ADVANCES IN NUCLEAR SCIENCE AND APPLICATIONS

Volume 1, No. 3 (2025), P. 179-185

Ultrasonic welding technology for straw trackers: from development to application

N. Azorsky[1], V. Bautin[1], T. Enik[1],
E. Kuznetsova[2], R. Petti[3],
S. Romakhov[1], K. Salamatin[1], D. Sosnov[4]

[1]Joint Institute for Nuclear Research, Dubna, Russia

[2]University of Florida, Gainesville, USA

[3]University of South Carolina, Columbia SC, USA

[4]NRC Kurchatov Institute - PNPI, Gatchina, Russia

e-mail: ekaterina.kuznetsova@cern.ch

DOI: 10.63907/ansa.v1i3.52
Received: 16 September 2025

Abstract

This article provides a comprehensive description of the straw production technology developed and refined at the Laboratory of High Energy Physics of the Joint Institute for Nuclear Research (JINR, Dubna), as well as its subsequent evolution at both JINR and the Institute of Nuclear Physics (INP, Almaty). It outlines all stages of the ultrasonic welding (USW) process and compares the properties of glued, wound, and welded straws, with particular emphasis on their mechanical stability. The successful operation of a Straw Tracker made from USW straws in the NA62 experiment at CERN highlights the advantages of this technology and underscores its relevance for experiments such as COMET, SHiP, DUNE, and SPD.

1 Introduction

Modern high-energy physics and neutrino experiments impose stringent requirements on tracking detectors. These systems must provide excellent spatial and temporal resolution, minimal material budget, and long-term operational reliability. Thin-walled, small-diameter drift tubes, commonly referred to as straws, satisfy these demands and have become a well-established technology. A notable example is the ATLAS Transition Radiation Tracker (TRT) at CERN, while the NA62 experiment at CERN and the COMET experiment at J-PARC also employ straw-based trackers. Future projects such as SHiP (CERN), DUNE (Fermilab), and SPD (NICA, JINR) are likewise developing large-scale straw tracking systems.

The Joint Institute for Nuclear Research (JINR) has played a leading role in the development and production of straw detectors over the past decades. Alongside the conventional gluing technology, JINR has pioneered an innovative ultrasonic welding (USW) technique that resolves several fundamental limitations of glued and wound straws. This paper reviews the evolution of straw production at JINR, highlights the technological aspects and advantages of USW, and demonstrates its successful application in operating and forthcoming high-energy physics experiments.

2 Evolution of Straw Production Technology

Originally, the main straw production method was the winding technology. In this case, a tube is formed from two strips of thin film, for example Kapton, as shown in Figure 1 (left). One side of the film is coated with a conductive layer and the other side with an adhesive layer. The two strips are wound and glued together. Development of this technology was initiated by the JINR group led by Vladimir Peshekhonov [1]. The developed technology found application in such ambitious projects as the ATLAS TRT [2] and the COMPASS Tracker [3], as well as in numerous other projects of smaller scale. The Transition Radiation Tracker (TRT) of the ATLAS experiment consists of about 300,000 straws with a diameter of 4 mm and a length of up to 144 cm, assembled into a cylindrical barrel structure complemented by two endcaps. The TRT operates with high detection efficiency even under large radiation occupancy.

A primary developer and producer of the COMPASS Straw Tracker was the JINR team as well. The Tracker consisted of individual straw tubes around 4 meters long with diameters of 6 and 10 mm. The total number of straw tubes was around 25,000. The entire production technology was developed and fine-tuned at JINR, including all steps, from the straw production and mechanical tracker assembling, see Figure 1, right, up to development of the tracker readout based on modified ATLAS TRT electronics. All tracker modules were produced at the JINR site. Tracker integration into the COMPASS detector and development of the infrastructure was implemented by the international COMPASS Collaboration.

Despite the successful implementation of these projects, several significant disadvantages of the winding technology were identified. The adhesive seam and the straw material absorb water molecules from air resulting in deformation of the tube geometry. Presence of glue reduces the range of elastic deformation, limiting the maximal achievable area of trackers build without additional supporting structures. For example, for the ATLAS TRT it was necessary to introduce four carbon fibers along each straw to reinforce it. Additionally, ensuring long-term hermeticity along the adhesive seam proved to be a challenging task.

Ultrasonic welding technology, successfully developed at JINR, allows to overcome those problems.

Figure 1: Left: Winded straw production. Right: Assembling of the COMPASS Straw Tracker modules.

3 Ultrasonic Welding Technology

A single strip of thin metallized Mylar film is used for ultrasonic straw welding. The strip is welded longitudinally to form a tube. Figure 2 shows a schematic view of the welding machine together with photos of the welding process. The welding system is based on a standard industrial ultrasonic welding apparatus, which was substantially adapted for this specific task. Key custom components, including the specialized sonotrode and the precise tape-forming mechanisms, were developed at JINR to achieve the required quality and stability for long straw production [5]. The ultrasonic part (1) consists of a transducer which generates mechanical vibrations at ultrasonic frequencies. The vibration is transmitted to the welding point through a sonotrode with spherical working surface (1a). The tape is supplied from a spool (2), and a tensioner (6) allows to adjust the tape tension. A roller (3a) and an adjustable U-shaped part (3b) lift up the tape edges helping a ring die (4) to forms the tape into a tube around a cylindrical anvil (5). This approach ensures the size of the overlapping tape regions to be stable during the straw welding procedure. The sonotrode (1a) is used to weld the edges together. A carriage (8) secures the end of the produced straw tube and moves along a guide (7). The carriage includes a nozzle (9) for supplying gas through the formed tube towards the welding point.

The supply tape spool (2), adjustable tensioner (6), adjusting U-device (3b), anvil (5), die (4) and sonotrode (1a) are aligned using a laser along the axis of the tape extraction. The die (4) is precisely adjusted with respect to the anvil position (5) in such a way, that the tape touches the anvil at the welding point only, while pressurized gas is supplied to the welded part of the tube. The tensioned tape, pulled with the tensioner and extraction carriage, is drawn between the anvil and the sonotrode. Welding is done at the place where the tape is formed into the tube.

The high quality of the welded seam allows the production of straws from extremely thin Mylar film, down to a few tens of micrometers. These straws can operate at overpressures of up to several bar. Gas permeability is determined mainly by the film material rather than by the seam area, and the inner straw surface, serving as the cathode electrode, remains sufficiently smooth due to the very limited seam width. Figure 3 shows microscopic views of a USW straw.

A primary visual inspection of the seam quality is done right during the straw welding process. After the production, the ends of the straw are cut off and used to characterize the straw elongation and breaking force. Furthermore, each produced

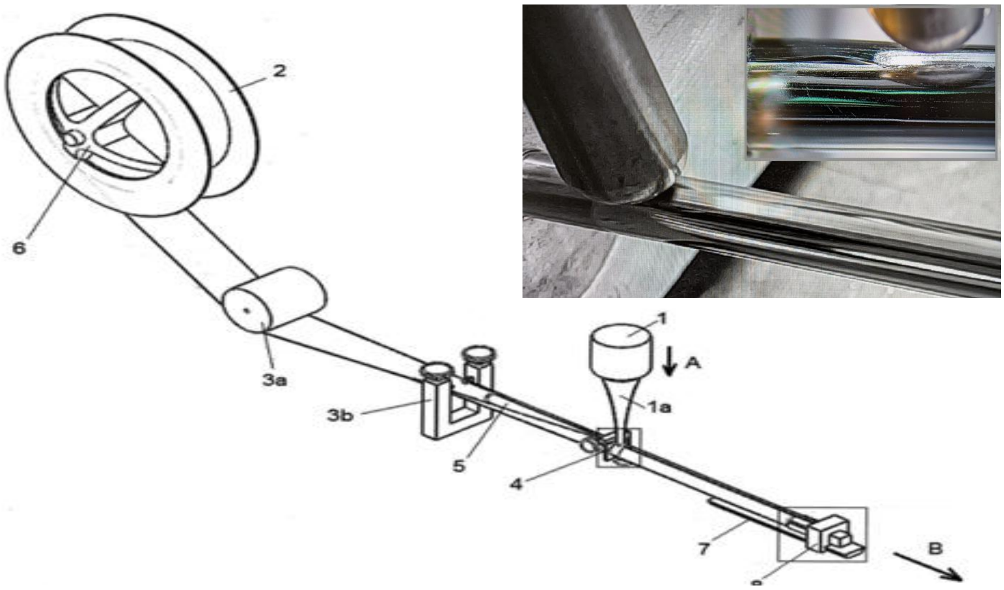

Figure 2: Schematic view of the welding machine [4], [5] and zoomed photos of the welding process.

straw undergoes overpressure tests. A short term high pressure test checks the transition boundary of non-elastic deformation. For instance, for NA62 straws, the overpressure tests were performed at 8 bar. A long term, up to several months duration, quality check is performed with the pressure of several bars. This test is sensitive to potential gas leaks which may be caused by seam imperfection or by the film material defects. The set of quality tests ensures stable operation of a straw tracker over 10-15 years, as is demonstrated by the NA62 Straw Tracker.

The USW straw production technology eliminates many of fundamental disadvantages of the winding technology. This has a direct impact on reliability and operational stability of large area straw trackers, especially the ones operating at gas overpressure or in vacuum.

The USW straw production technology continues to evolve. For the DUNE Straw Tracker, double-side metallization is used to compensate gas permeability of the extremely thin, of 20 micrometers, Mylar film. Since xenon is considered to be used as the main component of the working gas mixture, and the tracker consisting of 200,000 straws have rather large volume, the double-sided aluminum metallization is proposed to reduce gas diffusion through the thin straw walls. However, during the welding process, aluminum oxide originating from the top metallization layer damages the titanium surface of ultrasonic welding head. To address this issue, a dedicated technology has been developed to remove the top aluminum layer using a UV laser [6]. The quality of straw tubes manufactured this way are identical to the quality of straws produced from single-side metallized films.

Currently, a new (upgraded) production line is being manufactured in collaboration with colleagues from the Institute of Nuclear Physics (INP, Almaty, Kazakhstan). This line is planned to be deployed at the INP site, further expanding the geographical footprint and production capabilities of this advanced technology.

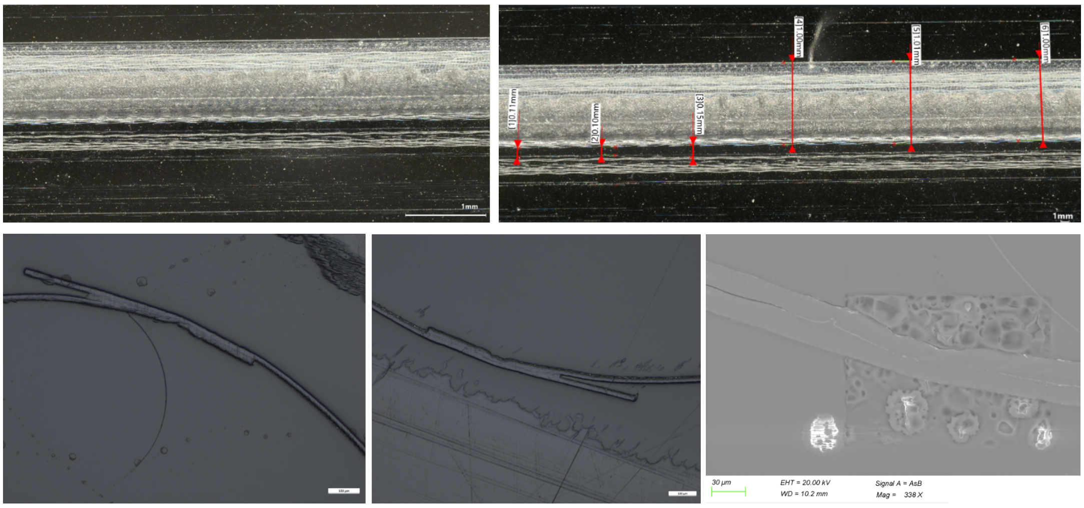

Figure 3: Microscopic images of a 5 mm diameter USW straw. Top: overview of the surface (left) and measurements of the seam width and position (right). Bottom: images of the straw cross-section arounds the seam area.

4 Applications

The straws are assembled into tracker modules consisting of hundreds or thousands of tubes. This modular design simplifies transportation, installation, and upgrade of the straw tracker. Each module undergoes testing for hermeticity, electrical integrity, and response to ionizing radiation. Due to their advantages, detectors made of USW tubes find application in High Energy and Neutrino Physics Experiments. Below are the examples of operating and developing Straw Trackers.

The Straw Tracker of the NA62 experiment [7] consists of four stations installed in a single vacuum chamber with pressure around 10^{-6} mbar. The vacuum allows to minimize multiple scattering and background interactions. Each station includes four layers of straw oriented in the X, Y, U, V projections, where U and V are rotated at $\pm 45^o$ relative to the primary axes, providing three-dimensional track reconstruction. The tracker consists of around 7,000 straws with lengths up to 2.1 m and a diameter of 9.8 mm. The straws are made of 36 μm thick Mylar film coated with copper (50 nm) and gold (20 nm) layers. The tracker operates with a 70% Ar + 30% CO_2 gas mixture.

The tracker has the spatial resolution of about 130 um, the detection efficiency higher than 99%, and low material budget, less than 0.5% X0 per tracker station. The NA62 Straw Tracker is the first large area tracker made from USW straws. The tracker operates in vacuum for over ten years without any degradation. Its successful operation has confirmed the reliability of the USW technology and established it as a benchmark for future Straw Tracker developing for COMET, SHiP, DUNE, FCC-ee and SPD experiments.

The Spin Physics Detector (SPD) [8] at the NICA collider at JINR is designed to explore the nucleon spin structure with colliding polarized proton and deuteron beams.The inner barrel tracker will consist of about 20,000 USW straws placed in a solenoidal magnetic field of up to 1 T. The single-straw hit resolution of about 150 μm will provide a transverse momentum resolution of about 2% for a particle

Figure 4: Left: Installation of the NA62 tracker module. Right: Photo of the NA62 tracker plane.

momentum of 1 GeV/ c. In addition to momentum measurements, the Straw Tracker will also provide particle identification at the first stage of SPD operation.

The Straw Tube Tracker (STT) for the near detector complex of DUNE [9] represents a novel detector concept for neutrino physics, alternating a large number of thin passive targets (each ~ 1.5 of radiation length) with tracking modules composed of four straw layers (XXYY) with negligible mass. The passive targets can be unmounted or replaced during data taking with a broad range of materials manufactured in the form of thin planes with high chemical purity. A key feature is the concept of "solid" hydrogen target, obtained by subtracting measurements on dedicated graphite (C) targets from those on polypropylene (CH_2) targets. This technique allows a determination of neutrino flux with precisions not achievable with other known approaches. The unique combination of hydrogen and nuclear targets within STT also allows to directly constrain the nuclear smearing resulting in an accurate calibration of the neutrino energy scale and, in turn, in a broad program of precision measurements and searches for new physics. The STT includes a total of about 200,000 straws with an average length of 3.2 m, a diameter of 5 mm, and 19 μm walls with 70 nm Al coatings on both sides. The straws are operated with Xe/CO_2 and Ar/CO_2 (70%/30%) mixtures at an absolute internal pressure of 2 bar. The tracking modules, only 28 mm thick, are designed to be self-supporting and integrate the electronic readout into a rigid carbon-composite frame, together with all required gas and electrical connections.

Particle identification is available throughout the STT volume by exploiting the ionization signals dE/dx by charged particles, the transition radiation by high energy electrons, momentum-range relations, and time of flight. The electronic readout provides measurements of both the drift time and the charge deposited in the straws, with a dynamic range of about 10^3. The detector is expected to start data taking in 2032.

5 Conclusion

The ultrasonic welding (USW) technology for straw tube production has been developed and refined to overcome the intrinsic limitations of glued and wound straws. It provides significant improvements in mechanical stability, hermeticity, and operational reliability under vacuum and overpressure conditions. The long-term stable performance of the NA62 Straw Tracker convincingly demonstrates the maturity and robustness of this method.

Further advances, including double-sided metallization and laser-assisted treatment, extend the applicability of USW to extremely thin films and large-volume detectors required in next-generation experiments. These achievements establish USW as a key enabling technology for future high-precision tracking systems in high-energy and neutrino physics.

References

[1] V.D. Peshekhonov, Phys. Part. Nucl. **46**, 94 (2015).

[2] E. Abat et al. [ATLAS TRT], JINST **3**, P02013 (2008).

[3] V.N. Bychkov et al., Part. Nucl. Lett. **111**, 64 (2002).

[4] N.I. Azorskii et al., Phys. Part. Nucl. Lett. **14**(1), 144 (2017).

[5] S.A. Movchan, V.V. Elsha, Yu.V. Ershov, S.N. Shkarovsky, Yu.K. Potrebenikov, V.D. Kekelidze, E.M. Kislov, T.L. Enik, N.I. Azorsky, A.O. Kolesnikov, *Device for cylindrical tubes manufacturing for gas filled drift detectors of ionisation radiation*, Russian Federation Patent No. RU 2555693 C1 (2015), Federal Institute of Industrial Property (FIPS).

[6] V. Bautin et al. [StrawTrackerRD team], Nucl. Instrum. Meth. A **1081**, 170767 (2026).

[7] H. Danielsson [NA62], *Performance and operation of the straw detector in the NA62 rare kaon decay experiment*, Proc. IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), San Diego, CA, USA, **2015**, 1 (2015).

[8] V. Abazov et al. [SPD], *Technical Design Report of the Spin Physics Detector at NICA*, Natural Sci. Rev. **1**, 1 (2024), arXiv:2404.08317 [hep-ex].

[9] V. Hewes et al. [DUNE], *Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report*, Instruments **5**(4), 31 (2021), arXiv:2103.13910 [physics.ins-det].