Development and applications of tracking of pellet streams

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Pellet generation conditions:

- nozzle $\Phi = 12.9 \mu m$
- $T_n = 14.1 K$
- $f_{\text{droplet}} \approx 63 \text{kHz}$
- $p_{H_2} \approx 400 \text{mbar}$
- $P_{\text{DropChamber}} \approx 21 \text{mbar}$
- $v_{\text{droplet}} \approx 22 \text{m/s}$
- $d_{\text{droplet}} = 0.34 \text{mm}$
- $\text{pellet} \Phi = 25 - 30 \mu m$ (guess)
- $v_{\text{pellet}} = 77.9 \text{m/s}$
- $\sigma_v / v_{\text{pellet}} = 0.42\%$

Pellet stream

Above skimmer:
- PR $\approx 57 \text{k/s}$
- FWHM $= 2.1 \text{ mm}$, FW $\approx 3.7 \text{ mm}$

PTR chamber:
- PR $\approx 22.5 \text{k/s}$
- FW $\approx 2.5 \text{ mm}$

Windows center
vert. dist. (mm)

-76.5 DC VIC exit
0 271.5 PTR gen

1513.0 Skimmer
$\Phi = 2 \text{ mm}$

1860.2 PTR up
1939.7 PTR low

(2690 Cosy beam)
(3500? HESR beam)
Pellet tracking - principle of operation

- Goal: improving the accuracy of data analysis by precise determination of the interaction vertex (helping e.g. in charged particle track reconstruction and background suppression). The accuracy in position should be better than 1 mm.

- 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
Measurement levels
(distance between levels)

Skmr – PTRlow
(427 mm)

PTRupp – PTRlow
(80 mm)
Pellet tracking
Pellet simulations
Tracking system design
“Pellet tracking” at WASA
Conclusions and outlook

Pellet track reconstruction

Extrapolation of pellet track

Experiment:

MC:

- extrapolated track position $\sigma \approx 100\mu m$ at VIC
- a position accuracy $\sigma \approx 20\mu m$ at the measurement levels

Slice at nominal VIC exit position (experiment):
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 0.75 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 level. It removes most pellets that diverge more than 0.7 mrad from the stream direction.

Pellet loss due to, e.g., pellet-pellet collisions was different for different simulations. The whole pellet loss is realized before the first measurement level and is adjusted to give the desired effective pellet rate at the measurement levels, 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 $3\sigma$. 
Gravity is not included 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 levels are located at the following Y positions:

- **First** measurement level is at position Y=2300 mm, 700 mm below generation point.
- **Second** measurement level is located 60 mm below the first one, at Y=2240 mm.
- **Third** measurement level, is located 140 mm below the previous one, at Y=2100 mm.
- The last, **fourth**, measurement level is located at Y=2040 mm, 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
Pellet detection (3)

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

![Diagram showing pellet movement and detection](image)
Pellet detection (3)

- 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 level, calculate **expected time** of arrival of the processed pellet to the next measurement level;
- 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;
- ...
... 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 level to calculate **more accurate** velocity of the pellet. Use it for **looking for** the pellet **at the next** measurement level;
- **repeat** until last measurement level 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
Distributions of differences between reconstructed and true pellet position in the interaction region.

For tracks about which we know that the same pellet was measured at all measurement levels.

Z (transversal)

Y (vertical)

Sigma of the distributions is taken as a number describing tracking resolution.
Resolution summary

Table: Resolution (sigma) of Y position (vertical) 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 (sigma) of X and Z (transversal) 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>XZXZ with VIC</td>
<td>75</td>
<td>65</td>
</tr>
<tr>
<td>XZXZ 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 model allows to simulate which pellets and tracks occupy the accelerator beam region at a given time.

- PR: 5 k/s, beam region size: 5mm
- There are pellets in the beam region 30% of the time only

"In the pellet tracking mode it is important to have a high fraction of pellets with useful tracking information" (TDR)

pellet $\Rightarrow$ simulated pellet

track $\Rightarrow$ reconstructed pellet
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>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle 2/2µs</td>
<td>0.780</td>
<td>0.70</td>
<td>0.878</td>
</tr>
<tr>
<td>Pellet rate 5 k/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 4/4µs</td>
<td>0.778</td>
<td>0.7</td>
<td><strong>0.865</strong></td>
</tr>
<tr>
<td>Pellet rate 5 k/s</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>
</tr>
<tr>
<td>Pellet rate 5 k/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 2/2µs</td>
<td>0.531</td>
<td>0.36</td>
<td>0.642</td>
</tr>
<tr>
<td>Pellet rate 14 k/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 4/4µs</td>
<td>0.537</td>
<td>0.36</td>
<td><strong>0.613</strong></td>
</tr>
<tr>
<td>Pellet rate 14 k/s</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>
</tr>
<tr>
<td>Pellet rate 14 k/s</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Probability of exactly one track in the beam (time fraction)</th>
<th>Probability of exactly one pellet in the beam (time fraction)</th>
<th>Probability of one-correct pellet in the beam when exactly one track is in the beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/2 µs, Pellet rate 5 k/s</td>
<td>0.194</td>
<td>0.25</td>
<td>0.806</td>
</tr>
<tr>
<td>4/4 µs, Pellet rate 5 k/s</td>
<td>0.195</td>
<td>0.25</td>
<td><strong>0.764</strong></td>
</tr>
<tr>
<td>6.25/5 µs, Pellet rate 5 k/s</td>
<td>0.158</td>
<td>0.25</td>
<td>0.642</td>
</tr>
<tr>
<td>2/2 µs, Pellet rate 14 k/s</td>
<td>0.335</td>
<td>0.37</td>
<td>0.591</td>
</tr>
<tr>
<td>4/4 µs, Pellet rate 14 k/s</td>
<td>0.332</td>
<td>0.37</td>
<td><strong>0.517</strong></td>
</tr>
<tr>
<td>6.25/5 µs, Pellet rate 14 k/s</td>
<td>0.293</td>
<td>0.37</td>
<td>0.403</td>
</tr>
</tbody>
</table>

Cycle 6.25/5 µs $\Rightarrow$ $\approx$ 20% inefficiency
The **MC** is 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 **adequate**

**Vertical resolution** with 3-4 microsec cycle **may be sufficient, but would be better** with 2 microsec (cameras commercially available)

**Efficiencies** as specified in the Technical Design Raport of pellet target for Panda, **can be achieved**; i.e. >70 % useful info with proper combination of PR (around 10 k/s) and beam size (5-10 mm)

**Further optimization work** in progress, both for equipment and procedures
Rest-gas event suppression using an external system.

- **Pellets** are in the beam only for a some fraction of the time
- Events from rest-gas happen all the time
- When pellet is in the beam it’s much more probable, that the event came from the pellet.

Exploit an alternative method, based on integrated rate of interactions, to check when pellets are in the beam.

When a pellet passes through the beam, there are more interactions.
Studies of "pellet" long-range TDC spectra

Rate of WASA “elastic“ trigger

- Pellet crosses COSY beam at its center in $\approx 70\mu$s
- Structures of such duration are visible in the spectra

Most straight-forward use of the TDC information

Select time intervals when single well sized pellets pass the central part of the COSY beam

Studies of the LR TDC spectra gives an experience of using a system external to the detector data acquisition.

It also (simply) demonstrates what information can be obtained thanks to a system operating on a different time scale than the event data.
Simulations of pellet-beam interactions

Basis:
- Beam shape
- Pellet size
- Pellet path inside the beam
- Time binning
- Probability of interaction
- Definition of a pellet inside the beam

- Wasa setup
- Effective pellet rate: 8 k/s
- Fraction of events from the background: 0.0
- Accelerator beam density: two dimensional Gaussian distribution
  - center: 0.0
  - sigma: 2.1 mm
  - range: from -4.2 mm to 4.2 mm
- Pellet stream diameter: ≈ 3.8 mm
Check of rest-gas event suppression

Reaction: $pp \rightarrow pp\pi^0 \rightarrow pp\gamma\gamma$

$P_{beam} = 1.023 \text{ GeV/c} \Leftrightarrow E_{kin} = 0.45 \text{GeV}$

Events selection:

- Condition on the number of tracks
  - Exactly two charged particle tracks in the forward detector
  - Exactly two neutral particle tracks in the central detector
  - No charged particle tracks in the central detector
- Particles in forward detector stopping in one of the layers of the Range Hodoscope.
- Theta angle of central detector tracks are greater than 27 deg.
Missing mass/ Invariant mass

$IM_{\gamma\gamma}$

Peak at $\pi^0$ mass

$MM_{pp}$
Reconstructed angles of gamma particles depend on the assumption, that the interaction vertex was in its nominal position \((0, 0, 0)\).

If the interaction occurred in rest-gas, the reconstructed angle will be incorrect.

(First gamma - higher energetic gamma
Second gamma - lower energetic gamma)
### Missing and invariant mass for different angles (2)

<table>
<thead>
<tr>
<th>Angle of lower energetic $\gamma$</th>
<th>[0, 50) deg</th>
<th>[50, 100) deg</th>
<th>[100, 180) deg</th>
<th>Angle of higher energetic $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[100, 180) deg</td>
<td></td>
<td></td>
<td></td>
<td>[0, 50) deg</td>
</tr>
<tr>
<td>[50, 100) deg</td>
<td></td>
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<td>[0, 50) deg</td>
<td></td>
<td></td>
<td></td>
<td>[100, 180) deg</td>
</tr>
</tbody>
</table>

- Influenced by rest-gas contribution:
  - Shape of the 2-dim distribution
  - Width and position of the $\pi^0$ peak
  - Distribution of events between the 9 classes
Missing and invariant mass for different angles (3)

Angle of lower energetic $\gamma$

- [0, 50) deg
- [50, 100) deg
- [100, 180) deg

Angle of higher energetic $\gamma$

- [0, 50) deg
- [50, 100) deg
- [100, 180) deg

WMC with 0% rest-gas

Data
Missing and invariant mass for different angles (4)

<table>
<thead>
<tr>
<th>Angle of lower energetic $\gamma$</th>
<th>Angle of higher energetic $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0, 50) deg</td>
<td>[0, 50) deg</td>
</tr>
<tr>
<td>[50, 100) deg</td>
<td>[50, 100) deg</td>
</tr>
<tr>
<td>[100, 180) deg</td>
<td>[100, 180) deg</td>
</tr>
</tbody>
</table>

WMC with 50% rest-gas

Data
Conclusions and outlook

Experience with Long Range TDC at WASA:

- The work on using information from a separate system (similar to the pellet tracking) in event data analysis is in progress.
- In this study the eventual difference of events supposed to originate from pellets and events supposed to originate from the rest-gas is investigated.
- A procedure of separating events from pellets and from rest-gas, based on the LR TDC spectra is used.
- Initial study looks promising.

**Outlook:** Further work on calibration and tuning procedure needed to obtain better agreement between simulations and experiment. Then a detailed comparison between $\pi^0$ events from different time intervals defined from the LR TDC spectrum will be done.

Tracking system design:

- A system for PANDA, based on fast line-scan cameras, has been designed.
- Extensive simulation studies have been used in the optimization of the system.
- The studies show that it is possible to have a useful tracking system meeting the requirements at PANDA.
- The designed system is based on one tracking section (at the pellet generator).

**Outlook:** A second section (at the dump), mainly for tuning and checks, is planned.