet tracking efficiency with no track/pellet in the beam, for 10 mm beam size

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Probability of no track in the beam (time fraction)</th>
<th>Probability of no pellet in the beam (time fraction)</th>
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<th>Probability of no track in the beam when no pellet is in the beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/2 µs</td>
<td>0.605</td>
<td>0.489</td>
<td>0.791</td>
<td>0.980</td>
</tr>
<tr>
<td>4/4 µs</td>
<td>0.607</td>
<td><strong>0.490</strong></td>
<td>0.779</td>
<td><strong>0.965</strong></td>
</tr>
<tr>
<td>6.25/5 µs</td>
<td>0.680</td>
<td>0.489</td>
<td>0.688</td>
<td>0.957</td>
</tr>
<tr>
<td>2/2 µs</td>
<td>0.282</td>
<td>0.130</td>
<td>0.436</td>
<td>0.946</td>
</tr>
<tr>
<td>4/4 µs</td>
<td>0.287</td>
<td><strong>0.131</strong></td>
<td>0.411</td>
<td><strong>0.900</strong></td>
</tr>
<tr>
<td>6.25/5 µs</td>
<td>0.391</td>
<td>0.129</td>
<td>0.297</td>
<td>0.899</td>
</tr>
</tbody>
</table>

Cycle 6.25/5 µs $\Rightarrow \approx 20\%$ inefficiency
### Table: Summary of pellet tracking efficiency with one track/pellet in the beam, for 5 mm beam size

<table>
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<tr>
<th></th>
<th>Probability of exactly one track in the beam (time fraction)</th>
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<th>Probability of correct match when there are one pellet and one track in the beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle 2/2µs</td>
<td>0.194</td>
<td>0.25</td>
<td>0.816</td>
<td>0.631</td>
<td>0.806</td>
<td>0.623</td>
</tr>
<tr>
<td>Pellet rate 5 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cycle 4/4µs</td>
<td>0.195</td>
<td>0.25</td>
<td>0.764</td>
<td>0.590</td>
<td>0.764</td>
<td>0.576</td>
</tr>
<tr>
<td>Pellet rate 5 k/s</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cycle 6.25/5µs</td>
<td>0.158</td>
<td>0.25</td>
<td>0.678</td>
<td>0.434</td>
<td>0.642</td>
<td>0.411</td>
</tr>
<tr>
<td>Pellet rate 5 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 2/2µs</td>
<td>0.335</td>
<td>0.37</td>
<td>0.619</td>
<td>0.557</td>
<td>0.591</td>
<td>0.531</td>
</tr>
<tr>
<td>Pellet rate 14 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 4/4µs</td>
<td>0.332</td>
<td>0.37</td>
<td>0.566</td>
<td>0.507</td>
<td>0.517</td>
<td>0.464</td>
</tr>
<tr>
<td>Pellet rate 14 k/s</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 6.25/5µs</td>
<td>0.293</td>
<td>0.37</td>
<td>0.483</td>
<td>0.384</td>
<td>0.403</td>
<td>0.320</td>
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<tr>
<td>Pellet rate 14 k/s</td>
<td></td>
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Cycle 6.25/5µs \(\Rightarrow \approx 20\%\) inefficiency
Introduction
Pellet stream simulation
Pellet detection
Pellet tracking
Tracking resolution
Tracking efficiency
Summary

Tracking efficiency summary (4)

Table: Summary of pellet tracking efficiency with one track/pellet in the beam, for 10 mm beam size

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</thead>
<tbody>
<tr>
<td>Cycle 2/2µs</td>
<td>0.307</td>
<td>0.355</td>
<td>0.772</td>
<td>0.668</td>
<td>0.763</td>
<td>0.660</td>
</tr>
<tr>
<td>Pellet rate 5 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 4/4µs</td>
<td>0.301</td>
<td><strong>0.348</strong></td>
<td>0.734</td>
<td>0.635</td>
<td>0.717</td>
<td><strong>0.620</strong></td>
</tr>
<tr>
<td>Pellet rate 5 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 6.25/5µs</td>
<td>0.264</td>
<td>0.354</td>
<td>0.652</td>
<td>0.486</td>
<td>0.624</td>
<td>0.464</td>
</tr>
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<td>Pellet rate 5 k/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 2/2µs</td>
<td>0.357</td>
<td>0.269</td>
<td>0.433</td>
<td>0.575</td>
<td>0.413</td>
<td>0.549</td>
</tr>
<tr>
<td>Pellet rate 14 k/s</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 4/4µs</td>
<td>0.358</td>
<td><strong>0.266</strong></td>
<td>0.405</td>
<td>0.545</td>
<td>0.373</td>
<td><strong>0.502</strong></td>
</tr>
<tr>
<td>Pellet rate 14 k/s</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Cycle 6.25/5µs</td>
<td>0.365</td>
<td>0.269</td>
<td>0.315</td>
<td>0.428</td>
<td>0.269</td>
<td>0.366</td>
</tr>
<tr>
<td>Pellet rate 14 k/s</td>
<td></td>
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Cycle 6.25/5µs $\Rightarrow \approx 20\%$ inefficiency

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Recent results from pellet tracking
we have MC able to reproduce experiments with pellets

various aspects of pellets behavior and detection are simulated

a procedure of pellet tracking has been implemented in the simulations

the MC is being used to determine predicted resolution and efficiency of pellet tracking for Panda

demonstrated transverse position resolution is ok

vertical resolution with 3-4 microsec cycle maybe ok, but better with 2microsec (cameras commercially available)

efficiencies according to TDR can be achieved i.e >70 % useful info with proper combination of PR (around 10 k/s) and acc. beam size (5-10 mm)

further optimization work in progress, both for equipment and procedures