High-precision measurements of proton-proton bremsstrahlung at 190 MeV
Huisman, Harry

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
1999

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Groningen: s.n.
In order to study bremsstrahlung reactions involving intermediate states that are far off the mass shell, one needs to measure high-energy photons. This restricts both protons to small laboratory angles. Furthermore, a measurement, which aims to probe small effects like the two-body current contributions, should be performed with high accuracy. The accuracy of any measurement is limited by two factors: statistics and systematics. In order to obtain the maximal statistical accuracy in a specific part of phase-space, one has to maximize two parameters: the luminosity and the azimuthal coverage of the experiment. The luminosity is limited by the maximal count rate the setup can handle. In proton-proton bremsstrahlung, the predominant background process is elastic scattering. At the angles of interest the elastic yield is roughly $10^6$ higher than the bremsstrahlung yield. This background is reduced by three orders of magnitude via a hardware trigger. The azimuthal coverage is maximal if the complete $2\pi$ range is covered. Since the unpolarized cross section, as defined in Eq. (2.39), is independent of the azimuthal angle, one can integrate the measured data over this variable.

The experiments that are subject of this thesis, were performed with the 190 MeV polarized-proton beam of the superconducting cyclotron AGOR at KVI. The beam current was typically 6 nA with a polarization of 0.65 in two opposite directions. A liquid-hydrogen target was used for these measurements [45]. A 6 mm thick cell of aluminum with a diameter of 20 mm was filled with liquid hydrogen. The operational temperature of 15 K and pressure of 140-190 mbar were somewhat above the triple point. This way, the exerted pressure on the window would be minimal enabling the use of very thin windows. For the entrance and exit windows of the target, 4 $\mu$m-thick Aramid (from Toray, Japan) was used. This is the first time that such a thin window of synthetic material has been used.
in a relatively high-intensity beam of protons. These windows were used for extended periods of running like 2 to 3 weeks at a time.

The Small-Angle Large-Acceptance Detector (SALAD) was specifically designed and built for these experiments [46]. It has a large solid angle of 400 msr and allows to make cylindrically-symmetric measurements around the beam axis. The covered scattering angle ranges from 6° to 26°. The detector is segmented to handle high count rates and allows a hardware trigger rejection of protons stemming from elastic scattering. The design and operation of this detector is the subject of the first section.

For the measurement of the bremsstrahlung photons, Two-Arm Photon Spectrometer, TAPS [47, 48] was used. TAPS consists of approximately 400 BaF$_2$ crystals, which were used in two different geometries. In the first geometry, known as the “supercluster”, all crystals were mounted at backward angles in a large hexagon, surrounding the beam pipe. This results in a polar angular range of 125° - 170° and a complete 2π azimuthal coverage. This cylindrical symmetry is essential in adding up the data for the whole azimuthal range for high statistics. In order to look at the angular distribution of the photons, a second experiment was performed where the cylindrical symmetry in photon detection was sacrificed. This second geometry, called the “block geometry” consists of six rectangular frames, each containing 64 crystals. These frames were positioned around the target on both sides of the beam-pipe. TAPS covered more than 20% of the full 4π solid angle in both geometries. The TAPS detector is the subject of the second section. An outlay of the data-acquisition and an overview of the triggers of both experiments are given in the third section.

3.1 The Small-Angle Large-Acceptance Detector

The Small-Angle Large-Acceptance Detector (SALAD) was used for the detection of the outgoing protons. It consists of two Multi-Wire Proportional Chambers (MWPC) for determination of the coordinates. Behind the two wire chambers, two stacks of segmented plastic scintillator are mounted. The first stack is used for energy determination of the protons and is therefore called the “energy detector”. Protons with an energy higher than 135 MeV will punch through the first layer and reach the second. These protons originate from elastic scattering and can be rejected via a hardware trigger. This second stack of scintillators is therefore called the “veto detector”. Fig. 3.1 shows a top view of SALAD, together with TAPS in the supercluster geometry. In Table 3.1 a summary is given of all the dimensions and distances of the different components of the SALAD detector.

3.1.1 The plastic scintillators

The energy detector consists of 24 detection elements, 12 on the top side and 12 on the bottom side. The elements are placed in a cylindrical configuration, such that the contact plane between each two elements is in the same plane as the target center. This way, a particle moving in a straight line (not suffering from any interactions) will not fire more than one element. A top view of the SALAD scintillators is shown in Fig. 3.2. The material is
3.1. **THE SMALL-ANGLE LARGE-ACCEPTANCE DETECTOR**

![Figure 3.1: Top view of the SALAD and TAPS detectors, configured in the supercluster geometry.](image)

**Figure 3.1:** Top view of the SALAD and TAPS detectors, configured in the supercluster geometry.

**Table 3.1:** The numbers, dimensions and distances of different components of SALAD. All dimensions are in mm.

<table>
<thead>
<tr>
<th>Component</th>
<th>#</th>
<th>Length</th>
<th>Width</th>
<th>Thickness</th>
<th>Dist. to target</th>
<th>Readout</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWPC #1</td>
<td>1</td>
<td>380</td>
<td>380</td>
<td>64.0</td>
<td>500</td>
<td>PCOSIII</td>
</tr>
<tr>
<td>MWPC #2</td>
<td>1</td>
<td>840</td>
<td>840</td>
<td>52.0</td>
<td>700</td>
<td>PCOSIII</td>
</tr>
<tr>
<td>ENERGY</td>
<td>24</td>
<td>436</td>
<td>61.2–68.7</td>
<td>112.5</td>
<td>915.5</td>
<td>XP2282/B</td>
</tr>
<tr>
<td>VETO</td>
<td>26</td>
<td>480</td>
<td>71.2–71.9</td>
<td>10.0</td>
<td>1048</td>
<td>R1398</td>
</tr>
</tbody>
</table>

![Figure 3.2: Top view of the arrangement of SALAD scintillators.](image)

**Figure 3.2:** Top view of the arrangement of SALAD scintillators. The 12 energy detectors and 13 veto detectors comprising the top part of SALAD are shown here. The bottom part is arranged in exactly the same fashion.
CHAPTER 3. EXPERIMENTAL SETUP

BC-408, which is a fast scintillation plastic (2.1 ns decay time). This scintillator is suited for large-area detection systems and can measure the energy of charged particles. The wavelength of maximum light emission is $\approx 425$ nm. The top 12 scintillators are read out at the top and bottom 12 scintillators at the bottom with Philips XP 2282/B photomultipliers (eight stages). These tubes must be able to handle extremely high rates ($\approx 1$ MHz). At these rates, the current delivered by the photomultipliers can become so high that its gain drops significantly. This is due to a decrease in voltage over the last stages of the phototube. An active voltage divider was developed by Philips specifically for this experiment to overcome this problem. A prototype of this base, type VD182K/B01, has been tested at KVI in combination with an XP 2282/B photomultiplier. A detailed description of the tests can be found in Ref. [49].

In the top panel of Fig. 3.3, the absolute gain as a function of the input voltage is plotted. The two points with a shown error bar come from single-photon measurements, while the other points are obtained from a relative measurement. The solid line is the factory specification for the XP 2282/B photomultiplier we tested in combination with a VD182K/B01 base. The bottom panel of Fig. 3.3 shows the voltage change over the final stage of the voltage divider as a function of the DC-current delivered by the tube. This is done for different input voltages of the phototube. At low input voltages, the voltage over the final stage drops earlier than at high input voltages. At these higher input voltages, however, the bleeder current of the tube is also higher and therefore the highest luminosity (number of photons per second on the cathode surface) the photomultiplier can handle, without a significant loss of gain, decreases more rapidly at higher voltages. For the experiment a slightly modified voltage divider, the VD182K/B02, is used, which has an even better stability at high currents. The typical input voltage during the experiment was 1450 V. The current delivered by the phototubes from the central scintillators is about 32 $\mu$A, which is well within the specifications. Another concern is the lifetime of the tubes. A phototube breaks down due to aging, after it has delivered a charge of approximately 300 - 1000 C. At the current of 32 $\mu$A, one can run under these conditions for at least 2600 hours, without any large damage to the tubes. The total running time of all bremsstrahlung experiments, including the commissioning was less than 800 hours and no significant loss of gain has been observed for any of the phototubes.

Since protons stemming from elastic scattering must punch through the energy detector and protons from bremsstrahlung have to be stopped, the thickness of the energy detector has to be chosen with care. In Fig. 3.4 the range of protons in the material is plotted as a function of the kinetic energy (solid curve). This curve is obtained from the empirical formula for the range of charged particles in matter $R$ as a function of their energy $E$ [50]:

$$R = \alpha E^{1.75}.$$ 

The constant $\alpha$ is dependent upon the type of material and it has been obtained from a fit to a Monte-Carlo simulation performed with GEANT (see chapter 4). The dotted curve shows the energy spectrum of protons originating from bremsstrahlung events with an incident beam energy of 190 MeV. The proton scattering angle is restricted between $5^\circ$ and $28^\circ$ and the photon scattering angle is restricted between $60^\circ$ and $180^\circ$. These restrictions correspond roughly to the widest detection range of the SALAD-TAPS setup. The dash-dotted curve is the energy spectrum of protons
Figure 3.3: The absolute gain of the phototubes as a function of the high voltage (top panel) and the voltage change over the final stage of the voltage divider as a function of the DC-current (bottom panel).
CHAPTER 3. EXPERIMENTAL SETUP

Figure 3.4: Range of protons in plastic scintillator material (solid curve) and the proton energy spectra of $p p \gamma$ (dotted curve) and elastic scattering (dashed-dotted curve).

originating from elastic scattering, where the proton scattering angle is restricted to the same range. Both spectra are the result of a Monte-Carlo simulation where a phase-space distribution is assumed. One can see that the two peaks are well separated. However, the high-energy tail of the bremsstrahlung spectrum has an overlap with the elastic spectrum. Evidently this part of the spectrum will be hardware-rejected. However, all high-energy protons correspond to a partner proton with a very low energy, which will not be detected, due to the low-energy threshold in the SALAD detector. Note that the two spectra are not scaled to each other. The ratio of the real-bremsstrahlung yield to the elastic yield is about $1 \times 10^6$. The thickness of the energy detector is chosen to be 11.25 cm.

The veto detector consists of 26 detection elements of 1 cm thickness each and is built in the same cylindrical shape as the energy detector (see Fig. 3.2). The top thirteen veto detectors are read out at the top and the bottom thirteen at the bottom with Hamamatsu R1398 phototubes. The trigger defining a bremsstrahlung candidate on SALAD side is that the number of energy elements firing minus the number of veto elements firing, should be larger than or equal to 2: $N_E - N_V \geq 2$.

In Fig. 3.5 the energy response of an energy scintillator element is shown at three different positions along its length. The solid histogram is the results of a measurement of elastically scattered protons which fired one energy and one veto element. This way the protons which suffered from hadronic interactions, are cut away. The position of the protons has been determined with the wire chambers. The dashed histogram is the result of a Monte-Carlo simulation performed with GEANT. The experimental data is calibrated to the middle of the scintillator. Since there are no resolutions folded with the GEANT simulation, the simulated energy peak is narrower than the measured peak. A gaussian has been fitted to both peaks. By subtracting the standard deviations quadratically, one
3.1. THE SMALL-ANGLE LARGE-ACCEPTANCE DETECTOR

Figure 3.5: The energy response of an energy scintillator element along its length at three different positions. The distances to the light guide are indicated in each plot. The solid histograms are the experimental results, while the results of a Monte-Carlo simulation are shown as the dashed histograms.

obtains the intrinsic resolution of the scintillator. The intrinsic resolution has been found to be 10% (FWHM). Another effect which can be observed is that the centroid of the simulated peak and the data peak do not coincide at the top and bottom of the scintillator. This is explained by the fact that the bottom part of the scintillator is far away from the phototube and has, therefore, a lower photon-yield, when compared to the center of the scintillator. The energy peak, as a result, is shifted to lower energies. The top of the scintillator, on the other hand, has a higher photon-yield, resulting in an energy peak which is shifted to higher energies. In order to obtain the best energy resolution achievable, one has to make a height-dependent calibration.

3.1.2 The Multi-Wire Proportional Chambers

Two Multi-Wire Proportional Chambers (MWPC) [51] were used for the measurement of the scattering angles of the outgoing particles. The two wire chambers are similar in design, the main difference being the size. The first chamber (MWPC1) has an active area of $38.0 \times 38.0$ cm$^2$ and the second an active area of $84.0 \times 84.0$ cm$^2$. The first
The wire chamber consists of three wire planes (x, y and 45°). This third plane (u-plane) is deployed to overcome ambiguities, arising when more than one particle fires the chamber. The second chamber has only two planes (x and y). Both chambers have a central hole in order to allow safe beam passage. The wire spacing for all planes is 2 mm, while two adjacent wires are connected to one readout channel in order to reduce the number of channels. The angular resolution in this geometry is about 0.5°. Each wire plane is sandwiched between its own two cathode frames, which enables a high voltage setting for each plane individually. A gas mixture of 80% CF4 and 20% isobutane is used. This gas has been chosen, because it allows for the high count rates of the bremsstrahlung experiments. Both chambers are equipped with aluminized-mylar foils, which act as a Faraday cage and are used for pressure equilibration and protection.

The efficiencies of each of the wire chambers have been tested with the 190 MeV proton beam from the AGOR cyclotron. The results are listed in Table 3.2. The efficiencies of each MWPC1-plane is measured via selecting single tracks in the two other planes and the scintillators. Subsequently, one can check for the presence of the first plane. The efficiency of the MWPC2-planes are checked in the same way with the additional use of the u-plane of MWPC1. The operational count rate was approximately 1 kHz/(cm wire). When more than one ionizing particle traverses the wire chambers, a set of x-, y- and u-coordinates is obtained. To find the corresponding x and y coordinates, one has to calculate the u-coordinate of each x-y pair and compare this with the set of measured u-coordinates. Fig. 3.6 shows a corresponded spectrum of the first wire chamber. A detailed description of the wire chamber can be found in Ref. [51].

### 3.1.3 The Electronics

The processing of the data from the phototubes is done with Fast-Encoding and Readout charge ADCs (FERA) and Time-to-Digital Converters (TDC). The FERA modules (LeCroy 4300B) integrate the charge produced by the phototubes and thus provide a measure of the energy deposited in the scintillator by a particle. The LeCroy 4300B FERA has 16 analog inputs with a range of 0 to –480 pC and a resolution of 230 fC (2048

---

**Table 3.2: The measured efficiencies (in %) for all the planes of MWPC1 and MWPC2 for different count rates. The statistical uncertainties are all smaller than 0.5%.**

<table>
<thead>
<tr>
<th>Wire plane</th>
<th>Count rate [kHz/(cm wire)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>MWPC1 x</td>
<td>98.9</td>
</tr>
<tr>
<td>MWPC1 y</td>
<td>98.8</td>
</tr>
<tr>
<td>MWPC1 u</td>
<td>99.3</td>
</tr>
<tr>
<td>MWPC2 x</td>
<td>98.9</td>
</tr>
<tr>
<td>MWPC2 y</td>
<td>98.4</td>
</tr>
</tbody>
</table>
3.1. THE SMALL-ANGLE LARGE-ACCEPTANCE DETECTOR

Figure 3.6: The $xy$-scatter of corresponded hits in the wire chamber. Events have been selected where the $pp\gamma$ trigger fired. One can observe a “lazy” $u$-wire in the plot. At two of the far corners of the plot, one can see two triangles due to the fact, that the $u$-plane was not read out there.
The TDC modules (LeCroy 3377) provide the time difference between the moment a detector fired and the moment the trigger is made. The trigger was timed with the TAPS discriminators, thus the TDC provided the difference in time-of-flight of the particle firing TAPS and the particle firing SALAD. The LeCroy 3377 TDC was used with a range of 512 ns and a resolution of 500 ps (1024 channels). The TDC has a multi-hit capacity, meaning that it can record a maximum of 16 particles in the time range of 512 ns. The TDCs were used in common-stop mode, i.e. the stop is the same for all channels. The TDCs and FERAs are CAMAC modules, but they are read out via an ECL bus by the FERA driver (LeCroy 4301), which decreases the readout time significantly. The FERA/TDC data is transported to a VME Dual-Port Memory (DPM) for VME access and to a FERA-memory (LeCroy 4302) for CAMAC access.

The flow of the signals from the phototubes is depicted in Fig. 3.7. The signals from the phototubes first go via 50Ω BNC cables to an active NIM splitter. One branch of the splitter output goes to the FERAs. Another branch goes to the Constant-Fraction Discriminators (CFD, type LeCroy 3420). A CFD gives a properly-timed logical pulse on the output, if the analog input exceeds a pre-programmed threshold value. This value was during the experiment set just above the noise level. This logical signal is connected to the TDCs, the scalers and the SALAD Trigger Module (STM). The scalers (LeCroy 4434) record the number of hits in a detector.

The wire chambers are read out via the commercially-available PCOSIII system. For both wire chambers, a total of 46 channel amplifiers and time-over-threshold discrimination cards (LeCroy 2735PC) are deployed. These cards are connected directly to the chamber. The signal from these cards is led to the delay-and-latch modules, which are placed in a dedicated CAMAC crate. The signals from the 2735PC cards are delayed here for a pre-programmed time, and are processed when a timed trigger arrives. This crate is controlled via a 32-channel encoder/system controller (LeCroy 2738PC). The processing (latching) involves the clustering of adjacent wires firing, providing a cluster centroid and cluster width. These data are transported via an ECL-line to a CAMAC databus (LeCroy 4299) for CAMAC access and to a VME dual port memory (DPM) for VME access.

The Salad Trigger Module (STM) [52] is a programmable multiplicity trigger unit (CAMAC), specifically designed for this experiment. It has, for example, the capability to select the $pp\gamma$ trigger condition on SALAD side: $N_E - N_V \geq 2$. The module has four trigger outputs which can be programmed independently. A trigger is only produced when the strobe signal is present. This strobe is an OR of the CFD-OR of the SALAD-energy scintillators ANDed with the TAPS-trigger. Since the width of the TAPS-trigger is made short when compared to the width of the SALAD-CFD outputs, the output of the STM has almost always the timing of the TAPS-trigger. The output of the STM is connected to a downscale unit (NIM module, type GS8000). This unit produces of each trigger three different outputs: the raw output, which is equal to the input, the inhibited output, which is equal the input if the unit is not inhibited and the downscaled output. All these outputs go to a scaler (LeCroy 4434). These scaler data are used in the analysis to calculate the deadtime of the system. The OR of all triggers is the event trigger, which goes to four different places. The data acquisition uses the event trigger as a signal to read
3.1. THE SMALL-ANGLE LARGE-ACCEPTANCE DETECTOR

Figure 3.7: Schematic drawing of the readout electronics and data acquisition of the SALAD detector.
out all modules. While doing this, it produces an inhibit for the GS8000 unit, to make sure no new triggers come in during readout. The event trigger also goes to the trigger input of the PCOS system as a signal that the wire-chamber data must be latched and read out. In addition, the trigger is also sent to the TDCs as a common stop and to a gate and delay generator to provide a gate for the FERAs.

3.2 The Two-Arm Photon Spectrometer

The Two-Arm Photon Spectrometer (TAPS) is a detector array developed by an international collaboration [53]. In the bremsstrahlung experiments at KVI it was used in two different geometries: the “supercluster” and the “block” geometries. The supercluster geometry has the full $2\pi$ azimuthal coverage for almost the complete polar angular range, whereas the block geometry has a larger coverage of scattering angles, but not the complete azimuthal range.

The TAPS detector consists of approximately 400 BaF$_2$ crystals. Because BaF$_2$ is a high Z scintillating material, it has a short radiation length for photons, making it well suited for their detection. The detection elements of TAPS are hexagonal crystals, as depicted in Fig. 3.8. The last part of a crystal is cylindrically shaped, to match the shape of the phototube. The signal from a BaF$_2$ has two different time components: a fast and a slow component. The ratio of these two different components is different for electromagnetic showers (photons and leptons) and for hadrons. The two different types of particles can then be distinguished by integrating the signal twice where the one ADC uses a short integration time and the other ADC a long integration time. This procedure is commonly referred to as “pulse-shape analysis”. In addition to the long and short gates, the signal timing is recorded with a TDC. The common start of the TDC comes from the RF of the cyclotron. The TDC provides thus the time of flight for particles in the TAPS detector.

When a high-energy photon or lepton enters the TAPS detector, it will generate an
3.2. THE TWO-ARM PHOTON SPECTROMETER

Electromagnetic shower of particles via subsequent pair creation and bremsstrahlung of the electrons/positrons. This shower of particles is in general not contained within one single detection element, but instead it will spread out over a number of adjacent detectors. Therefore, in the analysis one first has to "cluster" the hits in TAPS. The energy of the incoming particle is estimated to be proportional to the sum of the individual detector signals. The position at which the incoming particle hits the detector, has to be evaluated by a weighted sum of the detector positions. There exist several ways of weighting these positions [54], which can make a considerable difference in the GeV regime. However, the photon energies relevant for this work lie between 40-90 MeV, where the different methods of position reconstruction provide nearly the same result. In this work the linear energy weighting is used:

$$\bar{r}_i = \frac{\sum_i E_i \bar{r}_i}{\sum_i E_i}$$  \hspace{1cm} (3.1)

Here, $E_i$ is the measured energy in detector $i$ and $\bar{r}_i$ is the position of detector $i$.

In the supercluster geometry, the crystals are mounted in a large hexagon surrounding the beam pipe. The detector is placed at backward angles, such that the front face is at a distance of 50 cm upstream from the target. The angular range is $125^\circ$ to $170^\circ$ and the azimuthal scattering angular range is complete for nearly all scattering angles. In Fig. 3.9 the supercluster geometry of TAPS is depicted, as it is seen from the target. The outer two rings of BaF$_2$ crystals were equipped with phoswich detectors. These elements have a 15 mm thick plastic scintillator mounted in front of the BaF$_2$. The light produced by the phoswich element is detected with the same phototube as the light of the BaF$_2$. This was done with the hope to distinguish leptons from photons via pulse-shape analysis for the sake of the $pp$-dilepton experiment. The choice for phoswich detectors turned out

Figure 3.9: The TAPS detector in the supercluster geometry, seen from the target. This setup contains 390 detection elements.
to be unfortunate, since their trigger rate was more than a factor 5 higher than that of a normal BaF$_2$ detector. This is due to the fact that the phoswich detectors deliver a fast high amplitude pulse. This causes the CFD to fire even when very low energy particles enter the detector, but it hardly contributes to the total charge of the pulse. This is depicted in Fig. 3.10, where the two different pulse shapes are drawn. The resulting spectra are shown in Fig. 3.11, where the time (TDC) versus the energy (QDC, long gate) of a normal BaF$_2$-crystal and of a BaF$_2$ equipped with a phoswich detection element. Events have been selected where the LED-High has fired. A Leading-Edge Discriminator (LED) has the same function as a CFD, but it does not deliver a well-timed logical pulse. The LED-High trigger fires when a photon deposits more than 15 MeV of its energy in the crystal. One can observe two bands in the left panel. The vertical band consists of photons, which have a time-of-flight independent of their energy. The curved band consists of massive particles, e.g. protons produced in the target foils, whose time of flight is longer when their energy is lower. This band in the phoswich detector extends much further to lower energies than it does with the normal detector. Furthermore, one can observe in the phoswich detector a band with low energy particles, which are not time-correlated with the beam. These particles originate from the room background, and fire the LED of the detectors equipped with phoswiches. Increasing the LED-High threshold of the phoswich detectors in order to decrease their count rate, would render them useless for photon detection. One detail in Fig. 3.11 is that the massive-particle band and photon band are more separated in time in the phoswich detector. This is explained by the fact that this detector was mounted at a greater distance from the target.

In the block geometry, the crystals are mounted in six blocks each containing 64 BaF$_2$ crystals. In front of each crystal a plastic NE102A scintillator is mounted, which allows for a distinction between charged and neutral particles. These plastic scintillators are read out with separate phototubes. This configuration is depicted in Fig. 3.12. The six blocks are positioned around the target at a distance of approximately 66 cm from it. The angular range is $60^\circ - 170^\circ$.

The readout of the TAPS crystals is shown in Fig. 3.13. The analog signal of a BaF$_2$ module is connected to a QDC, where the signal is integrated twice, allowing particle identification via pulse-shape analysis. The signal is discriminated three times. The CFD signal is used for measuring the timing with respect to the RF of the cyclotron. This timing is thus a measure for the time of flight. Two Leading-Edge Discriminator (LED) signals, called LED-High and LED-Low, are used in the trigger logic. The level of the LED-High was set to 15 MeV in both experiments. This is depicted in Fig. 3.14, where the energy spectrum of TAPS, based on a minimum bias trigger, is shown for a BaF$_2$-crystal without a phoswich detection element.

In the supercluster geometry an OR of all LED-High signals was used as a TAPS trigger and provided the strobe for the STM. In the block geometry the Charged-Particle Vetos (CPVs) were available, allowing a veto of charged particles as well. The CFD-level of the CPVs was tuned such that electrons and positrons do not fire the CPV-detectors, but protons do. A quasi-neutral trigger, which allows for leptons, was obtained by Multiplicity-Pattern Units (MPU) by making an anti-coincidence with the CPV-LED.
3.2. THE TWO-ARM PHOTON SPECTROMETER

Figure 3.10: The two different pulse shapes, one originating from the fast plastic phoswich detector, and one from the normal BaF$_2$ crystal. Note that the area under the fast pulse is much smaller than the area under the BaF$_2$-pulse.

Figure 3.11: The Energy (QDC, long gate) versus relative time (TDC) of a normal BaF$_2$ crystal (left panel) and of a BaF$_2$-crystal equipped with a phoswich detector (right panel). Events have been selected where the LED-High has fired.
CHAPTER 3. EXPERIMENTAL SETUP

Figure 3.12: Top view of the SALAD and TAPS detectors in the block geometry. This setup contains 384 BaF$_2$ detection elements.
3.2. THE TWO-ARM PHOTON SPECTROMETER

Figure 3.13: Electronics of TAPS. Note, that the triggering part is only schematically put in the lower right box.

Figure 3.14: Energy spectrum of the TAPS detector. The levels of the two LED-triggers are indicated.
CHAPTER 3. EXPERIMENTAL SETUP

Table 3.3: A list of triggers used in the supercluster experiment and their rates at 6.5 nA nominal beam current. The livetime of the data acquisition was 58% at this current. DS stands for Down-Scale factor.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Description</th>
<th>DS log</th>
<th>Raw Rate [kHz]</th>
<th>ACQ Rate [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD</td>
<td>CFD OR BaF2</td>
<td>15</td>
<td>719</td>
<td>13</td>
</tr>
<tr>
<td>LEDLow</td>
<td>LED-Low OR BaF2</td>
<td>11</td>
<td>103</td>
<td>30</td>
</tr>
<tr>
<td>LEDHigh</td>
<td>LED-High OR BaF2</td>
<td>8</td>
<td>12</td>
<td>28</td>
</tr>
<tr>
<td>ppγ min bias</td>
<td>NE – NV ≥ 2 &amp; LEDHi</td>
<td>0</td>
<td>0.85</td>
<td>499</td>
</tr>
<tr>
<td></td>
<td>SALAD-OR &amp; LEDHi</td>
<td>8</td>
<td>9.6</td>
<td>22</td>
</tr>
<tr>
<td>pγ</td>
<td>NE – NV ≥ 1 &amp; LEDHi</td>
<td>7</td>
<td>3.6</td>
<td>4</td>
</tr>
<tr>
<td>RF</td>
<td>RF cyclotron / 225 x 10^3</td>
<td>0</td>
<td>0.27</td>
<td>177</td>
</tr>
</tbody>
</table>

and the BaF2 LED-High signals. The LED-Low was set to 5 MeV in the block geometry and was used in the more complex dilepton trigger via Multiplicity-Pattern Units (MPU) and Memory-Lookup Units (MLU) [55].

3.3 The data acquisition

The data were stored on DLT tape by the TAPS data acquisition. The CAMAC-crate controllers from TAPS side were chained via a VSB bus and are connected via a microprocessor to a VME-system. The data from SALAD side were passed to VME-based dual-port memory units (LeCroy DPM 1190), one for the scintillator data (TDC and FERA) and one for the wire-chamber data (PCOSIII); see Fig. 3.7. The data handling rate was about 300 kB/s, resulting in approximately 800 events/s. A fraction of the events was passed via ethernet to the online data analysis.

The triggers of the supercluster experiment are shown in Table 3.3. The most important trigger is, of course, the \( pp\gamma \)-trigger. Also, the heavily down-scaled RF of the cyclotron is used as a trigger. This trigger reads out the detector once every \( 225 \times 10^3 \) beam pulses. This trigger is used for the determination of the elastic cross section, which in turn is used for the absolute normalization of the \( pp\gamma \) data. The raw rate is the rate at which the trigger fires and the ACQ-rate is the rate at which this trigger was written to tape.

The triggers and their rates for the block-geometry experiment are listed in Table 3.4. In this geometry the two forward TAPS-blocks (A and F) (see Fig. 3.12) are in a position that elastically-scattered protons penetrate the BaF2 crystals. This results in the fact that in these blocks more than 80% of all LED-High triggers originate from protons. Therefore, the rate of the Quasi-Neutral (QN) trigger will be very much different from the rate of the LED-High trigger in these blocks. The situation is different for the four backward blocks, where the rate of the QN-trigger is approximately the same as the rate of the LED-High
3.3. THE DATA ACQUISITION

Table 3.4: A list of triggers used in the block experiment and their rates at 6.5 nA nominal beam current. The livetime of the acquisition is 52.9% at this current. DS stands for Down-Scale factor.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Description</th>
<th>DS</th>
<th>Raw Rate $^{2\text{log}}$</th>
<th>ACQ Rate [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD</td>
<td>CFD OR BaF$_2$</td>
<td>15</td>
<td>974</td>
<td>15</td>
</tr>
<tr>
<td>LEDLow</td>
<td>LED-Low OR BaF$_2$</td>
<td>11</td>
<td>205</td>
<td>52</td>
</tr>
<tr>
<td>LEDHigh</td>
<td>LED-High OR BaF$_2$</td>
<td>8</td>
<td>35</td>
<td>71</td>
</tr>
<tr>
<td>VETO</td>
<td>OR of the CPV</td>
<td>13</td>
<td>819</td>
<td>53</td>
</tr>
<tr>
<td>QN</td>
<td>LEDHigh with VETO</td>
<td>$\infty$</td>
<td>8.8</td>
<td>0</td>
</tr>
<tr>
<td>PN</td>
<td>QN A/F, LEDHI B,C,D,E</td>
<td>$\infty$</td>
<td>9.9</td>
<td>0</td>
</tr>
<tr>
<td>$\pi_1$</td>
<td>LEDLo coin. diff. blocks</td>
<td>$\infty$</td>
<td>2.7</td>
<td>0</td>
</tr>
<tr>
<td>$\pi_2$</td>
<td>LEDLo coin. same blocks</td>
<td>$\infty$</td>
<td>1.3</td>
<td>0</td>
</tr>
<tr>
<td>$pp\gamma$</td>
<td>$NE - NV \geq 2 &amp; Val$</td>
<td>0</td>
<td>0.92</td>
<td>494</td>
</tr>
<tr>
<td>$pp\gamma$ no val</td>
<td>$NE - NV \geq 2 &amp; LEDHi$</td>
<td>7</td>
<td>7.2</td>
<td>56</td>
</tr>
<tr>
<td>min bias</td>
<td>SALAD-OR &amp; Val</td>
<td>7</td>
<td>9.5</td>
<td>39</td>
</tr>
<tr>
<td>$p\gamma$</td>
<td>$NE - NV \geq 1 &amp; Val$</td>
<td>6</td>
<td>3.5</td>
<td>29</td>
</tr>
<tr>
<td>RF</td>
<td>RF cyclotron / $225 \times 10^3$</td>
<td>1</td>
<td>0.27</td>
<td>66</td>
</tr>
</tbody>
</table>

trigger. Therefore, a Pseudo-Neutral (PN) trigger was made, where an OR was made of the LED-High of the four backward blocks and the quasi-neutral trigger of the two forward blocks. In order to allow for low-energy lepton-pairs, two additional TAPS-triggers were made with the LED-Low trigger (5 MeV threshold) which are denoted as $\pi_1$ and $\pi_2$. The trigger from TAPS side indicating a $pp\gamma$ or $pp\gamma^+e^-\gamma$ candidate, was an OR of the QN-trigger, the $\pi_1$-trigger and the $\pi_2$-trigger. This OR of TAPS-triggers is called the validation trigger, which is used in combination with the different SALAD-triggers to generate the master trigger.