NA61/SHINE facility at the CERN SPS: 
beams and detector system
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ABSTRACT: NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a multi-purpose experiment facility to study hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the CERN Super Proton Synchrotron. It recorded the first physics data with hadron beams in 2009 and with ion beams (secondary $^7$Be beams) in 2011.

NA61/SHINE has greatly profited from the long development of the CERN proton and ion sources and the accelerator chain as well as the H2 beam-line of the CERN North Area. The latter has recently been modified to also serve as a fragment separator as needed to produce the Be beams for NA61/SHINE. Numerous components of the NA61/SHINE set-up were inherited from its predecessors, in particular, the last one, the NA49 experiment. Important new detectors and upgrades of the inherited equipment were by introduced the NA61/SHINE Collaboration.

This paper describes the NA61/SHINE facility - the beams and the detector system - before the CERN Long Shutdown I, March 2013.
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1. Introduction

NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) [1] is a multi-purpose facility to study hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the CERN Super Proton Synchrotron (SPS). One of the physics goals is precise hadron production measurements for improving calculations of the initial neutrino beam flux in the long-baseline neutrino oscillation experiments [2, 3] as well as for more reliable simulations of cosmic-ray air showers [4, 5]. The other is to study the properties of the onset of deconfinement [6] and search for the critical point of strongly interacting matter which is pursued by investigating p+p, p+Pb and nucleus-nucleus collisions.

The experiment was proposed to CERN in November 2006 [1]. Based on this proposal pilot data taking took place in September 2007. The Memorandum of Understanding [7] between CERN and the collaborating institutions was signed in October 2008. The first physics data with hadron beams were recorded in 2009 and with ion beams (secondary 7Be beams) in 2011.

NA61/SHINE has greatly profited from the long development of the CERN proton and ion sources and the accelerator chain as well as the H2 beam-line of the CERN North Area. The latter has recently been modified to also serve as a fragment separator as needed to produce the Be beams for NA61/SHINE. Numerous components of the NA61/SHINE setup were inherited from its predecessors, in particular, the last one, the NA49 experiment.

The layout of the NA61/SHINE detector is sketched in Fig. 1. It consists of a large acceptance hadron spectrometer with excellent capabilities in charged particle momentum measurements and identification by a set of six Time Projection Chambers as well as Time-of-Flight detectors. The high resolution forward calorimeter, the Projectile Spectator Detector, measures energy flow around the beam direction, which in nucleus-nucleus collisions is primarily given by the number of spectator (non-interacted) nucleons. For hadron-nucleus collisions, the collision centrality is determined by counting low momentum particles emitted from the nuclear target with the LMPD detector (a small TPC) surrounding the target. An array of beam detectors identifies beam particles, secondary hadrons and ions as well as primary ions, and measures precisely their trajectories.

This paper describes the NA61/SHINE facility, the beams and the detector system. Special attention is paid to the presentation of the components which were constructed for
Figure 1. The layout of the NA61/SHINE experiment at the CERN SPS (horizontal cut in the beam plane, not to scale). The beam and trigger counter configuration used for data taking on p+p interactions in 2009 is presented. The chosen right-handed coordinate system is shown on the plot. The incoming beam direction is along the z axis. The magnetic field bends charged particle trajectories in the x-z (horizontal) plane. The drift direction in the TPCs is along the y (vertical) axis.

NA61/SHINE. The components inherited from the past experiments and described elsewhere are described only briefly. The paper is organized as follows. In Sec. 2 the proton and ion acceleration chains are briefly presented and the North Area H2 beam-line is described. Moreover basic properties of hadron and ion beams are given. The NA61/SHINE beam and trigger detectors as well as the trigger system are presented in Sec. 3. Section 4 presents the TPC tracking system which includes the TPC detectors with front end electronics, two beam pipes filled with helium and two super-conducting magnets. The Time of Flight system is described in Sec. 5 and the Projectile Spectator Detector in Sec. 6. In Sec. 7 targets and the Low Momentum Particle Detector are presented. Finally, data acquisition and detector control systems are described in Sec. 8. Section 9 closes the paper with summary and outlook.

2. Beams

This section starts from the presentation of the CERN proton and ion accelerator chains, and continues with a brief description of the H2 beam-line and secondary hadron and ion beams for the experiment.

The CERN accelerator chain is shown in Fig. 2. From the source, the beams of ions and protons pass through a series of accelerators, before they reach the SPS for the final acceleration and extraction to the North Area and the NA61 experiment. The protons and
ion beams follow a different path in the pre-injector chain to PS, required to match the beam parameters for their acceleration.

Figure 2. Schematic layout of the CERN accelerator complex relevant for the NA61/SHINE ion and proton beam operation. *topview, nottoscale.*

2.1 The proton acceleration chain

The proton beam is generated from hydrogen gas by a duoplasmatron ion source, which can provide a current of up to 300 mA of beam current [8]. The Radio-Frequency Quadrupole RFQ2 [9] focuses and bunches the beam, and accelerates it to 750 keV for injection into LINAC2, a three-tank Alvarez drift tube linear accelerator. The three tanks have a total length of 33.3 m, and the energy of the beam at the exit of the tanks is respectively 10.3, 30.5, and 50 MeV. With a repetition rate of 0.8 Hz, LINAC2 delivers a current of up to 170 mA within a 90% transverse emittance of 15 π mm mrad, during a 120 µs pulse length [10]. The 50 MeV proton beam from LINAC2 is then distributed in the four rings of the PS booster (PSB) using a staircase-like kicker magnet in the transfer line. The multi-turn injection system of the PSB allows to accumulate for up to 13 turns, over $10^{13}$ protons per ring. After acceleration to 1.4 GeV, the beam from the four rings is extracted and recombined in the extraction line, to be sent to the Proton Synchrotron (PS), CERN’s oldest accelerator [11]. The PS has a circumference of 628 m and accelerates the beams
to 14 GeV/c for the injection to the Super Proton Synchrotron (SPS). In a typical proton cycle for the fixed-target experiments, the PSB beam after recombination consists of a train of eight bunches (two per ring), that is injected in the eight consecutive buckets of the RF of PS that operates at harmonic eight. During the acceleration to 14 GeV/c, the beam passes from an intermediate flat-top where the RF system splits the eight bunches in two and changes the operation to harmonic sixteen. At top energy, the beam is de-bunched and re-captured at harmonic 420 in order to easily match the RF structure of the receiving machine, the 6.8 km SPS. The beam is extracted from PS over five turns using a staircase-shaped kicker pulse. This "continuous transfer" multi-turn extraction is unique to the PS. As the SPS is 11 times larger than the PS in circumference, it takes two PS cycles to fill the SPS with the five-turn extraction. The remaining two half-turn gaps are used for the rising and falling edges of the SPS injection kicker. At SPS, the 14 GeV/c beam is accelerated to 400 GeV/c, on fixed harmonic 4620 (200 MHz). At top energy, the beam is de-bunched and slowly extracted over several seconds using a third-integer resonance. The spill duration for the North Area experiments depends on the overall optimisation for the SPS machine and its users, and can be between 4.5 s and 10 s with a duty cycle of around 30%.

2.2 The ion accelerator chain

The CERN heavy ion production complex was first designed in the 1990s for the needs of the SPS fixed target programme [13, 14]. It was rejuvenated at the beginning of the 21st century [15] in order to cope with the LHC’s stringent demands for high brightness ion beams [16]. The ions are generated in the ECR source. A sample of isotopically pure 208Pb is inserted in a filament-heated crucible at the rear of the ECR source, whilst oxygen is injected as support gas. With a 10 Hz repetition rate, a 50 ms long pulse of 14.5 GHz microwaves accelerates electrons to form an oxygen plasma, which in turn ionizes the lead vapor at the surface of the crucible. The source operates in the so-called afterglow mode, i.e. after the microwave pulse is switched off, where the intensity of the high charge state ions from the source increases dramatically. The ions are electrostatically extracted from the source with an energy of 2.5 keV/u. Out of the different ion species and charge states, a 135° spectrometer situated at the exit of the source selects those lead ions which have been ionized 29 times (Pb29+) to enter the LINAC3 accelerator. The beam is first accelerated to 250 keV/u by the 2.66 m long RFQ which operates at 101.28 MHz. The RFQ is followed by a four-gap RF cavity which adapts the longitudinal bunch parameters to the rest of the linear accelerator which is a three-cavity interdigital H (IH) structure, that brings the beam energy up to 4.2 MeV/u requiring about 30 MV of accelerating voltage, for a total acceleration length of 8.13 m. The first cavity operates at the same frequency as the RFQ (101.28 MHz), while the second and third cavities operate at 202.56 MHz. Finally, a 250 kV “ramping cavity”, also operating at 101.28 MHz, distributes the beam momentum over a range of ±1%, according to the time along the 200 ìs pulse. The LINAC3 currently only operates at 5 Hz. A 0.3 µm thick carbon foil provides the first stripping stage...
at the exit of LINAC3, followed by a spectrometer which selects the Pb54+ charge state. A current of about 22 \( \mu A \) of Pb54+ from LINAC3 is injected over about 70 turns into the Low Energy Ion Ring (LEIR), whose unique injection system fills the 6-dimensional phase space. This is achieved by a regular multi-turn injection with a decreasing horizontal bump, supplemented by an electrostatic septum tilted at 45°, and the time dependence of the momentum distribution coupled with the large value (10 m) of the dispersion function in the injection region. The injection process is repeated up to six times, every 200 ms. The whole process is performed under electron cooling reducing the transverse and longitudinal emittances. At the end of the seven injections, the beam is bunched on harmonic 2, accelerated to 72 MeV/u by Finemet\textsuperscript{TM} cavities, and fast-extracted towards the PS. At this point the total beam intensity is about \( 10^9 \) ions.

In the PS, the two ion bunches from LEIR are injected in two adjacent buckets of harmonic 16 and accelerated by the 3-10 MHz system to 5.9 GeV/u, with an intermediate flat-top for batch expansion. This process consists of a series of harmonic changes: \( h = 16, 14, 12, 24, 21 \), in order to finally reach a bunch spacing of 200 ns at top energy. Before the fast extraction to SPS, the bunches are finally rebucketed into \( h = 169 \), using one of the PS’s three 80 MHz cavities. At the exit of the PS, the beam traverses a final stripping stage to produce Pb82+ ions, through a 1 mm thick aluminium foil. The two bunches, now about \( 3 \cdot 10^8 \) ions each, are injected into the SPS, with a bunch-to-bucket transfer into the 200 MHz system. This process can be repeated up to 12 times every 3.6 seconds; the repetition rate is limited by the duration of the LEIR cycle, while the total number of injections is currently limited by the SPS controls hardware. At a fixed harmonic, the heavy mass of the ions during acceleration would yield a too large frequency swing (198.51 - 200.39 MHz) for the range of the travelling wave cavities of the SPS (199.5 - 200.4 MHz).

Hence, instead of using a fixed harmonic, the ions are accelerated using the "fixed frequency" method, in which a non-integer harmonic number is used, by turning the RF on at the cavity center frequency during the beam passage and switching it off during its absence, to correct the RF phase and be ready for its next beam passage through the cavities. The phase is adjusted by an appropriate modulation of the frequency. Aside from its complexity, one drawback of the method is that the beam has to be constrained in a relatively short portion (40%) of the circumference of the machine. In the SPS, the ion beam after acceleration is left to debunch naturally at top-energy and is then slowly extracted to the North Area using the third integer resonance like for protons. The acceleration range in SPS varies between the 13 GeV/u, which is the lowest possible operational range due to stability reasons, and 160 GeV/u due to the limits in the power supplies and energy in the magnets. The spill duration is preferred to be long at about 10 s, although as for the protons the overall structure depends on the number of users in SPS.

2.3 The H2 beam-line

The extracted beam from SPS is transported over about 1 km by bending and focusing magnets and then split into three parts each one directed towards a primary target where
secondary particles are created. The H2 secondary beam line emerges from the T2 primary target and is able to transport momentum selected secondary particles to the Experimental Hall North 1 (EHN1). The NA61/SHINE experiment is located in the middle part of EHN1, the NA61 production target being at 535 m distance from the T2 target. The H2 beam line can transport charged particles in a wide range of momenta from \( \sim 9 \) GeV/c up to the top SPS energy of 400 GeV/c. Alternatively the beam can transport a primary beam of protons or ions, of low intensity to comply with the radiation safety conditions for the experimental hall.

The North Area target cavern (TCC2) where the T2 target is located, is about 11 m underground in order to contain the produced radiation from the impact of the high-intensity extracted beam from SPS. In the proton mode the extracted intensity from SPS is typically a few \( 10^{13} \) protons per cycle at 400 GeV/c from which only a fraction of about 40% interacts in the targets, and the rest is dumped in a controlled way in the TCC2 cavern. The earth around acts as natural shielding for radiation and the height difference to the experimental hall is sufficient to reduce the muon background to the experiments. The T2 target station hosts several Bertrylium (Be) plates of different lengths. The actual target plate is chosen optimizing the yield of the secondary particle momentum and type. Beams for NA61 are usually produced using a target length of 100 or 180 mm. A further optimisation can be achieved using a set of upstream dipole magnets that can modify the incident angle of the primary proton beam to the target, thus the angular production of the secondary particles to the H2 beam line.

The momentum selection in the beam is done in the vertical plane, as shown in Fig. 3, where the beam line basically consists of two large spectrometers able to select particles according to their rigidity, i.e. the momentum to charge ratio \( B\rho \approx 3.33P/Z \), where \( B\rho \) in Tesla-meters is set by the beam optics, \( P \) is the particle momentum in GeV/c, and \( Z \) being the charge of the particle (in proton charge units). For the energies discussed here the particle momentum can be written in the relativistic limit as \( P = \gamma M \), where \( \gamma \) is the Lorenz factor and \( M \) the particle mass, which can itself be written in terms of the atomic mass number \( A \) times the atomic mass unit (1 amu = 0.931 GeV). So finally the rigidity relation for the beam line is \( B\rho \approx 3.31\gamma^2/2 \). Each spectrometer consists of six dipole magnets that make a total angle of 41 mrad and collimators to define the central trajectory. The beam spectrometer has an intrinsic resolution of about 0.13% and a maximum rigidity acceptance of \( \pm 1.7\% \). Besides the magnetic spectrometers, the beam line is equipped with dedicated devices which provide information on the beam position, profile and intensity at various locations, as well as particle identification detectors like Cherenkov or pulse height and spectrum analysis detectors to identify multiply charged particles like heavy ions.

For the NA61/SHINE experiment secondary hadron beam in the momentum range from 13 GeV/c to 350 GeV/c were used, as well as attenuated primary Pb82+ ion beams in the range from 13A GeV/c to 158A GeV/c. In addition for the initial physics program of the experiment, as other than Pb82+ primary ions won’t be available before 2015, the option to use secondary \(^7\)Be ion beams in the same momentum range produced via frag-
Figure 3. Schematic view of the vertical plane of the H2 beam-line in the configuration used for the ion fragment separation. The dimensions are not to scale, e.g. the beam line is more than 600 m long, the height difference between T2 and the EHN1 is about 12 m, the aperture of the quadrupoles is ±45 mm.

2.4 Hadron beams

The H2 beam line can transport and deliver positively or negatively charged secondary hadrons (p, K+, π+ and p, K−, π−) to the NA61/SHINE experiment, produced at the T2 target at the impact of the primary proton beam from SPS. For a given beam tune, i.e. rigidity selection, the momentum selected hadrons are mixed with muons, electrons and tertiary hadrons from the interactions of the beam particles with the collimators or the beam aperture limits. To positively identify the wanted hadrons, the beam line is equipped with a special differential Cherenkov counter, the Cherenkov Differential Counter with Achromatic Ring Focus (CEDAR) [17] counter. This counter uses a gas as radiator, He for beam momenta higher than 60 GeV/c and Nitrogen for lower momenta. The counter has a sophisticated optical system that collects and focuses the Cherenkov photons to the plane of a diaphragm whose opening can be tuned, in relation to a given gas pressure, such to allow only those photons from the wanted species to go through and detected by the 8 PMTs of the counter. By using a coincidence logic, 6-, 7- or 8-fold, a positive tagging of the wanted particles can be achieved. For the NA61/SHINE experiment the 6-fold coincidence signal is used for the beam trigger.
The pressure at which the proton/pion signal reaches its maximum is found by running a pressure scan in the range where $p (\bar{p}), \pi^+ (\pi^-),$ and $K^+ (K^-)$ peaks are expected. The final setting is the pressure for the center of the plateau of the proton/pion counts per incident beam particle. The actual value of the optimal pressure depends on possible admixtures in the gas, as well as on temperature, since the production angle of Cherenkov radiation is a function of the gas density. The width of the plateau or peaks and their separation can be modified by changing the aperture of the diaphragm. The counter is installed in a special location of the beam line where the beam has almost zero divergence, however to make sure the light is collected with high symmetry, an angular alignment of the CEDAR counter has to be performed each time the beam position at the detector changes. In the worst case, only 95% of the particles crossing the detector are identified. The number of misidentified particles is lower than 0.8%. For beam momenta lower than 40 GeV/c, the trigger definition also requires the signal from a carbon dioxide-filled Threshold Cherenkov [18, 19] detector in anti-coincidence.

The H2 beam optics is such to provide a smooth focus at the NA61/SHINE experiment target with an $rms$ width slightly larger than 2 mm at the lowest momenta and 1.2 mm at 158 GeV/c. The momentum spread is typically lower than 1%, defined by the collimator settings in the line.

2.5 Primary and secondary ion beams

The physics program of NA61/SHINE requires beams of Berrylium (Be), Argon (Ar) and Xenon (Xe) ions. For reasons of compatibility with the LHC program the Be beam is obtained from the fragmentation of Pb ions, whereas the Ar and Xe beams will be specifically produced for NA61.

The transport of primary ions in the H2 beam-line is straightforward. The beam tune, i.e. rigidity is set to match the ion momentum extracted from SPS, and the detectors in the beamline are adapted to the non-standard (high) charge of the beam particles. To respect the radiation limits and classification in the Experimental Hall, the intensity in the SPS machine is kept to a minimum, typically using a single (or double) injection to SPS thus a total of $\sim 6 \times 10^8$ ions. The intensity is further reduced in the H2 beam line by collimation, to arrive in a rate of a few $10^5$ ions at the experiment.

The selection and transport of a specific ion species from a fragmented heavy (Pb82+) ion beam for nuclear reaction experiments is not straightforward. The H2 beam line selects on rigidity, i.e. $\sim \gamma_b (A/Z)$, and the desired ions produced from the fragmentation of the primary Pb beam will be mixed with a variety of other nuclei with similar mass to charge ratios and slightly different rigidity values within the beam acceptance. Moreover, rigidity overlaps occur not only for ions with the same mass to charge ratio but also for neighbouring elements due to variations in the ion momentum due to the nuclear Fermi motion

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1The citation [13] concerns H2 filled Cherenkov detectors, similar in construction we use nowadays, useful up to 5 GeV/c.
of the fragments (set free in the interaction and breakup of a Pb beam particle). Without
Fermi motion the fragments would leave the interaction region almost undisturbed with
the same velocity (or momentum per nucleon) as the incident Pb-ions. The Fermi motion
depends on the fragment and projectile mass, and can spread the longitudinal momenta for
light nuclear fragments by up to 3-5%, much larger than the beam acceptance.

The $^7$Be ion ("wanted ion") was selected for the NA61/SHINE beam, because it has
no long-lived near neighbors and thus allows to make a light ion beam with large ratio of
wanted to all ions. The near neighbors to $^7$Be are isotopes $^6$Be and $^8$Be and the nuclei with
a charge difference of one and a similar mass to charge ratio (e.g. $^5$Li, $^9$B). Furthermore
$^7$Be has more protons ($Z = 4$) than neutrons ($N = 3$). Such nuclear configurations are
disfavored with increasing nuclear mass, since a surplus of protons causes a Coulomb
repulsion which cannot be balanced by the attractive potential of the fewer neutrons. As
can be seen in Fig. 4, $^7$Be fragments are accompanied mainly by $^2$D and He ions whose
rigidity overlaps with the one of the wanted ions due to Fermi motion. A problematic
choice of wanted ion species would be a nucleus with mass to charge ratio of two, which
would be accompanied by stable or long lived nuclei from $^2$D up to $^{56}$Ni.

![Figure 4](image-url)  

**Figure 4.** Charge spectrum measured with the Quartz Z-detector for 13A and 150A GeV/c ion beams.

At low energies, a better selectivity of the wanted ions is achieved with the "fragment
separation" method [20], profiting from the double spectrometer of the H2 beam line (see
Fig. 3). In the first spectrometer, ions are selected within a rigidity value that maximizes
the wanted to all ratio for the fragments as produced by the primary fragmentation tar-
get. At the focal point of the first spectrometer, a piece of material (called degrader) is
introduced, in which ions lose energy in dependence of their charge. Then in the second
spectrometer the different ions will be spatially separated according to their charge state,
which then can be selected using a thin slit (collimator). The drawback of this method is
a loss of beam intensity due to nuclear interactions and the beam blow-up due to multiple
scattering in the material of the degrader which rises with increasing thickness. Thus a
high separation power of the fragment separator spectrometer goes along with a high loss
of intensity. Furthermore, for a given degrader thickness both the nuclear cross section and
the energy loss are to a large extent energy independent. This means that the separation
power ($\Delta E/E$) increases with decreasing energy.

Under typical running conditions a beam of several $10^8$ Pb ions per spill from the SPS
is focused onto the 180 mm long fragmentation target made of Be. During its passage
through the target the Pb beam undergoes (mostly peripheral) collisions with the (light)
target nuclei. Part of the resulting mix of nuclear fragments is captured by the H2 beam-
line, tuned to a rigidity such that the fraction of the created $^7$Be to all ions is maximized
(see Fig. 4). Ion fluxes at the NA61 apparatus were 5000 to 10 000 $^7$Be particles with 10
to 20 times more unwanted ions.

Figure 5. The $tof$ spectra of ions for the carbon ($left$) and beryllium ($right$) peaks resulting from
fragmentation of the primary Pb beam at 13.9A GeV/c. The spectrum of carbon is fitted by a sum of
two Gauss functions, whereas that of beryllium by a single Gaussian. Bottom: The $Z^2$ spectra with
the selected (gray area) peaks of carbon ($left$) and beryllium ($right$). The spectra were measured
by the A-detector.

The optional degrader (1 or 4 cm thick Cu plate) is located between the two spect-
rometer sections (see Fig. 3). The composition of the ion beam can be monitored by
scintillator counters which measure the charge ($Z^2$) and time of flight ($tof$) of the ions.
The latter allows mass (A) determination of the ions for momenta lower than 20 GeV/c
per nucleon and thus a check of the purity of the $^7$Be beam. This is illustrated in Fig. 5 where the spectra of ions for the carbon (left) and beryllium (right) peaks resulting from fragmentation of the primary Pb beam at 13.9 A GeV/c are shown. The carbon spectrum shows clear evidence for two isotopes, whereas only the single Be isotope ($^7$Be) is seen in the Be spectrum.

The fragment separation method was tested in 2010 with a 13.9A GeV/c Pb beam incident on the primary target of the H2 beam-line with the 4 cm thick degrader in place. Figure 6 shows for a given rigidity setting the charge distributions resulting from two collimator settings which optimize either the $^7$Be (filled purple histogram) or the $^{11}$C (open blue histogram) content.

![Graph](https://via.placeholder.com/150)

**Figure 6.** Fragment charge distributions obtained with the H2 beam-line in fragment separator mode and collimator settings optimized for $^7$Be (filled purple) and $^{11}$C (open blue) fragments. The primary Pb beam momentum is 13.9A GeV/c.

During the 2011 running period the NA61/SHINE collaboration used the beam line configuration without degrader at beam momenta of 158A, 80A, and 40A GeV/c. In 2012 and early 2013 fragmented ion beams at 30A, 20A, and at 13A GeV/c down to the lower momentum limit of the accelerator capabilities were provided to NA61.

### 3. Beam detectors and trigger system

A set of scintillation and Cerenkov counters as well as the beam position detectors located upstream of the target provide precise timing reference, along with charge and position measurement of the incoming beam particles. An interaction counter located downstream of the target allows to trigger on interactions in the target.

The locations of the beam detectors in 4 exemplary configurations of the beam line are indicated in Fig. 7. Colours represent detector roles in the NA61 interaction trigger: green units are used in coincidence, red in anti coincidence, blue ones do not participate in the
trigger. Panel a) shows the configuration used in 2011 p+p data taking with beam momenta of 13 and 158 GeV/c. Panel b) illustrates the setup of 2009 and 2010 p+C data taking with T2K replica target. In this setup S3 detector was glued to the surface of the target, since due to target length all beam particles hitting its upstream surface were assumed to interact inelastically in the target. Panel c) indicates beam detectors used in 2009 h−+C data taking at beam momenta of 158 and 350 GeV/c. In this period an additional interaction trigger was used with S5 counter instead of S4 to control trigger bias. Panel d) corresponds to 2013 Be+Be data taking at beam momenta of 13A, 19A and 30A GeV/c.

3.1 Beam counters

 CONTRIBUTORS: Zoltan, Roman

Minimization of the total detector material in the beam-line is a major concern, especially with ion beams. A minimal set of beam counters (see Fig. 7) is therefore used. The first detector S1 is located upstream of the target at position z = -36.38 m. As the time of flight resolution in low-multiplicity events has to rely on a precise reference time, the S1 counter (0.5 cm thick) is equipped with four photo-multipliers directly coupled to the scintillator. The second beam counter S2 (0.2 cm thick) is located just behind the BPD-2 detector at z = -14.39 m. In the case of primary heavy ion beams the S1 and S2 scintillator detectors will be replaced by quartz detectors of 200 µm thickness yielding sufficient timing and pulse height resolution from the Cerenkov effect. Downstream of the S2 detector two 1 cm thick veto scintillator detectors V0 and V1 are positioned at z = -14.11 m and z = -6.71 m, respectively. The round V0 detector has outer diameter of 8 cm and in the center a hole of 1 cm diameter. The square (10×10 cm²) V1 detector also has a 1 cm central hole. The S4(S5) detector (2 cm diameter, 0.5 cm thickness), located downstream of the target at z = -2.11(9.80) m, indicates an interaction in the target by the absence of the beam particle signal. The beam counter parameters are summarized in Table 1. In the plane transverse to the beam direction (the x−y plane) the detectors are centered at the maximum of the beam profile.

3.2 A-detector

 CONTRIBUTORS: Fedor, Sasha

The A-detector was constructed to verify that the secondary Be beam consists only of the single isotope ⁷Be. It was located about 140 m upstream of the target and measured the time-of-flight (tof) of beam ions between A- and S1 detectors. It consists of a plastic scintillator (BC-408) bar (15x0.5x1.5 cm³) with light readout from both sides of the scintillator bar by the two fast PMTs, EMI 9133. The time resolution of the A-detector was measured to be about 80 psec during a test in the T10 beam of the CERN PS using pions.

The time-of-flight spectra measured by the A-detector at 13.6A GeV/c are shown in Fig. 5 (top) for carbon and beryllium ions selected by the Z² proportional signal ampli-
Figure 7. Beam detectors in 4 configurations of the beam line (see text). The colour represents detector’s role in the NA61 interaction trigger: green units are used in coincidence, red in anti coincidence, blue ones do not participate in the trigger. S5 counter was used in an additional interaction trigger instead of S4 to control trigger bias.

388 tude simultaneously measured in the A-detector (bottom). The single isotope beryllium
389 ($^7$Be) spectrum demonstrates a $tof$ resolution of 60 psec. The expected difference of
390 $tof$ between $^7$Be ions and its nearest isotopes is about 170 ps at the beam momentum
391 13.6A GeV/c and distance of 140 m.

392 3.3 Beam Position Detectors

393 contributors: Roman
Table 1. Summary of beam counter parameters: dimensions, positions along the beam-line (z coordinates) and their material budget.

<table>
<thead>
<tr>
<th>counter</th>
<th>dimensions [mm]</th>
<th>hole [mm]</th>
<th>position [m]</th>
<th>material budget [x₀]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>60 × 60 × 5</td>
<td></td>
<td>-36.38</td>
<td>??</td>
</tr>
<tr>
<td>S2</td>
<td>φ = 28 × 2</td>
<td></td>
<td>-14.39</td>
<td>??</td>
</tr>
<tr>
<td>S3</td>
<td>φ = 26 × 5</td>
<td></td>
<td>-6.57(6.53)</td>
<td>??</td>
</tr>
<tr>
<td>S4</td>
<td>φ = 20 × 5</td>
<td></td>
<td>-2.12?</td>
<td>??</td>
</tr>
<tr>
<td>S5</td>
<td>φ = 20 × 5</td>
<td></td>
<td>9.80</td>
<td>??</td>
</tr>
<tr>
<td>V0</td>
<td>φ = 80 × 10</td>
<td>φ = 10</td>
<td>-14.11</td>
<td></td>
</tr>
<tr>
<td>V1</td>
<td>100 × 100 × 10</td>
<td>φ = 8</td>
<td>-6.71</td>
<td></td>
</tr>
<tr>
<td>V1&lt;sup&gt;p&lt;/sup&gt;</td>
<td>300 × 300 × 10</td>
<td>φ = 20</td>
<td>-6.78??</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8. Left: The schematic layout of BPD detector. Right: The signal generated by a BPD pre-amplifier (upper curve) and the corresponding signal at the output of a shaper (lower curve). The time scale of the x axis is 500 ns per division.

The positions of the incoming beam particles in the transverse palne are measured in a telescope of three Beam Position Detectors (BPDs) placed along the beam-line upstream of the target. The NA61/SHINE BPDs (see Fig. 8 (left)) with active areas of 48×48 mm<sup>2</sup> were constructed in 2009. These detectors are proportional chambers operated with Ar/CO<sub>2</sub> 85/15 gas mixture. Two orthogonal sense wire planes (15 µm tungsten wires with 2 mm pitch) are sandwiched between three cathode planes made of 25 µm aluminized Mylar. The outer cathode planes of these detectors are sliced into strips of 2 mm pitch which are connected to the read-out electronics. In order to detect beam particles at high intensities (about 10<sup>5</sup> particles/second ) shapers based on AD817 integrated amplifiers were constructed. The width of their output signal is about 350 ns. Negative undershoots of output signals observed with the NA49 shapers are practically eliminated (see Fig. 8 (right)).
In order to reconstruct a beam particle track, a least squares fit of a straight line is performed to the positions measured by the three BPDs in $x - z$ and $y - z$ planes. Distributions of residuals associated with those fits are shown in Fig. 9. The RMS widths of the distributions indicate the order of magnitude of the accuracy of the BPD measurements, which is in agreement with the design value of $\sim 100 \mu m$. Differences of the RMS widths are mainly due to non-equal distances between the detectors in the $z$ direction ($d(\text{BPD-1, BPD-2}) = 21 m, d(\text{BPD-2, BPD-3}) = 8 m$).

![Figure 9.](image)

**Figure 9.** Distributions of residuals associated with beam track fits in each of the BPDs in the $x - z$ (top row) and $y - z$ (bottom row) planes. Differences in RMS widths are mainly due to non-equal distances between the detectors in the $z$ direction. Plots are for the negatively charged hadron (mainly $\pi^-$) beam at 158 GeV/c.

### 3.4 Z-detectors

**contributors: Seweryn, Pawel, text updated**

In order to select secondary ions by their charge at the trigger level, two Cerenkov counters (Z-detectors) were constructed. These are:

(i) The Quartz Detector (QD) with a quartz (GE214P) plate $160 \times 40 \times 2.5 \text{ mm}$ as the radiator is equipped with two photo- multipliers (X2020Q) attached to both sides of the quartz plate. Optical grease (BC630) is applied between the PMTs and the quartz plate in order to achieve good light transmission.

(ii) The Gas Detector (GD) uses a 60 cm long $C_4F_{10}$ gas radiator. The construction of this detector is based on the standard CERN threshold Cerenkov unit. Cerenkov photons are reflected by a 25 $\mu m$ thick aluminized Mylar foil and focused by a parabolic mirror onto a single photo-multiplier, Hamamatsu R2059.

The large refraction index of the quartz radiator of about 1.458 leads to a low Cerenkov threshold momentum of $\approx 0.88 \text{ GeV}/c$ per nucleon. Thus the detector performance is...
largely independent of the beam momentum in the momentum range relevant for the
NA61/SHINE energy scan program. The refraction index of the C₄F₁₀ gas at normal con-
ditions is about 1.00142 leading to a Cerenkov threshold momentum of about 17.6 GeV/c
per nucleon. For the momentum of 13A GeV/c the lowest acceptable value of the refraction
index is \( \approx 1.0023 \) requiring a minimum gas pressure of 1.63 bar.

Both detectors were tested during the 2011 run using the secondary ion beam at
150A GeV/c. The ADC signals measured in the Quartz and Gas Detectors showed well
separated peaks for proton and He beam particles. Both detectors performed well at this
momentum, namely the measured width to mean value ratio for the \(^4\)He peak was 18-19%.
However, it was estimated that at the lowest beam momentum the performance of the GD
will deteriorate both in terms of the charge resolution and the material budget (at the suf-
ciently high gas pressure it is about factor of 2.5 larger than for the QD). Therefore the
GD was the choice of Z-detector for the physics data taking with secondary \(^7\)Be beams in
2011-2013.

Figure 4 presents \( Z^2 \) distributions measured by the QD for secondary ion beams of
13A, and 150A GeV/c momentum used in the data taking on \(^7\)Be+\(^9\)Be interactions.

### 3.5 Trigger system

*contributors: Sandro, Oskar*

In designing the NA61/SHINE trigger system, particular attention was paid to de-
veloping a flexible and robust system capable of handling and selecting different reac-
tions using a variety of beams (pions, kaons, protons, ions) and targets as required by the
NA61/SHINE physics program [1].

The trigger is formed using several beam counters, listed in Table 1, the Cerenkov
detectors for beam particle (hadrons or ions) identification, and the PSD calorimeter, as
illustrated in Fig 7.

The core of the trigger logic is an FPGA (Xilinx XC3s1500) running at 120 MHz
embedded in a CAMAC Universal Logic Module, the CMC206 [21]. CAMAC is used for
backward compatibility with the legacy NA49 electronics. The trigger logic is divided into
three main logic blocks:

(i) beam logic

(ii) beam particle identification

(iii) interaction logic

Up to four different triggers can be run simultaneously with a selectable 12 bit pre-scaler
for each trigger. Different trigger configurations are recorded in a pattern unit on an event-
by-event basis for off-line selection.

Analog signals from the beam counters are first discriminated with constant fraction
and leading edge discriminators before entering a second discriminator, whose role is to
shape the logic signals (12 ns width) and convert them to ECL levels, as required by the FPGA trigger logic. These logic signals are also recorded in pattern units on an event-by-event basis for verifying the trigger logic in the analysis of trigger data. The combined use of two discriminators with different output widths prevents also the pile-up in the trigger logic (the length of the output of the first discriminator is around 100 ns, while the length of the second discriminator is 12 ns). Correspondingly, the dead time of the trigger system is around 100 ns, small compared to the dead time gated trigger rate of $\approx 100$ Hz.

The simultaneous use of the beam ($T_{BEAM}$) and interaction triggers ($T_{INT}$) allows for the direct determination of the interaction probability, $P_{INT}$:

$$\frac{N(T_{BEAM} \land T_{INT})}{N(T_{BEAM})},$$

where $N(T_{BEAM})$ is the number of events which satisfy the beam trigger condition and $N(T_{BEAM} \land T_{INT})$ is the number of events which satisfy both the beam trigger and interaction trigger conditions.

4. TPC tracking system

The main tracking devices of the NA61/SHINE experiment are four large volume Time Projection Chambers (TPC). Two of them (Vertex TPCs: VTPC-1 and VTPC-2) are located in the magnetic field, two others (Main TPCs: MTPC-L and MTPC-R) are positioned down-stream of the magnets symmetrically to the beamline. In addition a smaller TPC (GAP-TPC) is mounted between the two VTPCs. It is centered on the beamline for measuring particles with the smallest production angles. Also the Low Momentum Particle Detector presented in Sec. \ref{sec:low_momentum_detector} consist of two small TPC chambers. The TPCs allow reconstruction of over 1000 tracks in a single Pb+Pb interaction. Up to 234 track positions and samples of energy loss per track provide high statistics for precise measurements.

The TPCs consist of a large gas volume in which the particles leave a trail of ionization electrons. A uniform vertical electric field is established by a surrounding field cage made of aluminized Mylar strips that are kept at the appropriate electric potential by a voltage divider chain. The electrons drift with constant velocity under the influence of the field towards the top plate where their position, arrival time, and total number are measured with proportional wire chambers. In order to achieve high spatial resolution the chamber top plates are subdivided into pads of about one square centimeter area, a total of about 180 000 for all TPC’s. From the recorded arrival times of the track signals and the known pixel positions one gets a string of 3-dimensional measured points along the particle trajectories.

An overview of the main parameters of the different TPCs is given in Table \ref{table:tpc_parameters}.
<table>
<thead>
<tr>
<th></th>
<th>VTPC-1</th>
<th>VTPC-2</th>
<th>MTPC-L/R</th>
<th>GAP-TPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>size (L×W×H)[cm]</td>
<td>250 x 200 x 98</td>
<td>250 x 200 x 98</td>
<td>390 x 390 x 180</td>
<td>30 x 81.5 x 70</td>
</tr>
<tr>
<td>No. of pads/TPC</td>
<td>26 886</td>
<td>27 648</td>
<td>63 360</td>
<td>672</td>
</tr>
<tr>
<td>Pad size [mm]</td>
<td>3.5 x 16</td>
<td>3.5 x 28</td>
<td>3.6 x 40, 5.5 x 40</td>
<td>4 x 28</td>
</tr>
<tr>
<td>Drift length [cm]</td>
<td>66.595</td>
<td>66.595</td>
<td>111.735</td>
<td>58.97</td>
</tr>
<tr>
<td>Drift velocity [cm/µs]</td>
<td>1.4</td>
<td>1.4</td>
<td>2.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Drift field [V/cm]</td>
<td>13</td>
<td>13</td>
<td>175</td>
<td>200</td>
</tr>
<tr>
<td>drift gas</td>
<td>Ar/CO₂ (90/10)</td>
<td>Ar/CO₂ (90/10)</td>
<td>Ar/CO₂ (95/5)</td>
<td>Ar/CO₂ (90/10)</td>
</tr>
<tr>
<td># of sectors</td>
<td>2 × 3</td>
<td>2 × 3</td>
<td>5 × 5</td>
<td>1</td>
</tr>
<tr>
<td># of padrows</td>
<td>72</td>
<td>72</td>
<td>90</td>
<td>7</td>
</tr>
<tr>
<td># of pads/padrow</td>
<td>192</td>
<td>192</td>
<td>192, 128</td>
<td>96</td>
</tr>
</tbody>
</table>

Table 2. Parameters of the NA61/SHINE TPCs. In the MTPCs the 5 sectors closest to the beam have narrower pads and correspondingly more pads per padrow.

4.1 VTPC, MTPC, GAP-TPC

Each Main TPC has a read-out surface at the top of 3.9×3.9 m² and a height of the field cage of about 1.1 m. It is filled with a gas mixture of Ar/CO₂ in the proportion 95/5. The track signals are read out by 25 proportional chambers providing up to 90 measured points and ionization samples on each particle trajectory. The accuracy of the measurement of the average ionization energy loss for a particle is about 4%.

Each Vertex TPC consists of a gas box with 2.0×2.5 m² top surface area and 0.67 m depth. The inserted field-cage structures exclude the region of 0.12 m on either side of the beamline in which the particle density in Pb+Pb reactions is so high that trajectories cannot be resolved. A gas mixture of Ar/CO₂ in the proportion 90/10 is employed. The read-out is performed by 6 proportional chambers on the top which provide up to 72 measurements and ionization samples on the particle trajectories. More details about the Vertex and Main TPCs can be found in Ref. [22].

Between VTPC-1 and VTPC-2 directly on the beamline an additional tracking device is located: the GAP-TPC [23]. It covers the gap left for the beam between the sensitive volumes of the TPCs. High momentum tracks can be better extrapolated back to the primary vertex due to the additional points. Particles originating from the primary vertex but measured only in the MTPCs can be better distinguished from conversion electrons faking high momentum tracks outside the magnetic field. Since the beam passes through this detector its material budget was minimized to 0.15 % of a radiation length and 0.05 % of an interaction length. The design follows that of the other TPCs described above (the schematic layout is shown in Fig. 10). The electric field in the drift volume is generated by a field cage made from aluminized Mylar strips connected by a resistor chain. The electric
field is 13 kV over 58.97 cm (220 V/cm) with a resulting drift time of about 50 µs. The support of the Mylar strips is provided by tubes of glass-epoxy with a wall thickness of 100 µm. The drift volume is enclosed by a gas box made of a single layer of 125 µm Mylar. The read-out plane consists of 7 paddrws with 96 pads each, the pad dimensions are 28 mm by 4 mm. The gas composition is Ar/CO₂ (90/10) like in the VTPCs. For the readout three standard TPC frontend cards are used together with one concentrator board.

Figure 10. Schematic layout of the GAP TPC: front view (left) and top view (right).

4.2 He beam pipe

contributors: Grigori (text updated)

He filled beam pipes were installed in April 2011 in the gas volume of the Vertex TPCs in order to reduce the number of δ-electrons by a factor of about 10. This is needed in order to decrease significantly event-by-event fluctuations of the track density in the TPCs and thus reduce systematic uncertainties of fluctuation measurements in nucleus-nucleus collisions. Installation of the pipe necessitated cutting openings in the double wall Mylar envelopes of VTPC-1 and VTPC-2. The openings were drilled using specially developed tools which prevented dust and debris of material from getting into the inner volume of the TPCs. These openings into the gas volume were precisely positioned around the beam axis and were used for gluing the lightweight interface units (200µm wall thickness carbon fiber rings) providing support for the He beam pipe and ensuring a hermetic VTPC volume. The lightest possible He beam-pipe structure was produced that is feasible with present technology. The close-to-normal gas pressure conditions allow to use thin (30 µm) gas-leakage tight Tedlar polyvinyl fluoride (PVF) film to produce 2.5 m length cylinder envelopes (pipes of 75 and 96 mm diameters), which formed the He gas and protective gas volumes. The pipes were made by gluing the Tedlar film to
The construction is gas tight allowing separation of the working gas of the TPC from the helium used in the central pipe. In addition, during the operation an inert gas (CO$_2$) is flushed through the outer envelope of the pipe (the protective gas volume). The He beam pipe installed in the VTPC-1, with gas supply lines connected, is shown in Fig. 11. A special gas supply system was constructed to maintain the overpressure gradients in the two gas volumes of the pipe with respect to the pressure in the VTPCs. This is mandatory to ensure the mechanical stability of the pipes. The He pipes were tested under working conditions of the VTPCs. They showed good mechanical stability when operating different modes of gas circulation in the VTPCs. No leakage of helium from the central pipe to the outer envelope was observed. The surface of the pipe did not show any excessive charging-up which could distort the drift field in the active TPC volume. Gas tightness of the fixations of the pipes to the Mylar foils closing the VTPC field cage was tested by monitoring of the oxygen content in the TPC gas. The oxygen contamination of the working gas decreased to a few ppms during the first 48 hours of purge (Fig. 12) and remained constant at this level. The measured level of oxygen impurity after gas stabilization in the VTPCs was the same as that observed during the normal operation before the installation of the He beam pipes.

**Figure 11.** *Left:* Schematic layout of the He beam pipe installed in the VTPC-1 gas-volume between the two field cages. *Right:* The He beam pipe photo.
Figure 12. Oxygen level in the VTPC volumes during the gas purging period.

Figure 13 shows the interaction vertex distribution along the beam axis (data for p+p interactions at 158 GeV/c) before the He beam pipe installation (2009 and 2010 data) and with the He beam pipes installed and filled with helium gas (2011 data). Clearly, the He beam pipes reduce the number of background interactions in the volume of the VTPCs by about a factor of 10.

Figure 13. Interaction vertex distribution along the beam axis (data from p+p interactions at 158 GeV/c) before the He beam pipe installation (2009 and 2010 data) and with the He beam pipes installed and filled with helium gas (2011 data).

4.3 Magnets

contributors: Rainer, Zoltan, based on NIM paper but shortened a lot
The two identical super-conducting dipole magnets with a maximum total bending power of 9 Tm at currents of 5000 A have a width of 5700 mm and a length of 3600 mm. Their centers are approximately 2000 mm and 5800 mm downstream of the target. The shape of the magnet yokes is such that the opening in the bending plane is maximized at the downstream end. Inside the magnets a gap of 1000 mm between the upper and lower coils leaves room for the VTPCs. The coils have an iron-free central bore of 2 m diameter. This causes large field inhomogeneities where the minor components reach up to 60% of the central field at the extremities of the active TPC volumes. The magnetic field inside the sensitive volumes of the Vertex TPCs was precisely measured by Hall probes.

The standard configuration for data taking at beam momentum per nucleon of 150 GeV/c and higher is nominally 1.5 T, in the first and 1.1 T in the second magnet. At lower beam momenta the fields are reduced proportional to the beam momentum keeping the ratio of the two fields constant. More details about the magnets can found in Ref. [22].

4.4 Gas system and monitoring

The gas in the VTPCs and MTPCs is supplied by four independent gas systems. A schematic drawing of one gas system is presented in Fig. [14]. Each system recirculates the gas with a compressor at a rate of about 20% of the detector volume per hour, i.e. 0.9 and 3 m$^3$/h for VTPCs and MTPCs, respectively. Fresh gas is mixed through mass flow controllers from pure Ar and CO$_2$. In normal operation, the fresh gas is supplied at only 3% detector volume per hour; in purge mode, the full recirculation rate is achieved. The recirculation flow is controlled by regulating the TPC overpressure to 0.50 ± 0.01 mbar via frequency modulation of the compressors.

Oxygen is cleaned from the detector gas by filter columns containing active Cu-granules chosen for use with the CO$_2$ gas mixtures. The filters are regenerated after typically 4-6 months operation periods, using Ar/H$_2$ (93/7) mixture at 200°C. Fresh filters absorb water contamination in the gas for about 2 weeks, such that the water content may vary by 10 to 20 ppm.

Two bypass lines allow to start the recirculation with TPC isolated, and to replace the oxygen filter without stopping the system. In case of compressor failure a safety bubbler protects the TPC from overpressure.

The TPC walls are made of two layers of 125 µm Mylar. Nitrogen is flushed between the layers, to prevent air from contaminating the TPC gas by diffusion through the walls, or a potential leak.

The control of gas quality is one of the major issues in the NA61/SHINE TPC system. Small amounts of gas can be directed to measurement units. Non-linearities and calibration drift of the flow controllers are taken care of by on-line control of drift velocity and gas amplification, as the required setting accuracy is beyond the specifications of the flow
Figure 14. Layout of one of the four TPC gas recirculation systems. The gas flow direction is marked by arrows next to the valves. The letters A, B, C and D mark points where small amounts of the gas can be directed to the measurement devices.

regulators. It is possible to measure the fresh gas mixture (point A in Fig. 14), and the gas from the TPC (point B). Each of the gas systems has a system of a drift velocity monitor and four gas amplitude monitors. Drift velocity is measured in a drift detector using the drift time difference from a pair of $^{241}$Am $\alpha$ sources at 10 cm distance. The gas amplification is checked in the amplitude monitors. The amplitude monitors measure the signal from $^{55}$Fe photons in a proportional tube. The mixing and monitoring equipment is temperature stabilized to better than 0.1°C.

Oxygen and water contaminations in the TPC gas (point B), filtered gas (point C), and the input gas mixture (point D) can be measured with two pairs of $\text{O}_2$/H$_2$O sensors. Gas purities of 2–5 ppm oxygen and about 20–100 ppm water are typically achieved.

The gas circulation is typically started on 1–2 weeks before the start of detector operation. First, the detector is flushed with fresh gas for 2 days in the purge mode. Due to limited precision of the input flow meters the gas mixtures needs several days to stabilize after purge. The drift velocity approaches a stable value exponentially with a time constant of approximately 28 hours for the VTPCs and 35 hours in the case of the MTPCs (Fig. 15).

The drift velocity decreases by about 1% after purge which is attributed to out-gassing of the detector material. This is compensated by a slight increase of the argon content.
Figure 15. (a) Drift velocity after purge measured for VTPC-1 (circles) and VTPC-2 (squares). The curves show the exponential dependence fitted to the data. (b) Change of the drift velocity in the MTPCs after the reduction of CO$_2$ contents by 0.1% at $t=0$. Note that the vertical scale is expanded by a factor 2 with respect to the panel (a).

Also, when the water contamination increases, the drift velocity decreases; the effect is of order of 1% for the typical water content of several tens of ppm. The change is slow (about 0.0002 cm/$\mu$s per day) and is taken into account in the drift velocity calibration based on the drift velocity measurements.

The GAP-TPC with a volume of only about 150 l uses a much simpler system. About 20 l/h of fresh gas mixture is flushed through this detector. The gas coming out from the GAP-TPC is also passed through a drift velocity monitor.

The gas composition is Ar/CO$_2$ 90/10 in the VTPCs and GAP-TPC, and 95/5 in the MTPCs. The higher argon content in the MTPCs is required to obtain higher drift velocity necessary to read out the longer drift length. Typical drift velocities are 1.4 cm/$\mu$s in the VTPCs, 2.3 cm/$\mu$s in the MTPCs and 1.3 cm/$\mu$s in the GAP-TPC.

4.5 TPC Front End Electronics

contributors: Andras, Zoltan (Actually I moved the main text under DAQ section – AL)

The electron trace of the track ionization drifts in the electric field to the amplification plane of the TPCs, which is operated proportional amplification range. After passing through the gating grid and the cathode grid, the drifted electrons get amplified by gas
electron multiplication on the sense wires of the field and sense wire plane by order of \( \approx 5 \cdot 10^4 \). The disappearance of this amplified electron signal on the sense wires capacitively induces an opposite sign signal on the two-dimensionally segmented pad plane just behind the field and sense wire plane. Readout of the charge signal of the pads in consecutive short time intervals provides 3 dimensional information on the particle trajectories traversing the the TPCs. The electronic read-out of the pads is performed by the TPC Front End Electronics (FEE).

One FEE channel is dedicated to each readout pad, which pre-amplifies the signal and stores the analog charge of a given time sample in a capacitor array. Either 256 time slices with 200 ns time bins or 512 time slices with 100 ns time bins are used. The time sampling is driven by a global clock for the full TPC system in order to eliminate the relative phase shifts. 32 channels are handled by each FEE card, thus the full TPC system comprises about 6000 TPC FEE cards. After the analog charges are stored in the capacitor arrays their digitization is performed via a Wilkinson ADC on the card, and the digitized charge values are forwarded to the read-out electronics.

The TPC FEE system [27, 28] was inherited from NA49 along with the TPC system.

4.6 Physics performance

contributors: Antoni, Szymon

Several examples of the physics performance of the TPC system are presented in this section.

The quality of measurements was studied by reconstructing masses of \( K_S^0 \) particles from their \( V_0 \) decay topology. As an example the invariant mass distributions of \( K_S^0 \) candidates found in p+p interactions at 20 and 158 GeV/c are plotted in Fig. 16. The measured peak positions 497.4\( \pm \)0.6 and 498.5\( \pm \)0.1 MeV/c are in a reasonable agreement with the PDG value \( m_{K_S^0} = 497.6 \) MeV/c.

The track reconstruction efficiency and resolution of kinematic quantities were studied using a simulation of the detector. Estimates were obtained by matching of generated tracks to their reconstructed partners. As examples, the reconstruction efficiency as a function of rapidity and transverse momentum for negatively charged pions produced in p+p interactions at 20 and 158 GeV/c is shown in Fig. 17. The resolution of pion rapidity and transverse momentum measurements is illustrated in Fig. 18. The resolution was calculated as the r.m.s. of the distribution of the difference between the generated and reconstructed \( y \) and \( p_T \). These results were obtained for negatively charged pions passing the the standard event and track selection criteria.

The specific energy loss in the TPCs for positively (right) and negatively (left) charged particles as a function of momentum measured for p+p interactions at 80 GeV/c is shown in Fig. 19. Curves show parametrizations of the mean \( dE/dx \) calculated for different particle species.
Figure 16. Invariant mass distribution of reconstructed $K^0_S$ candidates selected within $0 < y < 2$ and $0.1 < p_T < 0.6$ [GeV/c] in p+p interactions at 20 (left) and 158 GeV/c (right). The fitted peak position is given in the legend.

Figure 17. The reconstruction efficiency of negatively charged pions produced in p+p interactions at 20 (left) and 158 GeV/c (right) as a function of pion rapidity and transverse momentum.

5. Time of Flight systems

Since particle identification based only on energy loss measurement proves not to be sufficiently precise (especially for kaons), NA61/SHINE also uses additional and independent particle identification by Time of Flight (ToF) detectors. The ToF-L and ToF-R detectors were inherited from NA49. In order to extend the identification of NA61/SHINE to satisfy neutrino physics needs, a new forward detector (ToF-F) was constructed. It is placed between the ToF-L/R, just behind the MTPCs.
Figure 18. The resolution of rapidity (top, scaled by $10^3$) and transverse momentum (bottom) measurements for negatively charged pions produced in p+p interactions at 20 (left) and 158 GeV/c (right) as a function of pion rapidity and transverse momentum.

5.1 ToF-L, ToF-R

contributors: Jovan, text updated

Two walls, ToF-L(left) and ToF-R(right), of 4.4 m$^2$ total surface (see Fig. 20) are placed behind the MTPCs. The length of flight paths of particles produced in the target are about 14 meters. Each wall contain 891 individual scintillation detectors with rectangular dimensions, each having a single photo-multiplier tube glued to the short side. The scintillators have a thickness of 23 mm matched to the photo-cathode diameter, a height of 34 mm and horizontal widths of 60, 70 or 80 mm, with the shortest scintillators positioned closest to the beamline and longest on the far end. The operating voltage for the PMTs in the ToF-L is about 1600 V and in the ToF-R is around 1300 V. For the ToF-L photo-multiplier signals enter constant-fraction discriminator modules (CFD, KFKI custom made), housed in VME crates (WIENER) where the analog signals are split. One output is then passed to
Figure 19. The specific energy loss in the TPCs for positively (right) and negatively (left) charged particles as a function of momentum measured for p+p interactions at 80 GeV/c. Curves show parametrizations of the mean $dE/dx$ calculated for different particle species.

FASTBUS analog-to-digital converters (96 channel ADC LeCroy 1885F) while the other is sent to the CFD modules and then to time-to-digital converters (64 channel FASTBUS TDC LeCroy 1775A). For ToF-R the PMT signals are first split, then one line is sent to an ADC (96 channel ADC LeCroy 1882F) while the other line goes into a FASTBUS CFD (Struck DIS Str138) followed by a TDC (64 channel FASTBUS TDC LeCroy 1772A). The start signal for the TDCs is provided by the S11 PMT of the upstream S1 beam counter (scintillator) while the stop signal comes from the CDFs if their input is above a threshold.

The calibration procedure is based on extrapolation of the tracks reconstructed in the MTPCs into the area of the ToF detectors, identifying scintillators they extrapolate to and checking for appropriate signals in the corresponding TDC and ADC channels. Afterwards detailed corrections are performed depending on charge deposition and relative position of the incident particle in each scintillator. Corrections for the position of the main interaction (in case of thick targets) and position of the beam particle in the S1 counter are also done.

The overall time resolution of the ToF-L/R system is estimated based on the distribution of the differences between the measured time-of-flight for particles identified as pions and that predicted from the measured momentum and trajectory assuming the pion mass. The distribution can be described by a Gaussian where, in p+p and Be+Be collisions, a standard deviation of 95 ps was observed for TOF-L, while a standard deviation of 80 ps was observed for TOF-R. This value for the time resolution includes all contributions to the tof measurement (start detector, lengths of cables, uncertainties in tracking, etc. as well as intrinsic detector resolution).
This resolution allows to separate pions and kaons for momenta up to 3 GeV/c (up to 5 GeV/c if tof information is used along with dE/dx information) and pions and protons for even higher momenta. Figure 21 (top, left) shows mass squared as a function of particle momentum for p+p interactions at 80 GeV/c. The resulting resolution in $m^2$ is plotted as a function of momentum in Fig. 21 (bottom, left).

Due to aging of the electronics two upgrades are foreseen. The HV supply will be partially replaced and an upgrade of the readout electronics is planned. This should, modernize the whole system, ensure its long term functioning, and also improve the quality of the obtained tof information, primarily the resolution.

5.2 ToF-F

contributors: Sandro, Sebastien

The NA61/SHINE data taking for the T2K neutrino oscillation experiment requires particle identification in a phase space region which is not covered by the ToF-L/R. When operating at the T2K proton beam at 31 GeV/c, a large fraction of the tracks are produced by low-momentum particles which exit the spectrometer between the ToF-L and ToF-R. An extra time of flight detector, the forward ToF (ToF-F), was therefore constructed to provide full time of flight coverage of the downstream end of the MTPCs (see Fig. 1).

The ToF-F consists of 80 scintillator bars oriented vertically (see Fig. 22). The bars were tested and mounted in groups of 10 on independent frames (modules) out of which half were placed on the left side and half on the right side of the detector in order to match the left/right symmetry. The size of each scintillator is $120 \times 10 \times 2.5$ cm$^3$. They are staggered with 1 cm overlap to ensure full coverage in the ToF-F geometrical acceptance. This configuration provides a total active area of $720 \times 120$ cm$^2$. Each scintillator bar is
Figure 21. *Top:* Mass squared versus momentum measured by ToF-L/R (*left*) and ToF-F (*right*) detectors for particles produced in p+p interactions at 80 GeV/c. The lines show the expected mass squared values for different hadrons. *Bottom:* The resolution of the $m^2$ measurement as a function of particle momentum for the ToF-L/R (*left*) and the ToF-F (*right*).

read out on both sides with 2” photo-multipliers (PMT) Fast-Hamamatsu R1828, for a total of 160 read-out channels. The scintillators are plastic scintillator (*Bicron BC-408*) with a scintillation rise time of 0.9 ns, a decay time of 2.1 ns and attenuation length of 210 cm. Their maximal emission wavelength is about 400 nm perfectly matching the PMT spectral response. Fish tail PMMA (Poly methyl methacrylate) lightguides were glued on both ends for the readout. The bars and lightguides were wrapped in aluminium foils to ensure light reflection towards the light-guide and covered with black plastic foils and tape. In order to ensure proper optical contact between the PMTs and the lightguides a 3 mm thick silicone cylinder matching the diameter of the PMT and lightguide is inserted at the interface.

Most of the electronics for the ToF-F were inherited from the two NA49 Grid ToFs [29] which were removed since their acceptance coverage is marginal for the T2K runs. Each PMT channel is operated near 1700 V supplied by LeCroy1461 independent 12-channel high voltage (HV) cards. The analog signals are transported from the ToF to the counting house by 26 m RG58 50Ω coaxial cables. To obtain fast logic signals and not be influenced
by the variations in amplitude of the PMT response the cables are plugged into Constant Fraction Discriminators (16-channel KFKI CFD5.05 VME module). At the input these include an internal passive divider of 1:3 to provide the signals for the integrated charge and time measurements, respectively, and the necessary delay lines at their output. In order to minimize the crosstalk of the neighboring channels an appropriate order is chosen between the PMT outputs and the CFD inputs. The output signals of the CFDs of the PMT-channels serve as “stop” signals for the time of flight measurements. The start signal is provided by the fast beam counter S1 of the central trigger system. The time measurement is carried out by LeCroy FASTBUS Time-to-Digital Converter (TDC) units digitizing the time in 12 bits dynamic range with a sampling time of 25 ps. The analog signals of the PMTs are converted by LeCroy Analog-to-Digital Converter (ADC) units into 12 bits. The time measurement, \( t \), has an offset, \( t_0 \), which is specific to each channel as it depends on cable length, PMT gain or CFD response. \( t_0 \) was therefore carefully adjusted on a channel by channel basis by first assuming that all produced particles are pions and shifting the mean value of the \( t - t_\pi \) distribution accordingly. In a first iteration, this method allows to discriminate pions from protons and was then repeated by selecting only pions.

The particle’s mass squared is obtained by combining the information from the particle’s time of flight, \( t_{of} \equiv t - t_0 \), with the track length, \( l \), and momentum, \( p \), measured in the TPCs:

\[
m^2 = p^2 \left( \frac{c^2 t_{of}^2}{l^2} - 1 \right)
\]

The mass-squared distribution and the resolution of its measurement as a function of

Figure 22. The schematic layout of scintillators in the ToF-F detector.
momentum are presented in Fig. 21 (right). The intrinsic resolution of the ToF-F was also determined (see Fig. 23). This was achieved by selecting particles that hit the region where the scintillators overlap and plotting the time difference between the two signals. The Gaussian fit to the distribution gives a resolution \( \sigma_{\text{tof}} = \frac{155}{\sqrt{2}} \approx 110 \text{ ps} \).

![Distribution of the difference between a particle’s time-of-flight measured independently by the overlapping scintillator bars of the ToF-F detector. The width of the distribution is about 155 ps, indicating a tof resolution of about 110 ps for a single measurement.](image)

**Figure 23.** Distribution of the difference between a particle’s time-of-flight measured independently by the overlapping scintillator bars of the ToF-F detector. The width of the distribution is about 155 ps, indicating a tof resolution of about 110 ps for a single measurement.

### 6. Projectile Spectator Detector

*contributors: Fedor, Sasha*

The development and construction of the forward hadron calorimeter was one of the most important upgrades of the NA61/SHINE experimental setup. This calorimeter is called the Projectile Spectator Detector (PSD). The purpose of the calorimeter is the measurement of projectile spectator energy in nucleus-nucleus collisions. The PSD is used to select central (with a small number of projectile spectators) collisions at the trigger level. Moreover, the precise event-by-event measurement of the energy carried by projectile spectators enables the extraction of the number of interacting nucleons from the projectile with the precision of one nucleon. The high energy resolution of the PSD is important for study of fluctuations in nucleus-nucleus collisions which are expected to be sensitive to properties of the phase transition between the quark-gluon plasma and hadron-resonance matter. Namely, the PSD provides the precise control over fluctuations caused by the variation of the number of interacting nucleons and thus excludes the "trivial" fluctuations caused by variation of the collision geometry. Basic design requirements of the
PSD are good energy resolution, $\sigma_E/E < 60\%/\sqrt{E\text{(GeV)}}$, and good transverse uniformity of this resolution. The PSD is a fully compensating modular lead/scintillator hadron calorimeter [30, 31] and meets these requirements.

6.1 Calorimeter design

The PSD calorimeter consists of 44 modules which cover a transverse area of 120x120 cm$^2$. A schematic front view of the PSD is shown in Fig. 24 (left). The central part of the PSD consists of 16 small modules with transverse dimension of 10x10 cm$^2$ and weight of 120 kg each. Such fine transverse segmentation decreases the spectator occupancy in one module and improves the reconstruction of the reaction plane. The outer part of the PSD consists of 28 large 20x20 cm$^2$ modules with a weight of 500 kg each.

Figure 24. The NA61/SHINE PSD: schematic front view (left), schematic view of single module (center) and the fully assembled detector (right).

Each module, schematically shown in Fig. 24 (center), consists of 60 pairs of alternating lead plates and scintillator tiles with 16 mm and 4 mm thickness, respectively. The stack of plates is tied together with 0.5 mm thick steel tape and placed in a box made of 0.5 mm thick steel. Steel tape and box are spot-welded together providing appropriate mechanical rigidity. The full length of the modules corresponds to 5.7 nuclear interaction lengths.

Light readout is provided by Kyraray Y11 WLS-fibers embedded in round grooves in the scintillator plates. The WLS-fibers from each 6 consecutive scintillator tiles are collected together in a single optical connector at the end of the module. Each of the 10 optical connectors at the downstream face of the module is read out by a single photodiode. The longitudinal segmentation into 10 sections ensures good uniformity of light collection along the module and delivers information on the type of particle which caused the observed particle shower. Ten photodetectors per module are placed at the rear side of the module together with the front-end electronics. A photograph of the fully assembled calorimeter is shown in Fig. 24 (right). In order to fit the PSD transverse dimensions to the region populated by spectators the distance between the NA61 target and the calorimeter...
is increased from 17 m to 23 m with increasing collision energy. Interactions of spectators upstream of the PSD were minimized by the installation of a helium tube of length 5.5 m and diameter 125 cm between the upstream PSD face and the hut housing the MTPCs. The entrance and exit Mylar windows of the tube had a thickness of about 125 µm. This tube in data taking with ion beams at momenta larger than 40 A GeV/c when the distance between the target and the PSD was 23 m.

6.2 The PSD photo-detectors

The longitudinal segmentation of the calorimeter modules requires 10 individual photo-detectors per module for the signal readout. Silicon photomultipliers SiPMs or micro-pixel avalanche photodiodes, MAPDs [32, 33] are an optimum choice due to their remarkable properties such as high internal gain, compactness, low cost and immunity to the nuclear counter effect. Moreover, forward hadron calorimeter applications have some specific requirements such as large dynamical range and linearity of the photodetector response to intense light pulses. However, the dynamic range and linearity of MAPDs are limited by the finite number of pixels. Most of the existing types of MAPD with individual surface resistors have a pixel density of $10^3$ pixels/mm$^2$. Such a limited number leads to serious restrictions of MAPD applications in calorimetry, where the number of detected photons is comparable and even larger than the pixel number. The effect of saturation, when a few photons hit the same pixel, leads to significant non-linear MAPD response to light pulses with high intensity. Evidently, the MAPD has linear response only if the number of pixels is much larger than the number of incident photons. This feature represents a disadvantage of MAPDs compared to the traditional PMTs. However, this drawback is essentially reduced for MAPDs with individual micro-well structure [32], for which a pixel density of $10^4$/mm$^2$ and higher is achievable. The above considerations motivated the choice of photo-diodes of type MAPD-3A produced by Zecotek Photonics Inc. (Singapore) [33] for the readout of the PSD hadron calorimeter. These MAPDs have a pixel density of 15000/mm$^2$. Their 3x3 mm$^2$ active area fits well the size of the WLS-fiber bunch from one longitudinal section of the PSD modules and provides a total number of pixels of more than $10^5$ in a single photodetector.

The MAPD-3A photon detection efficiency (PDE) for the Y11 WLS-fiber emission spectrum reaches 15 % at 510 nm and is similar to the performance of PMTs. The operation voltage for different samples of MAPD-3A detectors ranges from 65 V to 68 V. The maximum achieved gain is $4 \times 10^4$, see Fig. 25 (left).

Since the PSD calorimeter has no beam hole to ensure maximum acceptance for the spectators, the central part of the PSD will be irradiated by ion beams with intensities up to $10^5$ Hz. Therefore, an important requirement for the calorimeter readout is a high count rate capability, at least in the central region. Here, the average amplitude in one longitudinal section of a PSD module is expected to be about 1500 photoelectrons. In other words, the recovery time of the selected MAPD-3A photodiode must be fast enough to deliver stable amplitudes at signal frequencies up to 100 kHz. To check the count rate ca-
pability of the MAPD-3A the dependence of its amplitude on the frequency of light pulses was measured. The stability of the amplitude of the pulses at different operation frequencies of the light emitting diode was checked by a normal PMT. The obtained behavior of the amplitude produced by the MAPD-3A is presented in Fig. 25 (center). As seen, the MAPD-3A amplitude would drop about 5% for the maximum beam intensity foreseen in the NA61/SHINE experiment.

In order to check the photodetector linearity, measurements of MAPD amplitudes were performed with light pulses of different intensity. The number of incident photons was determined by a reference photodiode with known quantum efficiency and gain equal to one. The dependence of the MAPD amplitude on the number of incident photons is shown in Fig. 25 (right). As seen, the MAPD linearity is preserved for light pulses with numbers of photons up to $6 \times 10^4$. Taking into account the different photon detection efficiencies of about 25% for the tested MAPD (with the same pixel density as the MAPD-3A type) and 15% for the MAPD-3A) linear response is expected for amplitudes up to 15000 photo-electrons.

The reported comprehensive studies confirm that the selected MAPD-3A photodetectors satisfy the requirements of the NA61/SHINE experiment. At present, 440 MAPD-3A detectors are installed in the 44 PSD modules and show stable operation during data taking for calibration and physics with beryllium and proton beams.

6.3 Performance of the PSD calorimeter

In order to check the performance of the calorimeter, several tests were performed with hadron beams of various momenta. During the first stage of the R&D (in 2007) a PSD module array of nine small modules ($3 \times 3$ array) was assembled and tested in the H2 beamline using hadron beams of 20-158 GeV/c momentum. The calibration of all readout channels was done with a muon beam. The energy resolution of the tested array was estimated from data taken with the hadron beams.

The dependence of the measured energy resolution on the pion energy is shown in Fig. 26 (left).
The tested prototype with $30 \times 30 \text{ cm}^2$ transverse size is too small to contain the entire hadron shower. Therefore, a non-negligible lateral shower leakage is expected. Monte Carlo simulations confirm that about 16% of hadron shower energy escapes from the tested array. The influence of shower leakage on the energy resolution was considered in Refs. [34, 35], where a third term in addition to the stochastic and constant terms was added in the parameterization of the resolution. The fit of the experimental data with the three-term formula, assuming a fixed leakage term of 16%, gives the coefficient of the stochastic term equal to 56.1% and of the constant term equal to 2.1%. The non-zero constant term might be an indication that the selected lead/scintillator sampling does not provide full compensation.

The spectrum of deposited energy in the first section of the central module exposed to the 30 GeV/c beam is shown in Fig. 26 (right). The right-side peak in the spectrum corresponds to full positron energy absorption in the first longitudinal section which can be regarded as an electromagnetic calorimeter with rough sampling. The energy resolution for positrons at 30 GeV/c is about 6.5%.

During the 2011-2013 data taking for $^7\text{Be} + ^9\text{Be}$ collisions the PSD was also used in the trigger for online rejection of the most peripheral events. As a secondary $^7\text{Be}$ beam was used other ions were also present in the beam. The distribution of the energy deposited in the calorimeter by 75A GeV/c beam ions is shown in Fig. 27 (left) without cut (red) and with cut (blue) on the $^7\text{Be}$ peak in the amplitude distribution of the Z-detector. Clear identification of Be ions in the fragmented beam is seen here as well as contamination of deuteron and helium ions. Figure 27 (right) shows the PSD energy spectra recorded during the data taking for $^7\text{Be} + ^9\text{Be}$ collisions at 75A GeV/c. Spectra are shown for the beam trigger (blue) and interaction trigger (red).

Figure 28 (top) shows the measured energy of 158 GeV/c protons as a function of the module number on which at which the beam was centered. Histograms and curves in Fig. 28 (top) distinguish different energy reconstruction methods by color. Red corre-
Figure 27. Left: PSD energy distributions for the secondary ion beam at 75A GeV/c with and without selection of the $^7$Be ions by the Z-detector. Right: PSD energy distributions recorded during the data taking for $^7$Be+$^9$Be interactions at 75A GeV/c. Spectra are shown for the beam trigger (blue) and for the interaction trigger (red) events.

 corresponds to the energy sum of all PSD modules, while blue is for the sum of the corresponding clusters of modules around the beam spot. As seen, the mean values of reconstructed energies are close to the real beam energy in both cases.

Figure 28. Mean values of reconstructed incident 158 GeV/c proton energy in the PSD modules (topleft) and distributions of mean values for the 44 modules (topright). Energy resolution for 158 GeV/c protons (bottom left) and distributions of resolution for the 44 modules (bottomright).

Figure 28 (bottom) presents the energy resolution obtained for each of the 44 modules from the scan with 158 GeV/c protons. The small variations in the energy resolution could be explained by the precision of the energy calibration. These results are fully consistent
with the prototype tests and with the MC simulations.

7. Targets and other subsystems

The targets used by NA61/SHINE are positioned upstream of the VTPC-1 and centered at $z \approx -581$ cm.

7.1 Targets

contributors: Zoltan, Sandro (LT), Andras (LMPD)

For data taking on p+p interactions the liquid hydrogen target (LHT) of 20.29 cm length (2.8% interaction length) and 3 cm diameter was placed 88.4 cm upstream of the VTPC-1. The target was filled with para-hydrogen obtained in a closed-loop liquefaction system which was operated at 75 mbar overpressure with respect to the atmosphere. At the atmospheric pressure of 965 mbar the liquid hydrogen density is $\rho_{LH} = 0.07$ g/cm$^3$. The boiling rate in the liquid hydrogen was not monitored during the data taking and thus the liquid hydrogen density is known only approximately. Data taking with inserted and removed liquid hydrogen in the LHT was alternated in order to calculate a data-based correction for interactions with material surrounding the liquid hydrogen. The density of gaseous hydrogen $\rho_{GH}$ present in the target after removal of liquid hydrogen was estimated from the ratio of high multiplicity events observed in a small fiducial volume around the target center for data taken with inserted and removed liquid hydrogen. The density ratio $\rho_{GH}/\rho_{LH}$ varied within the range 0.4-0.6%. This indicates that the operational conditions of the LHT varied during the data-taking period.

For data taking on $^7$Be+$^9$Be collisions in the period 2011-2013 two beryllium targets were used. Their density was $\rho = 1.85$ g/cm$^3$ at 20°C and dimensions $2.5(W) \times 2.5(H) \times 1.2(L)$ cm$^3$ and $2.5(W) \times 2.5(H) \times 0.3(L)$ cm$^3$. The targets consisted of more than 99.4% $^9$Be. The most abundant contaminant were oxygen nuclei (about 0.4%). The Be targets were placed in an aluminium container filled with helium gas.

For data taking on p+Pb collisions a special thin Pb target plate was used in order to reduce in-target absorption of slow protons which are used for event centrality tagging. Two different target thicknesses, 0.5 mm and 1 mm, were used to allow an experimental study of in-target absorption of slow protons. The transverse shape of the target was circular, with a diameter of 1 cm. The target material purity was 99.98% lead with natural isotope composition (52.4% $^{208}$Pb, 22.1% $^{207}$Pb, 24.1% $^{206}$Pb, 1.4% $^{204}$Pb). The target density was 11.34 g/cm$^3$ at 20°C with a molar mass of 207.2 g/mol. The target plate was placed in a Tedlar [23] foil container filled with atmospheric pressure helium gas in order to reduce background of off-target collisions in the vicinity of the target. The target was removable from the beamline using a pneumatic piston for taking target-out reference data in order to estimate off-target background.
Two different graphite targets were employed by NA61/SHINE in the two kinds of hadro-production measurements of interest for the T2K neutrino oscillation experiment in Japan. The thin target of dimensions $2.5(W) \times 2.5(H) \times 2(L)$ cm$^3$ and density $\rho = 1.84$ g/cm$^3$ was used to extract information about primary interactions of protons on carbon. The thickness of this target along the beam axis is equivalent to about 4% of a nuclear interaction length ($\lambda_I$). The thin C target was placed in the aluminium container filled with helium gas.

The second graphite target is a replica of the T2K target used in Japan. It consists of a 90 cm long rod with a radius of 1.3 cm and a density of $\rho = 1.83$ g/cm$^3$. The replica and the actual target of T2K are shown by the drawings in Fig. 29. The upstream part of the graphite target is surrounded by aluminium flanges which are inserted into a target holder. Three screws in the target holder allow to align the target parallel to the beam axis. The target thickness along the beam axis is equivalent to about 1.9 interaction lengths. The downstream face of the replica target was placed at around 50 cm from VTPC-1. Hadro-production measurements taken with the T2K replica target allow to constrain primary and secondary interactions within the target.

![Figure 29. Technical drawing (side view) of the replica target used during the NA61/SHINE data taking (left) consisting of a 90 cm long graphite rod and aluminium support flanges. Drawing of the complete geometry of the T2K target (right). The overlaid red rectangle represents the simplified geometry of the replica target.](image)

7.2 Low Momentum Particle Detector

contributors: Andras

In hadron-nucleus interactions the collision centrality can be deduced from the number of emitted low momentum protons (the so-called grey protons). For this purpose a special detector, the Low Momentum Particle Detector (LMPD), was developed. The detector consists of two small size TPC chambers on the two sides of the target with a vertical drift field, and a sequence of detection layers picking up the ionization signal of radially emitted particles. Between the detection layers plastic absorber layers are inserted. Therefore the range of particles in the detector material can be determined. The range and energy loss by ionization of a particle depends on its energy and type, and therefore event-by-event
counting of the number of emitted low energy protons becomes possible. Prototypes of the detector were tested in 2009 and 2010.

The final version of the LMPD, see Fig. 30, was manufactured in 2011, and was first tested in the NA61/SHINE experimental area, downstream of the NA61/SHINE detector, in parasitic mode. The tests showed the expected performance of the detector, namely its capability of proton identification and of counting the low energy (grey) protons. A typical raw event overlayed with its reconstructed clusters and tracks is seen in Fig. 31 (left). The ionization produced by particles with fixed range is shown in Fig. 31 (right). The broad peak corresponds to the signal of protons with a selected penetration range. The cluster reconstruction uses a closest neighbor search algorithm, while the track reconstruction uses Hough transform combined with maximum likelihood principle for pattern recognition.

![Figure 30. Left: Schematic top view of the LMPD. Red lines indicate the absorber layers. Each absorber layer is placed between sensitive layers in order to determine whether a given particle from the target traversed the absorber layer or stopped inside the absorber. Right: Front view photograph of the LMPD detector from the direction of the beam at the NA61/SHINE target position. The Pb target is located in the center of the picture. The thin Tedlar foil He container tube surrounding the target is not shown as it was removed in order to make the target plate well visible. The field cage strips (copper strips on capton) of the LMPD are also visible. Standard NA61/SHINE TPC front-end electronics were used for readout (on top).](image)

The main operational parameters of the LMPD were optimized during the 2011 test operation. In particular, a gradual decrease of amplification in the layers close to the target was introduced. This is necessary in order to adjust the dynamical range for the expected highly ionizing particles. After optimization, large statistics physics-quality data were recorded in parasitic mode, still in the position downstream of NA61/SHINE. They allow a systematic study of gray proton production and absorption in the target material. During the last 3 days of the 2011 NA61/SHINE 158 GeV/c p+p run, the LMPD was mounted at the normal target position of NA61/SHINE, and preliminary physics-quality p+Pb data were recorded with the LMPD integrated into the full NA61/SHINE detector for final run parameter tests. Then, in 2012 large statistics 158 GeV/c p+Pb physics data were taken.
Figure 31. Left: Raw event display of the LMPD for a typical 158 GeV/c p+Pb collision, overlayed with the reconstructed clusters and tracks. Green color indicates the raw energy deposit (ADC), red points indicate the position of the reconstructed clusters, blue lines depict the straight particle tracks fitted to the clusters. The particle tracks point to a common production vertex within the target. Right: Energy deposit of particles traversing the first absorber, but stopped within the second absorber layer. The wide peak in the middle corresponds to the expected response of protons.

with the LMPD around the target, providing detection and tagging of grey protons and thus characterizing the event centrality of p+Pb collisions.

8. Data acquisition and detector control systems

8.1 Read-out electronics and DAQ

contributors: Andras

The readout electronics consists of three main parts: the electronics responsible for reading out the TPC FEEs, the electronics for reading out the FASTBUS based ToF system, and the electronics for reading out the CAMAC based beam detectors (Fig. 32).

In case of the TPC system, the FEE cards only host pre-amplifiers, shapers, and time sampling capacitor arrays for 32 channels, along with ADCs. The necessary commanding logic is managed by the readout Mother Boards, which transmit the necessary clock signals to steer the time sampling, ADC conversion and data transmission process. The FEE cards produce a 9 bit ADC value for each time slice of each TPC pad. These are pedestal subtracted, noise suppressed and zero compressed on the Mother Board. The 250 Mother Boards, which are capable of serving 24 FEE cards, were implemented using Cyclone II FPGA (EP2C35F672) arrays and SRAM units for pedestal table storage. Upon an event trigger, which is fanned out to all Mother Boards, the time sampling with subsequent digitization begins on the FEE cards, after which the ADC values are read out and
processed on the fly by the Mother Boards with polling. The processed data stream is serialized onto a ground-independent LVDS connection line toward the Concentrator Boxes, which can receive data from 32 Mother Boards. These boxes act like further serializers and are implemented on Cyclone II FPGA (EP2C20F484) arrays. In order to ensure galvanic ground independence for the long-distance transfer, the DDL optical transfer line is used from this point to the Central DAQ PC. The data reaches the Central DAQ in push-data mode, i.e. the data stream is triggered by the lower level electronics and not via the Central DAQ. Upon the arrival of the first data headers at the Concentrator Box level, a Busy signal is issued as a feedback to the trigger electronics.

The ToF system uses legacy front-end electronics based on FASTBUS technology. The readout of the beam-related detectors (Beam Position Detectors, beam counter pattern units, scalers, ADCs and TDCs) is based on traditional CAMAC units. A FASTBUS-to-VME bridge and a CAMAC-to-VME bridge, makes connection to VME crates dedicated to ToF and CAMAC readout, respectively. In each of these two VME crates a FIC8234 processor-based controller runs a low level OS9 based software as low level DAQ. As the processors are capable of receiving external signals as interrupt, the latter are used to

Figure 32. The overview of the three main parts of the NA61/SHINE readout system: TPC readout, ToF readout and CAMAC readout of beam detectors.
initiate low level data taking. The measurement units are triggered by the experiment’s accurate pre-trigger signal, but the measurement data are only read out if this is confirmed by the main-trigger signal within the time-out limit. In that case an interrupt is passed to the FIC8234 controllers to initiate readout. These transfer the data via the bridges to a MM6390 memory unit in the VME crate. The received data are stored in a ring buffer overwriting older data and a trigger counter is incremented. Meanwhile the Central DAQ polls for the incrementation of the trigger counter, and the new events are drained via a CAEN V1718 VME-to-USB bridge to the Central DAQ’s ring buffer. Feedback and control to the Busy logic is performed via RCB8047 CORBO register units in the pertinent VME crates.

The readout of the PSD, is designed along the principles of the TPC readout, and acts similarly to the Mother Boards in the TPC read-out system. Due to the push-data mode philosophy, the event data in the different hardware channels arrive at the Central DAQ software asynchronously. The synchronization is performed via trigger counters in the sub-events on the final event-building level. For periodic checks the data stream is halted each minute, the data pipelines are drained and the trigger counter synchronicity is verified. In addition, the Busy signal of each hardware channel is monitored via a custom made galvanically isolated TTL to RS232 register in order to make sure that the event stream is never halted due to a stuck Busy signal caused by a hardware failure.

The Central DAQ software runs on a single Central DAQ PC (X7DB8-X motherboard, 64 bit, total 8 cores of Intel Xeon CPU @ 2 GHz, 8 GB memory, 10 PCI-X slots, 4 USB ports, and a serial port). The main components of the software are listed below.

(i) The GUI script written in Tcl/Tk language.
(ii) The actual Central DAQ itself which is written in C and can be used also without GUI. Its user interface is a command line interpreter written using the GNU libreadline library.
(iii) Upon program start a second process, the event server, is created for event monitoring. This is a fork-server serving up to 16 monitoring clients.
(iv) Upon run start the following processes are created:

   (i) The logger and monitoring / consistency checking process.
   (ii) The communication unit with the trigger system for summary information. This periodically gets scaler status information from the trigger server.
   (iii) The communication unit with the DCS system for summary information. This periodically gets information from the DCS server.
   (iv) The recorder process building the event, writing to disk and forwarding to the above event server upon request. This starts the following two processes for efficient parallelization of data receiving.
(i) The receiver process for the DDL channels. This looks for data on any DDL channel on a first-come first-served basis.

(ii) The receiver process for the VME channels. This looks for data on any VME channel on a first-come first-served basis.

The GUI and the command line interpreter communicate via standard Unix pipes and log files. The processes of the forked C program communicate via Linux shared memory. The data itself gets read into a special fast shared memory, called Physmem, outside the reach of the Linux kernel. Physmem is mapped by a special Linux kernel module shipped with the DDL libraries.

The central DAQ software is completed by a system of failure-tolerant scripts with checksum and size verification, which move the recorded data after consistency and Quality Assessment check onto the tape system of CASTOR.

8.2 Detector Control System

contributors: Wiktor, Krzysztof, Tobiasz

The NA61/SHINE Detector Control System (DCS) is responsible for on-line monitoring and controlling of the working conditions of the detectors.

The system monitors parameters of the gas mixture in the TPCs (temperatures, pressure, flow, water and oxygen content, drift velocity, amplification, etc.). It also sets and monitors parameters of the high voltage in the sub-detectors: LMPD, TPCs, BPDs and the beam counters. The system also controls low voltage power supplies of the front-end electronics and enables its cooling.

The block diagram of the DCS is shown in Fig. 33. Although the system logically
consists of the following subsystems:

(i) Gas,

(ii) High Voltage,

(iii) Low Voltage,

(iv) PSD,

the main part of the system is one EPICS-based [38] measurement server distributed over a few PCs. It communicates with various hardware (CAMAC, VME, PLC, etc.) via various interfaces (RS232, Caenet, TCP/IP, GPIB, etc.), performs all the measurements and makes the results accessible for the clients via the Channel Access protocol. The server runs constantly regardless of the presence of the clients or the database availability.

All measured data is stored in the relational database (PostgreSQL) by one of the EPICS clients. It can be accessed only via the Database Accessed Server by issuing ASCII commands.

There are two GUIs available. One of them, which controls the Measurement Server and monitors its performance, is an EPICS client and can be run only in the experimental area. The other one can be run anywhere and is graphically presenting results of measurements retrieved from the database.

9. Summary and outlook

NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a multi-purpose facility for the study of hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the CERN Super Proton Synchrotron.

NA61/SHINE has greatly profited from the long development of the CERN proton and ion sources and the accelerator chain as well as the H2 beamline of the CERN North Area. The latter has recently been modified to also serve as a fragment separator as needed to produce the Be beams for NA61/SHINE. Numerous components of the NA61/SHINE setup were inherited from its predecessors, in particular, the last one, the NA49 experiment.

This paper presented the facility - the beams and the detector system - up to March 2013, the start of the CERN Long Shutdown I. Special attention was paid to the presentation of the components which were constructed for NA61/SHINE. These are: the Projectile Spectator Detector, the Forward-ToF wall, the Low Momentum Particle Detector, the Z- and A-detectors, the Beam Position Detectors, the upgrade of the TPC readout and DAQ system, the Trigger System, the Detector Control System and the He-beam pipe. Moreover the upgraded CERN accelerator chain and the H2 beamline modified to serve as a fragment separator are described. The components inherited from the past experiments and
described elsewhere are presented only briefly. These are the Time Projection Chambers and their gas system, the two super-conducting magnets, the ToF-L/R walls as well as the beam and trigger counters.

The facility is being continuously upgraded and its physics goals are being extended [89]. Among NA61/SHINE upgrades under preparation are: construction of the Forward-TPCs and the Silicon Vertex Detector, upgrade of the ToF and PSD readout systems, upgrade of the ToF HV system and extension of the gas system.

This paper will be followed by further publications in which the already existing components of the NA61/SHINE facility will be presented in detail and the new ones will be described.

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