Prepared for submission to JINST

# The Forward TPC system of the NA61/SHINE experiment at CERN: a tandem TPC concept

---

**Brant Rumberger,[a] Antoni Aduszkiewicz,[c,†] Jan Boissevain,[a] Magdalena Kuich,[c] András László,[b] Yoshikazu Nagai,[a] László Oláh,[b,*] Piotr Podlaski,[c] Dezső Varga,[b] Martin Wensveen,[d] Eric D. Zimmerman[a]**

[a] *University of Colorado Boulder, Boulder, USA*
[b] *Wigner Research Centre for Physics, Budapest, Hungary*
[c] *Faculty of Physics, University of Warsaw, Poland*
[d] *CERN, Geneva, Switzerland*
[*] Current address: *University of Tokyo, Tokyo, Japan*
[†] Current address: *University of Houston, Houston, USA*

*E-mail:* brant.rumberger@colorado.edu, antoni.aduszkiewicz@cern.ch, jgboissevain@comcast.net, magdalena.kuich@cern.ch, laszlo.andras@wigner.hu, yoshikazu.nagai@colorado.edu, olah.laszlo@wigner.hu, piotr.podlaski@cern.ch, varga.dezso@wigner.hu, martin.wensveen@cern.ch, edz@colorado.edu

Abstract: This paper presents the Forward Time Projection Chamber (FTPC) system of the NA61/SHINE experiment at the CERN SPS accelerator. This TPC system applies a novel tandem-TPC design to reduce the background originating from particle tracks not synchronous with the event trigger. The FTPC system is composed of three chambers with alternating drift field directions. The chambers were installed directly along the beamline region of the NA61/SHINE detector in a medium- to high-intensity (10 – 100 kHz) hadron or ion beam. The tandem TPC system has proved to be capable of rejecting out-of-time background tracks not associated with a primary interaction. In addition, the system performs tracking and inclusive $\mathrm{d}E/\mathrm{d}x$ particle identification for particles at and near the beam momentum. This shows that a tandem-TPC-based chamber design may be used also in other experimental applications with a demand for low material budget, tracking capability, and the need for $\mathrm{d}E/\mathrm{d}x$ particle identification, all while in the presence of a relatively high particle flux.

Keywords: Time projection chambers (TPC), Particle tracking detectors (Gaseous detectors), Large detector systems for particle and astroparticle physics

ArXiv ePrint: 2004.11358

## Contents

## 1 Introduction

NA61, also known as the SPS Heavy Ion and Neutrino Experiment (SHINE) [1], is a large-acceptance hadron spectrometer experiment that recieves beam from the CERN Super Proton Synchrotron (SPS). The original design of the NA61 tracking system, mainly optimized for heavy-ion physics, lacked full phase space coverage in the forward region. Complete coverage of this part of phase space is of particular importance to the neutrino area of the NA61 physics program, which provides hadron production measurements of neutrino ancestors to long-baseline neutrino oscillation experiments. Covering this missing region of phase space with a tracking detector capable of performing particle identification is crucial for making accurate neutrino flux predictions for such experiments.

In this paper, we describe a time projection chamber (TPC) detector system used for instrumenting this missing region of phase space of the NA61 experiment. Since this missing region encompasses the beam, and since not all beam particles result in a physicswise interesting event, the separation of the true in-time tracks from the out-of-time particle tracks (not synchronous to the interaction trigger) becomes essential.[1] In order to address the recognition of out-of-time tracks, a TPC concept was proposed consisting of separate drift volumes with alternating drift field directions. We call this the *tandem-TPC* concept. The idea is illustrated in Figure 1. Specifically, our design incorporates three separate consecutive TPCs (plus a fourth that already existed) with alternating drift fields. The chambers are collectively referred to as the Forward Time Projection Chambers (FTPCs), as they cover the most forward region of the phase space of the NA61 experiment.

---

[1] We call a particle *in-time* if it originates from the interaction on which the event was triggered. A particle is called *out-of-time* if it originates from a previous collision, not synchronous to the interaction trigger, and therefore ideally should be rejected or tagged. Since TPC chambers in general are intrinsically relatively slow devices, with a typical total drift time of the order of a few 10 $\mu$secs, TPC chambers close to the beam region are generally contaminated with out-of-time tracks if the beam intensity is not very low.

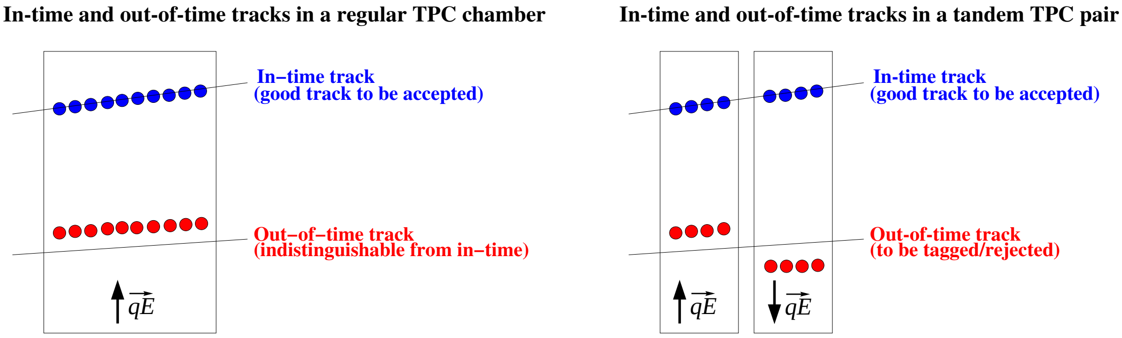

**Figure 1**. (Color online) Illustration of the tandem-TPC concept. Left panel: in a regular TPC, in-time tracks and the out-of-time particle tracks are indistinguishable. Right panel: in a tandem-TPC pair the drift directions ($q\vec{E}$) are not the same in the two drift volumes, and therefore the segments of an out-of-time particle track already start to drift apart by the time of the arrival of the interaction trigger. Thus, by their discontinuity, the out-of-time particle tracks become distinguishable from true in-time tracks.

Due to a relatively long total drift time (~50 $\mu$sec) of the TPC chambers, and a beam intensity of 10 – 100 kHz, the presence of out-of-time particles is rather common in a typical NA61 event. These out-of-time particles can be of any species, as the SPS beam used is typically secondary in nature. Out-of-time particles are not subject to the NA61 particle identification criteria during triggering, and thus can introduce bias in analyses.

The NA61 FTPCs satisfy additional design constraints imposed by the multi-purpose nature of the experiment. In order to preserve the data taking environment for the NA61 heavy-ion program, the FTPCs were constructed using a novel low material budget technique, using etched copper-coated polyimide film for the field cages. The film is coated with copper on one side only, resulting in only 0.3 % radiation lengths of material. In order to maintain a low oxygen contamination within the active volume, an additional thin Mylar foil wall envelopes the field cage from the outside. The two foils provide a buffer volume, which is flushed by the exhaust gas in order to reduce the diffusion from the air into the active volume. This design minimized the gap between these two walls, in order to use the available detector space economically.

Using TPCs with opposite drift direction has been successfully applied earlier for small TPC systems in high rate environments. The Sextant [2] was a high precision tracking component, proposed to be part of the KABES upgrade of the CERN NA48 experiment, using a Micro-mesh readout plane. The “Twin-configuration GEM TPC” [3], with similar geometry as Sextant but using GEM on the readout plane, was designed for beam particle tracking from protons up to uranium ions. The present paper demonstrates that the “tandem-TPC” concept can be used not only for large TPCs, but also in a more general setting, having TPCs of different sizes and geometries, and with different drift velocities. The specific choice presented in this paper, as discussed above, was guided by the general environment of the NA61 detector.

## 2 The NA61/SHINE experimental facility

The NA61/SHINE detector is a multi-purpose fixed-target hadron spectrometer [1] at the CERN SPS accelerator. Large parts of its main tracking devices were inherited from a previous experiment called NA49 [4]. Its main physics goals are to search for the critical point of strongly-interacting matter, to study the onset of deconfinement in quantum chromodynamics, and to measure identified particle production spectra in hadron-nucleus collisions as reference data for long-baseline neutrino experiments and large area cosmic ray observatories.

The outline of the NA61/SHINE experiment is presented in Figure 2. Two superconducting bending magnets (Vertex I and II) are responsible for particle deflection for momentum determination, with a total maximum bending power of ∼9 Tm (up to 1.5 Tesla in Vertex I and 1.1 Tesla in Vertex II). A target holder with target moving capability sits just upstream of the first Vertex TPC. Thin targets can be placed inside a silicon vertex detector (VD) upstream of Vertex I for precise vertex determination. NA61/SHINE also has the ability to measure interactions in extended replica targets for long-baseline neutrino experiments. The tracking devices for spectrometry are composed of eight large volume TPCs (total ∼40 $\mathrm{m}^3$ and ∼1 m drift length), capable of performing both tracking and $\mathrm{d}E/\mathrm{d}x$ measurements. Three Time-of-Flight walls (ToF-L, ToF-R, ToF-F) complete the particle identification (PID) phase space coverage and enable two-dimensional separation of particle species. A calorimeter is placed at the end of the beamline, called the Projectile Spectator Detector (PSD), which helps to estimate centrality in heavy-ion collisions. Upstream of the target position, a set of scintillator and Cherenkov detectors serves as beam and beam PID trigger (not shown on the figure). Between VTPC-1 and GapTPC on the beamline, a small plastic scintillator of 1 cm diameter serves as an interaction trigger in most collision types (not shown on the figure).

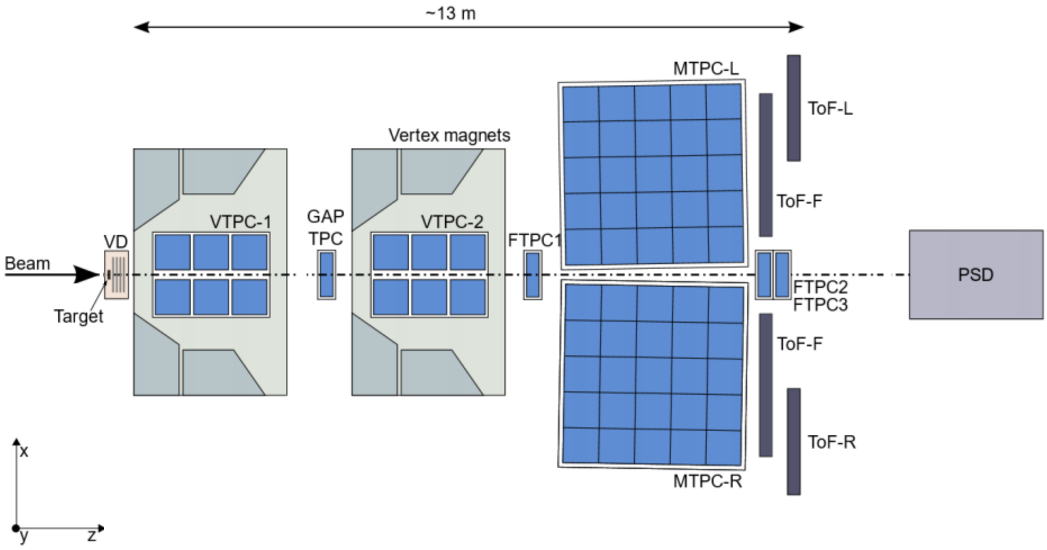

**Figure 2**. (Color online) The NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) detector configuration, with the Forward Time Projection Chambers (FTPCs). Prior to 2017 the GapTPC was the only detector capable of measuring particles in the beamline region. With only seven measurement planes, the GapTPC could not perform accurate $\mathrm{d}E/\mathrm{d}x$ estimation on its own, nor could it alone determine the momentum of very forward particles. Additional detectors displayed: Vertex Detector (VD), Vertex TPC 1 & 2 (VTPC-1 & VTPC-2), Main TPC Left & Right (MTPC-L & MTPC-R), Time-of-Flight wall Left & Right & Forward (TOF-L & TOF-R & TOF-F), Projectile Spectator Detector (PSD).

The pre-existing NA61 TPCs (VTPC-1, VTPC-2, MTPC-L, MTPC-R, GapTPC) were designed primarily to meet the experimental needs of the heavy-ion program of the NA49 experiment. The Vertex TPCs (VTPC-1 and VTPC-2) sit in the vertex magnets and each provide 72 position measurement planes in order to determine track momentum. They are not instrumented along the beamline due to the high concentration of charged ion fragments and delta electrons in this region, where high levels of ionization would make wire plane instrumentation difficult. The Main TPCs (MTPC-L and MTPC-R) provide 90 additional measurement planes for tracks, enabling accurate particle identification via $\mathrm{d}E/\mathrm{d}x$ and increasing the tracking lever arm. The removable GapTPC was added to in order to improve the momentum and vertex resolution of MTPC-only tracks, and also in order to have some charged particle detection capability in the beamline region, for non-heavy-ion measurements. The GapTPC contains only seven detection planes, and on its own cannot accurately perform momentum and $\mathrm{d}E/\mathrm{d}x$ measurements for particles near the beam momentum.

The shortcomings of the original tracking and PID capabilities near the beamline of the spectrometer became a bottleneck for the NA61/SHINE physics program related to long-baseline neutrino experiments. In order to close the pertinent missing tracking and PID acceptance gap, the FTPCs (FTPC-1, FTPC-2 and FTPC-3) were constructed in 2017. FTPC-1 is located downstream of the second Vertex magnet, and FTPCs 2 and 3 are located downstream of the MTPCs. Each FTPC contains 12 measurement planes, giving 36 total tracking and $\mathrm{d}E/\mathrm{d}x$ points.

## 3 The FTPC design concepts

When selecting a detector design and technology for instrumenting the forward region of NA61, several performance goals were considered:

- low material budget in order not to disturb performance of MTPC and PSD,
- tracking capability for covering the missing acceptance,
- PID capability, meaning at least inclusive proton-pion separation,
- powerful out-of-time track rejection capability,
- compatibility with the existing NA61 infrastructure,
- cost-effectiveness.

The low material budget assures that the new forward detectors do not detract from other physics programs: the first chamber is situated upstream of the MTPCs, which provide crucial $\mathrm{d}E/\mathrm{d}x$ samples along particle trajectories. The MTPC track samples need to be biased as little as possible in order to preserve the existing $\mathrm{d}E/\mathrm{d}x$ resolution of NA61. Furthermore, downstream of the FTPC-2 and 3 stations the PSD calorimeter resides for detection of heavy-ion fragments. Thus, excessive material had to be avoided upstream of the PSD calorimeter as well, in order not to initiate premature electromagnetic or hadronic showers.

The inclusive proton-pion separation capability proved to be necessary in order to make the planned production measurements useful for the long-baseline neutrino experiments. The design goal of the forward detectors was to achieve statistical separation of protons and pions at 100 GeV/$c$ forward momentum. In the NA61 configuration, this momentum is within the relativistic rise region of the Bethe–Bloch curve for Ar/$CO_2$ gas mixture, which is the working gas for the existing NA61 TPCs (for VTPCs 90:10 Ar/$CO_2$ is used, whereas for all the other TPCs 95:5 mixture is used). This fact was one of the main motivations for choosing the TPC concept as a detector technology, as a TPC is capable of implementing inclusive proton-pion separation via $\mathrm{d}E/\mathrm{d}x$ to a sufficient quality at a relatively low cost.

The issue of out-of-time track rejection was foreseen to be crucial due to the position of the detectors in the medium-intensity beamline. A typical 4 sec long spill contains $10^5$ – $10^6$ beam particles, while the total TPC drift time in NA61 is 51.2 $\mu$s over the ~1 m of drift distance. The beam particles in a typical spill are not necessarily uniformly spaced in time — the spill structure can vary significantly due to changes in the accelerator chain. Non-uniformity in the spill time structure results in significant intensity fluctuations, causing a large fraction of collected events to contain more than 10 out-of-time beam particles. Moreover, upstream collisions in the beamline also contribute to the yield of out-of-time particles close to beam momentum.

Detector compatibility is an important point for selecting a detector technology. The forward region has limited physical space due to the presence of the existing NA61 TPCs. Existing infrastructure such as the Ar/$CO_2$ gas supply were also be taken into consideration. Data Acquisition System (DAQ) and software compatibility also influenced the design decisions.

The tandem-TPC concept was selected in order to satisfy these requirements. Advantages of the resulting system, with the specific choice of the solutions, are the following:

- Low material budget field cage constructed from copper-coated polyimide foil.
- 36 FTPC + 7 GapTPC $\mathrm{d}E/\mathrm{d}x$ points for effective proton-pion separation at 100 GeV/c.
- Tandem field cage design for out-of-time track rejection.
- Backward compatibility with existing NA61 front-end electronics and gas system.
- Relatively low-cost detector technology and construction.

Two solutions ensured a low contribution to the overall detector material budget. First, the field cage was constructed using a 75 $\mu$m thick polyimide film bonded to an 18 $\mu$m layer of copper foil. The foil was etched into 4.5 mm parallel strips spaced 0.5 mm apart serving as the equipotential surfaces of the field cage, which are joined by low-profile 1 MOhm resistors. The field cage was surrounded by a layer of 50 $\mu$m thick Mylar foil, providing the outer seal for the gas volume. Overall, the field cage and Mylar windows comprise 0.34 % radiation lengths. The active Ar/$CO_2$ (95:5) gas volume comprises 0.41 % radiation lengths. Second, the upstream FTPC was designed to be removable during heavy ion data taking periods. The FTPC1 support structure includes a sliding rail system and easily detachable chamber infrastructure, allowing the entire chamber to be moved out of NA61 active region, when not used. The downstream FTPCs were not designed to be removable, since they are installed downstream of the MTPCs. When out of use, they can be filled with helium in order to reduce material shadowing of the PSD.

In order to achieve statistical separation of protons and pions at 100 GeV/c, multiple $\mathrm{d}E/\mathrm{d}x$ samples must be collected along particle tracks. NA61 TPC front-end electronics allow for charge measurement at each measured position. The FTPC system segments the tracks into 12 point and charge measurements per chamber, giving 36 total measurements over 144 cm of instrumented track length. The existing beamline TPC, the GapTPC, provides 7 additional measurements, totaling to 43 $\mathrm{d}E/\mathrm{d}x$ points. Using the relation $\sigma_{\mathrm{d}E/\mathrm{d}x} \sim \frac{1}{\sqrt{N}}$ where $N$ is the number of measurement points [4], we have determined that the instrumentation will be sufficient to statistically separate protons from pions above 10 GeV/c, well above the Bethe–Bloch crossing for protons and pions in the used detector gas composition.

Oxygen contamination of the active gas reduces $\mathrm{d}E/\mathrm{d}x$ resolution. The contamination in the FTPCs is mitigated by including a buffer volume of detector gas around the outside of the sensitive volume. The field cage forms a gas tight seal with the supply gas, which is forced through a hole pattern in the cathode. The flow is then redirected near the wire plane up through the gas-tight envelope formed by the backside of the field cage and the Mylar window. This design is illustrated in the right panel of Figure 3. Gas contamination due to diffusion through the Mylar is thus relegated to the exhaust gas, and the contamination penetration to the sensitive volume is reduced. For larger volume TPCs, many experiments [1, 4] apply an additional gas circuit for constantly flushing the gas envelope around the chamber, usually with dry Nitrogen. The relatively modest volume of the FTPC chambers allowed us to avoid such a complication, by reusing the exhaust gas for filling the buffer volume. That simplification in the design also made it possible to make the buffer volume rather thin, of the order of 1 cm, allowing for more economic usage of the available detector space.

The tandem design was achieved by orienting the field cage drift directions of the most upstream and most downstream FTPCs (FTPCs 1 & 3, respectively) in the downward direction, while orienting the drift direction of FTPC-2 upward. The readout wire planes for these two chambers are on the bottom of the chambers, while for the rest of NA61 and for the center FTPC (FTPC2) the readout wire planes are on top of the chambers. This creates a tandem TPC system between four TPCs: GapTPC & FTPC2 drift directions are oriented in the $+y$ direction, while FTPC1 & FTPC3 drift directions are oriented in the $-y$ direction.

The pre-existing NA61 TPC design is mainly an updated version of TPCs inherited from NA49. Several design aspects were selected in order for the new FTPCs to be compatible with existing detector infrastructure. The wire plane readout is compatible with the NA61 front-end electronics (FEE), allowing for the FTPCs to be easily integrated with the existing detector DAQ system. The gas volume accepts an identical gas mixture to the one used in the MTPCs (Ar/$\mathrm{CO_2}$, 95:5), allowing for smooth integration into the existing infrastructure. Additional drift velocity monitors similar to ones for existing TPCs were constructed and installed in the experiment [5].

The FTPCs were constructed at two different facilities in two logical parts: the field cage and gas volume, and the amplification and readout wire plane. The design concept of the field cage and gas volume was largely motivated by an earlier small volume TPC chamber, called the LMPD [6]. The actual real scale design and prototyping was done at the University of Colorado Boulder in the USA, and the assembly was done at CERN in Switzerland/France, due to the problems of transportation of a fragile pre-assembled field cage. The readout and amplification wire plane was constructed at the Wigner Research Centre for Physics, Budapest, Hungary, and was subsequently shipped to CERN, since a pre-assembled wire plane proved to be strong enough for transportation. The above strategy necessitated a modular structure, such that the above two main components could be constructed and tested independently, and eventually joined together at CERN.

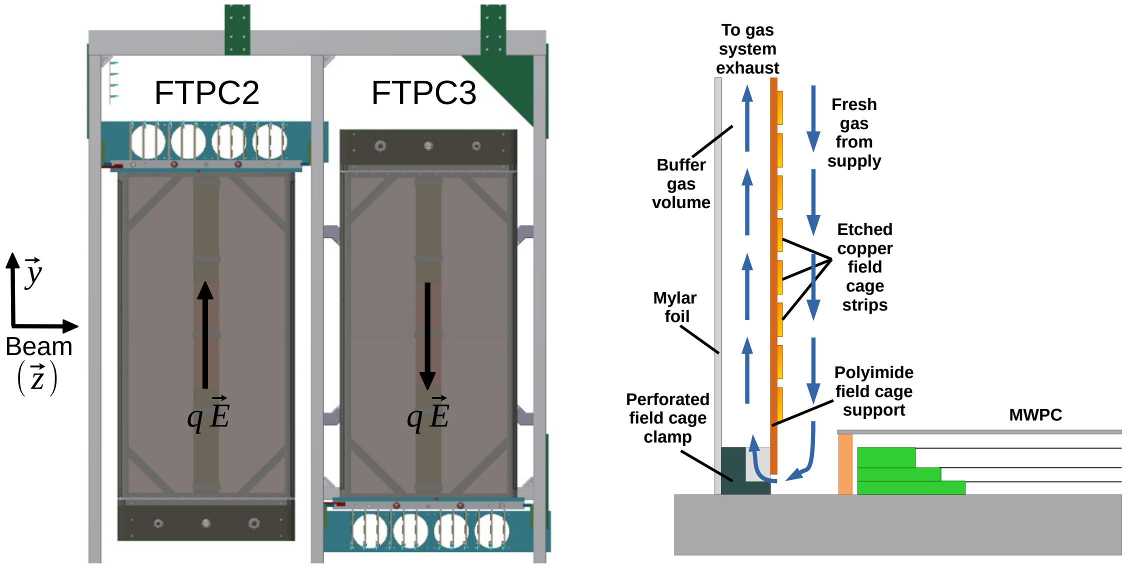

**Figure 3**. (Color online) Left: Mechanical realization of the tandem-TPC concept in the FTPC2-FTPC3 tandem pair chambers. The actual drift field directions $q\vec{E}$ along with the NA61 coordinate axis convention is also depicted in the figure. Right: Detail of the buffer volume and field cage near the readout plane. Gas flow is shown in blue.

## 4 Engineering solutions

### 4.1 Field Cage

The main TPCs are shadowed by not only the active areas of the FTPC1 field cage but also the support posts for the field cage. These must therefore be made with minimal material, unlike the rigid posts that support tensioned field cage strips in the older chambers. The single-sheet copper plated polyimide field cage is therefore supported under minimum tension by a four-windowed Noryl® frame manufactured at the University of Colorado Boulder. This support structure consists of four 1 m tall C-shaped support posts. The polyimide side of the field cage is adhered to the inside of the support posts, and the outer Mylar window is adhered to the outside of the posts. The single foil field cage solution avoids issues related to fine positioning of field cage strips, as the copper strips are situated directly on the sheet of polyimide.

A clamping retention mechanism also constructed from Noryl® keeps the field cage in place along the tops and bottoms of the support windows. The top edge of the field cage is clamped to the cathode retention box, and the bottom edge is clamped to the aluminium flange used for attachment to the readout wire plane. This system maintains proper field cage positioning and tension over the windows, which cover an area of $101 \times 71\,\mathrm{cm}^2$ on the longest sides.

The Noryl® cathode retention box electrically isolates the 20 kV cathode from the outside of the chamber and the gas supply lines. It also houses the gas distribution and exhaust systems. Fresh chamber gas flows into a PerFluoroAlkoxy (PFA) inlet tube, which in turn forces the gas through a “shower head” hole pattern in the cathode. The use of PFA tubing as opposed to metallic tubing ensures that the cathode is well-isolated from any potential grounding routes. This gas then flows through the active chamber volume before being forced into the buffer volume between the outside of the field cage and the outer Mylar window. This gas is forced back into the cathode retention box and out through an exhaust line.

The fully constructed field cage unit can be sealed with an aluminium sheet in place of the wire frame assembly, via insertion of an O-ring in the wire plane attachment flange. This allowed for independent construction of the field cages, along with gas tightness and high voltage testing.

The rendering of the mechanical design of the FTPC2-FTPC3 tandem pair is presented in the left panel of Figure 3.

### 4.2 Amplification and readout wire plane

As usual in a TPC setting, the ionization electrons which form along the particle track are guided by the homogeneous drift field towards the readout plane, which resides at the end of the drift volume. The technology for the amplification and readout plane was chosen to be based on the multi-wire proportional chamber (MWPC) concept. This choice was made for the sake of simplicity of design, construction and integration with existing NA61 components, such as the Data Acquisition (DAQ) [7] and the offline software (Shine) [8].

The primary geometric design of these planes was largely informed by the original NA49/NA61 TPC setting [1, 4], since the pad response function of the new FTPC system was required to conform to the standards of the existing upgraded NA61 TPC readout system [7]. The construction of the amplification and readout plane took place at the Innovative Detector Development Laboratory at the Wigner Research Centre for Physics, Budapest. A representative photograph of an FTPC wire plane with its annotated structure is seen in Figure 4.

Using a typical approach, from the drift direction it begins with a metal window (“skirt”) electrode set to transparent voltage, which defines the boundaries of the amplification and readout plane. Then, the wire plane of the gating grid follows: when open, it is set to a transparent voltage level. Otherwise when the chamber is idle, it is configured such that it blocks the drifting electrons from entering the amplification region and blocks ions from flowing into the active gas volume. Below that, the Cathode (Frisch) grid follows, which defines the zero potential surface, closing the drift region. Finally, the electrons arrive at the sense wire/field wire amplification plane, where the actual electron multiplication happens. The field wires are kept at zero potential, which allows for a lower amplification voltage on the sense wires. Below that, a segmented pad plane is placed, reading out the mirror charges of the multiplied electrons around the sense wires.

In order to relax the accuracy requirements on the wire winding process, the final wire geometry is fixed by a laser-engraved plastic wire guide with about 30 $\mu$m precision [9, 10]. The cathode flatness is ensured by gluing of the Pad Plane PCB onto the aluminium strongback with its face against a 20 $\mu$m precision optical table.

In order to minimize the number of electronic readout channels, the FTPC2 and 3 chambers were subdivided into two sectors: for the downstream (upstream) half of FTPC2 (FTPC3), the pads are 67% broader. This solution, while sparing readout channels, keeps the tracking lever arm and the number of $\mathrm{d}E/\mathrm{d}x$ sampling points intact. The main geometric parameters of the amplification

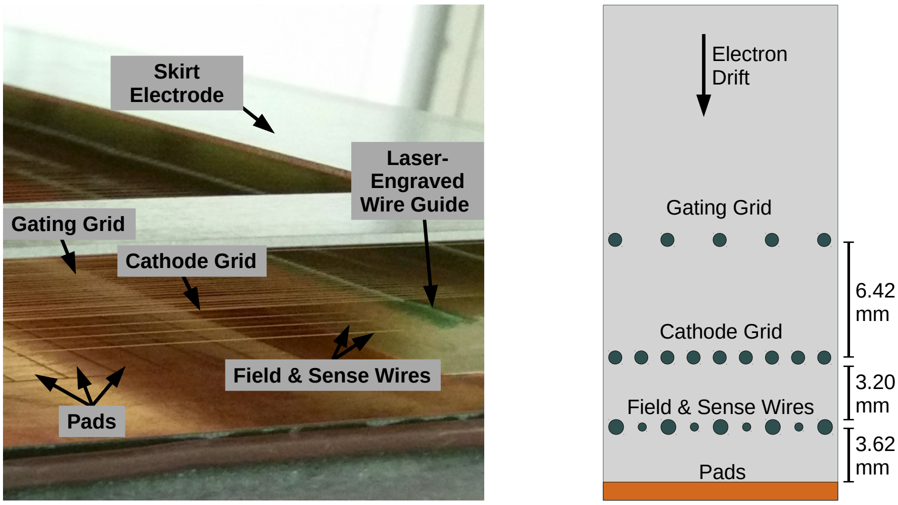

**Figure 4**. (Color online) The structure of an FTPC amplification and readout wire plane. Left: image of constructed MWPC and individual wireplanes. The Gating Grid, Cathode (Frisch) Grid, and the Field Wire / Sense Wire Grid wire planes are stretched above the Pad Plane. The precision of the Field Wire / Sense Wire pitch is set by a laser engraved plastic wire guide. All sharp metal structures, potentially sources of corona discharges, are covered by a protective epoxy resin layer, as seen in the left figure. Right: Wireplane design cross-sectional view.

and readout plane are listed in Table 1. A typical operational sense wire voltage in Ar/CO$_2$ (95:5) working gas was about 1.1 kV.

| *wire type* | *material* | *thickness* [$\mu$m] | *manufacturer* | *tension* [g] | *pitch* [mm] | *distance to Pad Plane* [mm] |
|---|---|---|---|---|---|---|
| Sense Wire | Au plated W | 22 | LUMA | 19 | 4 | 3.62 |
| Field Wire | Cu-Be alloy | 114 | CFW | 38 | 4 | 3.62 |
| Cathode Grid | Cu-Be alloy | 66 | CFW | 29 | 1 | 6.82 |
| Gating Grid | Cu-Be alloy | 66 | CFW | 29 | 2 | 13.24 |

| *chamber name* | *sensitive area width* [mm] | *sensitive area length* [mm] | *pad width* [mm] | *pad length* [mm] |
|---|---|---|---|---|
| FTPC1 | 512 | 480 | 4 | 40 |
| FTPC2 upstream sector | 640 | 240 | 4 | 40 |
| FTPC2 downstream sector | 640 | 240 | 6.6 | 40 |
| FTPC3 upstream sector | 640 | 240 | 6.6 | 40 |
| FTPC3 downstream sector | 640 | 240 | 4 | 40 |

**Table 1**. Main geometric and manufacturing parameters of the FTPC wire planes. Top table: details of the wire grid geometry. Bottom table: the geometric parameters of the readout pads.

## 5 Performance

The addition of the FTPCs has resulted in several performance increases in NA61. Primarily, the NA61 forward coverage has increased dramatically, now extending up to the beam momentum. This can be observed in Figure 5, showing the reconstructed track phase space occupancy in proton-carbon interactions at 120 GeV/c collected in 2017. The left hand panel shows accepted tracks ignoring FTPC contributions, while the right hand panel shows all accepted tracks including FTPC-GapTPC tracks. The observed increase in coverage corroborates simulated acceptance plots for identical beam and magnet configurations, shown in Figure 6.

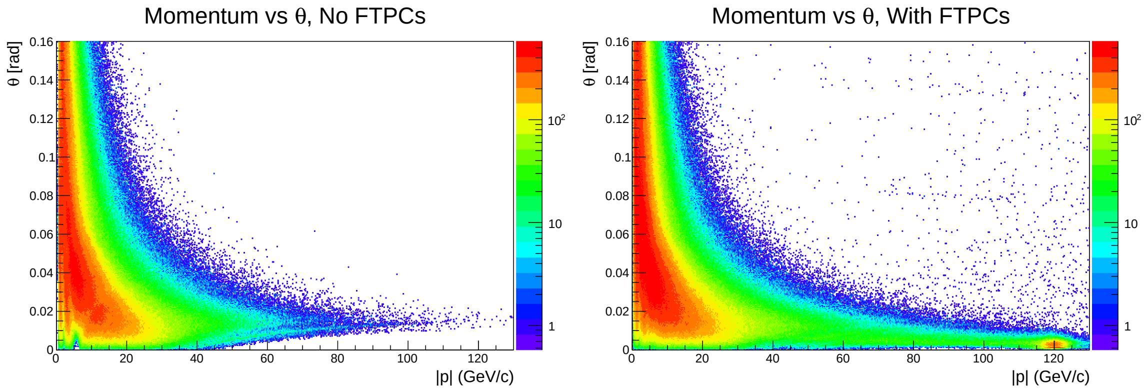

**Figure 5**. (Color online) Reconstructed track phase space coverage in 120 GeV/c proton-carbon interactions with and without inclusion of FTPC tracks. Left panel: tracks passing minimal cuts without inclusion of FTPC measurements. Right panel: tracks passing minimal cuts including FTPC tracks. Note the beam spot at 120 GeV/c.

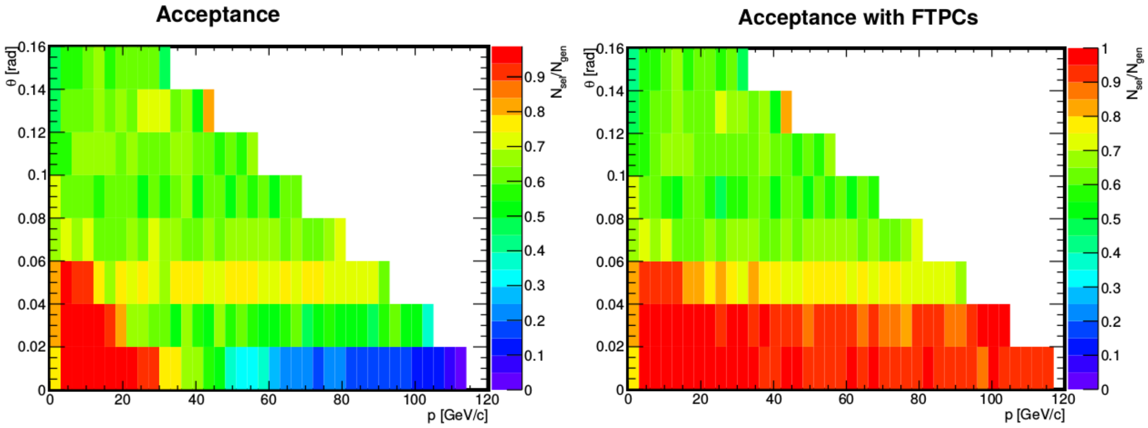

**Figure 6**. (Color online) Demonstration of NA61 detector acceptance in 120 GeV/c proton-carbon interactions before and after the addition of the FTPCs, as obtained from Monte Carlo simulation. $N_{\mathrm{gen}}$ denotes the number of generated tracks in a given $[p, \theta]$ bin, and $N_{\mathrm{sel}}$ means the number of tracks that generated sufficient measurement points to pass preliminary track selection in that bin. Left panel: NA61 acceptance before the integration of the FTPCs. Right panel: NA61 acceptance with FTPCs installed.

As was foreseen in the design phase, the tandem-TPC concept significantly reduces backgrounds related to out-of-time tracks. Figure 7 demonstrates the background reduction measured during the

2017 120 GeV/c proton-carbon data taking period, in which the typical beam intensity ranged from 1 to 25 beam particles per recorded event. Figure 7 shows events from this period separated into three intensity regimes: low beam intensity (1-5 beam particles per event), medium beam intensity (6-10 beam particles per event), and high beam intensity (more than 10 beam particles per event). Each intensity regime shows the distribution of track position mismatch $\Delta y$ between the tandem pairs, where the non-drift direction coordinate of the tracks are required to match ($|\Delta x| \leq 1$ cm). The peaks at $\Delta y = 0$ cm correspond to in-time tracks, while the continuous background corresponds to random matches of out-of-time track pieces. As the beam intensity increases, so does the background of out-of-time tracks.

This continuous background extends throughout the chamber in $y$, i.e. along the drift coordinate, for the full 100 cm of detector fiducial volume. If the tandem concept were not used, these tracks would match both in $x$ and in $y$ and thus would provide a significant background for data analysis. The method presented in Figure 7 can also be used for purity estimation of the out-of-time rejection of the tandem concept by extrapolating the out-of-time background passing to the region under the $\Delta y$ cut of the tandem pair.

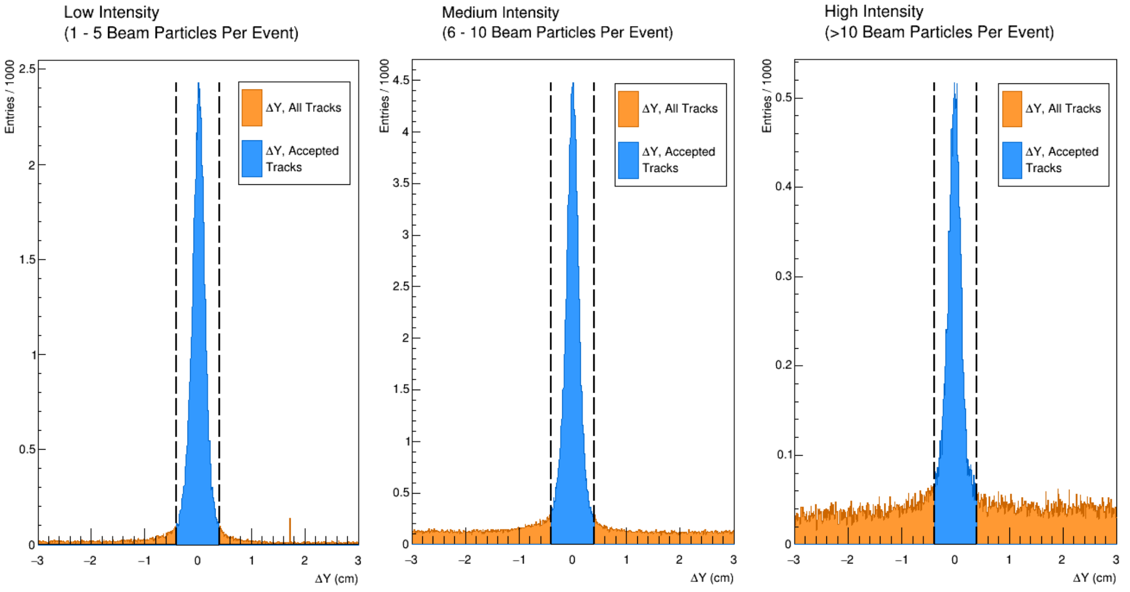

**Figure 7**. (Color online) Background rejection with the tandem concept. The peak in each plot at 0 cm corresponds to in-time particles, while the continuous background (orange) corresponds to out-of-time particles. The out-of-time track background increases with beam intensity. The measured out-of-time fraction of tracks for each intensity (ratio of tracks in orange histogram to all reconstructed tracks) is 56% (low-intensity), 76% (medium-intensity) and 83% (high-intensity). For a standard TPC configuration, these tracks would be indistinguishable from the in-time tracks.

Finally, we quantify the limitations of the tandem TPC system. Special cases may arise when minimally-separated tracks in $y$ are joined to the same TPC track, or in the extreme case two ionizing particles may arrive too close in time for a TPC to resolve the two distinct tracks. Finding the threshold for this behavior corresponds to measuring the two-track time resolution of the TPC system. We perform this measurement using sequential beam particles separated by just a few hundred nanoseconds. The timing reference of the beam particles were provided by the $S1_1$ scintillator counter in the upstream beamline of NA61. A CAEN V1290N Multi-Hit Time-to-Digital-Converter (MHTDC) records beam particle arrival time as measured on $S1_1$, with a resolution of about 25 psec [1], allowing for sub-nanosecond measurement of beam particle arrival time. The FTPC FEEs measure charge in 200 nsec time buckets in terms of drift time, and the clusterization algorithm for position estimation in the drift direction relies on at least three such samples. Thus, we expect the minimum two-track time resolution of the FTPCs to be of the order of 600 nsec.

In Figure 8 we plot the beam particle $\mathrm{d}E/\mathrm{d}x$ in the FTPCs vs the beam particle separation time as seen by the MHTDC. It is seen that for larger separation times, a typical minimum ionization (MIP) $\mathrm{d}E/\mathrm{d}x$ signal is returned, corresponding to a single beam particle. Then, for separation times less then 600 nsec we observe a contribution corresponding to a $\mathrm{d}E/\mathrm{d}x$ signal of ~2 MIP, even for tracks required to satisfy tandem cuts. These "double-$\mathrm{d}E/\mathrm{d}x$" tracks are comprised of two beam particles closely spaced in time and merged together in their TPC response.

This study shows that the limitation of the tandem-TPC based separation of out-of-time tracks comes mainly from the intrinsic two-track time resolution of a single TPC chamber, as expected. The "double-$\mathrm{d}E/\mathrm{d}x$" cut can, however, still be used to tag out-of-time contribution which are too close to be resolved by the tandem-TPC out-of-time rejection.

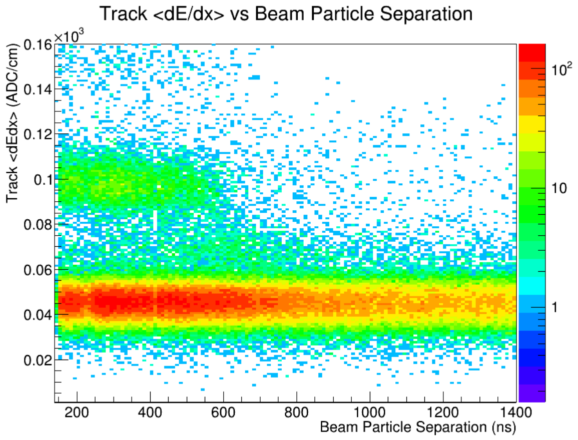

**Figure 8**. (Color online) The limitation of the tandem-TPC concept: if two beam particles arrive too close in time, the intrinsic two-track drift time resolution of a TPC system is not enough for the separation of such out-of-time tracks, even in a tandem-TPC configuration. In such situations, however, the typical amplitude ($\mathrm{d}E/\mathrm{d}x$) response of the chamber indicates anomalous amount of ionization signal: one observes a doubled signal amplitude with respect to a typical MIP signal. Thus, such merged beam tracks can be still labeled or rejected by their unusually large $\mathrm{d}E/\mathrm{d}x$.

## 6 Concluding remarks

In this paper the Forward TPC system of the NA61 experiment at CERN was described. The pertinent system was constructed in order to cover a previously uninstrumented part of the NA61 phase space in the very forward region, i.e. in and around the beam line. Since the FTPC system is installed in the beam region, recognition of background tracks originating from previous events (out-of-time particle tracks) is essential. In order to achieve this, we employed a novel technique, using alternating drift field directions, which we called a tandem-TPC concept. In such a setting, the tracks of out-of-time particles already start to drift in opposite directions in the subsequent chambers, thus the tracks of these will be discontinuous throughout the system.

As a primary objective, we have demonstrated that this new tandem-TPC concept excels at rejecting out-of-time background tracks, in a relatively high-intensity beam ($\sim$100 kHz). At the same time, due to the nature of the TPC concept, a good tracking and $\mathrm{d}E/\mathrm{d}x$ capability, as well as low material budget and cost effectiveness were also achieved. The tandem-TPC concept could also perform well at other relatively high-intensity beam facilities, and could satisfy the above requirements.

## Acknowledgements

We would like to thank to Leszek Ropelewski and Eraldo Oliveri of CERN for kindly providing laboratory space and basic facilities for the joining procedure of the FTPC field cage and the wire plane at CERN. We thank to the support and help from all the members of the CERN NA61/SHINE Collaboration. This work was supported by the Hungarian Scientific Research Fund (NKFIH 123842-123959), the Momentum ("Lendület") program of the Hungarian Academy of Sciences, the Hungarian National Research, Development and Innovation Office (NKFIH TÉT_16_CN-1-2016-0008), and the U. S. Department of Energy (grant DE-SC0010005).

## References

[1] N. Abgrall et al. (the NA61 Collaboration), *NA61/SHINE facility at the CERN SPS: beams and detector system*, *JINST* **9** (2014) P06005 [`arXiv:1401.4699`].

[2] P. Legou, R. Mazzucato, F. Nizery, *SEXTANT - A very fast beam spectrometer*, *IEEE Nuclear Science Symposium Conference Record* (2007) 9906685 [`doi:10.1109/NSSMIC.2007.4436416`].

[3] F. Garcia et al., *A GEM-TPC in twin configuration for the Super-FRS tracking of heavy ions at FAIR*, *Nucl. Instrum. Meth.* **A 884** (2018) 18.

[4] S. Afanasiev et al. (the NA49 Collaboration), *The NA49 Large Acceptance Hadron Detector*, *Nucl. Instrum. Meth.* **A 430** (1999) 210.

[5] M. Kuich, *Kaon production in mid-rapidity in Be+Be collisions at the CERN SPS*, PhD thesis, University of Warsaw (2019), sections D.4 and D.5 [`EDMS:2150851`].

[6] K. Márton, G. Kiss, A. László, D. Varga, *Low momentum particle detector for the NA61 experiment at CERN*, *Nucl. Instrum. Meth.* **A 763** (2014) 372 [`arXiv:1401.4392`].

[7] A. László, E. Dénes, Z. Fodor, T. Kiss, S. Kleinfelder, C. Soós, D. Tefelski, T. Tölyhi, G. Vesztergombi, O. Wyszynski, *Design and performance of the data acquisition system for the NA61/SHINE experiment at CERN*, *Nucl. Instrum. Meth.* **A 798** (2015) 1 [`arXiv:1505.01004`].

[8] R. Sipos, A. László, A. Marcinek, T. Paul, M. Szuba, M. Unger, D. Veberic, O. Wyszynski, *The offline software framework of the NA61/SHINE experiment*, *J. Phys. Conf. Ser.* **396** (2012) 022045.

[9] D. Varga, G. Kiss, G. Hamar, G. Bencédi, *Close cathode chamber: low material budget MWPC*, *Nucl. Instrum. Meth.* **A 698** (2013) 11.

[10] D. Varga, G. Hamar, G. Kiss, *Asymmetric multi-wire proportional chamber with reduced requirements to mechanical precision*, *Nucl. Instrum. Meth.* **A 648** (2011) 163.