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SUMMARY OF THE ARIES WORKSHOP ON MATERIALS AND ENGINEERING TECHNOLOGIES FOR PARTICLE ACCELERATOR BEAM DIAGNOSTIC INSTRUMENTS*

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Abstract

ARIES is an EU-sponsored programme for accelerator research and innovation. An international workshop was held online as part of this programme in June 2021 on the topic of 'Materials and Engineering Technologies for Particle Accelerator Beam Diagnostic Instruments'. The aim of the workshop was to bring together instrument designers, experts and industry and research groups to review the state of the art in the field, present designs and discuss future challenges, whilst also developing and strengthening collaborations between groups. There were sessions covering 'Instrument design and operation', 'Novel materials and applications' and 'New technology and components' over the three half-days of the online meeting. This paper reviews the key topics presented at the workshop.

INTRODUCTION

Over the years 2017 to 2021 the EU-funded ARIES programme [1] is funding a number of topical meetings on specific areas of interest to the accelerator beam instrumentation community through the work-package ARIES-ADA [2,3]. The workshop [4] under consideration within this publication was targeted at design and technology of physical instruments – an area which receives relatively little coverage in the literature. It was originally planned as a face-to-face meeting at Wadham College, Oxford but was postponed and finally re-structured as a remote meeting in June 2021 with a programme of 20 talks, reduced from the original 32. This included four talks from European industry, demonstrating close links to science in the field.

There were 205 participants registered from around the globe resulting in lively online discussions performed in dedicated break-out rooms for each talk.

BEAM INSTRUMENT DESIGN, PRODUCTION & OPERATION

Thibaut Lefevre (CERN) opened the scientific part of the workshop introducing the current beam instrumentation highlights from CERN. He showed how the trends in particle physics accelerators, both on the energy/brightness frontier and in areas such as antimatter and rare isotope physics are creating new challenges for beam instrumentation. CERN has just completed a major upgrade to the LHC injector complex. This required new instrument designs for highly radioactive environments, such as the BTV in the SPS synchrotron [5] as well as new simulation-driven designs for the mitigation of impedance heating. Designs for beam-intercepting devices such as screens and wire scanners have been upgraded with modern thermally resistant materials and faster movements. However, most innovation for current and future machines is related to non-invasive beam profile devices. New devices based on laser stripping of the LINAC4 H^- beams [6] and beam-gas ionisation in the Proton Synchrotron [7] are now operational at CERN whilst upgraded devices using synchrotron light and diffraction radiation are developed for the future High Luminosity LHC.

Gian Luca Orlandi (PSI) presented a collaboration between the Paul Scherrer Institut and Sincrotrone Trieste on electron beam lithography fabricated, freestanding wire scanners [8]. The project aims for minimally invasive electron beam profile measurements with sub-micron resolution. Applications are for FEL user operation and ultra-high precision, transverse beam diagnostics at novel laser and plasma driven accelerators. PSI produced 800 nm and 500 nm wide Au wires of 2 µm thickness and 2 mm beam clearance. FERMI manufactured a set of wires consisting of 3 µm thick sandwiches made of Au (1 µm) and Si_3N_4 (2 µm) and a Ti (20 nm) middle layer with a width of 0.7 µm, 0.8 µm, 1 µm and 2 µm, respectively [9, 10]. Beam tests were successfully conducted at SwissFEL, where a 300 MeV, low charge (1 pC), and low emittance ($\varepsilon_y \sim$ 55 nm) beam can be focused to transverse beam sizes of < 500 nm, see Fig. 1 and [11].

William Andreazza (CERN) presented a new generation of fast wire scanners built for the LHC Injector Upgrade project at CERN and the European Spallation Source in Lund, Sweden [12]. The high power beams require a wide

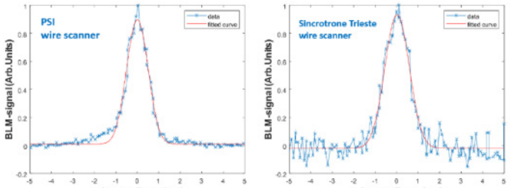

Figure 1: Vertical beam profiles at SwissFEL taken with single shot data acquisitions.The measured beam sizes are 434 ± 7 nm (PSI wire scanner) and 443 ± 33 nm (Sincrotrone Trieste wire scanner).

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range of measurement speeds (5 m/s to 20 m/s) and a position accuracy in the order of 1 µm. Key components are an in-vacuum drive system without kinematic links, a vacuum-compatible frameless electrical motor, a high precision optical encoder (mark width of 6 µm at a pitch of 40 µm) and a metal wire fork fabricated by 3D additive machining technology. Prototypes were extensively tested in all CERN injector rings, and the full series of wire scanners has been delivered to CERN accelerators and ESS.

The contribution by Serena Psoroulas (PSI) focused on the definition of requirements on beam monitoring for clinical applications at the medical cyclotron. The ICRU report (2007) and the IEC standard (60601-2-64, 2014) regulates patient-relevant beam quantities and requires that proton range, dose uniformity, and absolute delivered dose are determined permanently. The monitoring chain of PSI Gantry 1 is based on ionisation chambers for dose and position measurement and Hall probe detectors for position and energy monitoring. To avoid drawbacks caused by ionisation chambers, particularly at high beam currents [13], a new resonant position and current monitor prototype is being investigated [14].

Benjamin Moser (CERN) showed the recently developed production procedure for SEM-Grids at CERN as depicted in Fig. 2. The PCB substrate for the wire support consists of alumina (Al_2O_3) with a purity of 96-97 %. It is equipped with 1 MΩ SMD resistors to verify the condition of the wires without beam. For the electrical connection between the feedthrough and the wire support, PICAL NP polyimide film is used as a base for flex-PCBs. The properties of an improved winding machine were discussed. This machine allows for efficient preparation of the wires. CERN brought forward "sticking wires" as a topic for discussion. A potential solution has already been designed but has not yet been tested in the machine. The discussion at the end mainly revolved around different ways to maintain tension in wires lost due to thermal expansion from by beam heating.

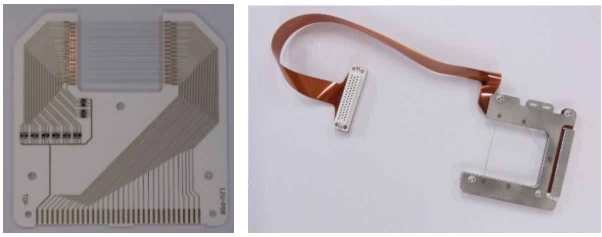


Figure 2: CERN standard SEM-Grid: Left: Alumina PCB with wires and resistors; right: assembly with Flex-PCB.

The contribution by Dirk Lipka (DESY) described a formalised approach for the realisation of a diagnostics system from design up to implementation of a large-scale accelerator, using the example of a button BPM [15, 16]. All requirements and conditions have to be collected, and subsequently, these conditions have to be divided into required sub-systems, e.g. mechanics and electronics. Here simulation tools speed up the design time as the tools can predict the behaviour with high precision. Attention has to be taken to the correct use of simulation tools, e.g. meshing and convergence. The design phase is completed with tolerance studies to prepare the construction. For a large number of items, initial pre-series are required to train companies for the final production. During the series production, the pieces should be checked to optimise the results and production process. In parallel, electronics should be developed and produced. Finally, the system has to be installed, calibrated and commissioned.

Alun Morgen (DSL) reported on a dedicated workshop on button BPM production held in May 2019 [17] and reported recently [18]. The topic is of great relevance due to the large quantity installed at any light source. Glass sealing technology is attracting increased interest, with several facilities receiving of prototype buttons to gain experience with this technology. Communication with the supplier at all stages of the process was identified as key to success. Particular care needed to be taken when the design is handed from one sub group to another e.g. subcontractors, or moving from design engineers to machinists. An increase in the in-house testing capability of facilities will be needed to establish and maintain the level of quality and tolerancing required for the successful operation of our diagnostics devices. In order to enable that and allow the tracking of individual components through the testing and validation processes, laser marking is being investigated.

Magnetically coupled drives are recently developed and commercially available for ultra-high vacuum applications, as Nick Clark (from the UHV-Design company) reported. There are several features: Non-polymer and without dry lubricant, all-metal and ceramic push-pulls for the lowest outgassing and lowest friction; high speed and high precision pneumatic and ball screw driven actuators designed explicitly for beam diagnostics. Different designs for the magnet assemblies exist, providing high coupling forces or torque and minimal external stray magnetic fields. Case studies are executed in collaboration between industry (here UHV-Design) and major institutes like BNL, CERN, Diamond and PSI, such as fast wire scanners.

NOVEL MATERIALS & APPLICATIONS

John Huber’s team at University of Oxford, together with the CERN beam instrumentation group, explored different candidates for wire materials which could be viable for fast wire scanners, as current materials are expected to be unsuitable due to the associated temperatures and mechanical loads. Using the concepts behind Ashby diagrams [19, 20], a merit index was developed for selecting the wire material as depicted in Fig. 3 [21]. It suggested the best materials would be carbon-based, such as carbon nanotubes (CNT) and CNT ropes. Nearby competitor materials including beryllium and boron carbide were also identified. The force displacement response was measured for candidate materials including CNT ropes of different thicknesses. Combining this with thermal properties and density data, it was possible to identify CNT ropes on the Ashby diagram and confirm their superior performance. The group had also examined failure mechanisms in some of the wires, identifying the CNT ropes as preferable to ordinary carbon fibres due to having less statistical variation in breaking strength.

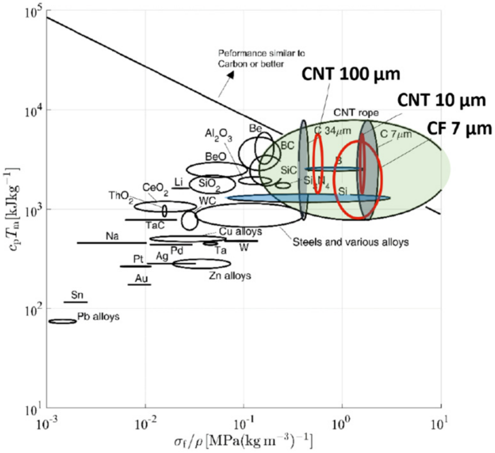


Figure 3: Ashby map showing the thermal and mechanical performance for potential wire scanner materials [21].

Alexandre Mariet (CERN) extended the discussion of carbon-based wire materials. For intense beam interactions local overheating can lead to sublimation, and hence premature failure during subsequent usage. He provided the properties of different CNT allotropes. These included both individual CNTs as well as wound strand CNT. A novel process for manufacturing the CNT wires was presented. Subsequent examination confirmed the presence of only carbon, indicating a material of high quality. In particular, Alexandre contrasted the mechanical behaviour and performance of 30 µm diameter CNTs and CNT wires, showing clear differences in their mode of failure.

Mike Barnes (CERN) discussed the design and optimisation of ferrite-based materials used for kickers, and the challenges posed by the high temperatures that can be developed due to beam-induced current. For the specific work described, hot-isostatic pressing (HIP) was employed to manufacture a bulk ferrite material from constituent powder, resulting in a near net dense compact. HIP exhibited a noticeable improvement in thermal properties, while the frequency-dependent magnetic permeability limits the rise-time to a few hundred ns. Adding a thin protective buffer to the magnet (e.g., 3 µm Ti), resulted in shifting its activation time by ~100 ns. These measurements were shown to be in good agreement with a thermal model which includes radiation transport.

Kevin Jordan (JLAB) talked about the use of boron nitride nanotubes (BNNT) as scintillators. In recent years, several studies were carried out at BNL, GSI and JLAB using BN as a scintillator, showing outstanding performance with electrons between 1.6 MeV and 7.4 GeV, and Au ions at 4.8 MeV/u. The presentation showed BN nanotubes of 2-6 nm diameter, providing mechanical properties (like tensile strength, Young modulus), as well as scintillator properties: decay time in the order of ns, photon yield four times lower than Chromox, and peak emission wavelength below 500 nm. The material can withstand high beam powers, and studies for its lifetime and resolution were presented.

Silke Vilcins (DESY) talked about changes to 316LN ESR material properties after high-temperature treatment. She provided practical advice and pragmatic solutions based on experience over the last 30 years. Processes like welding, brazing and stress relief heat treatments require special attention because they affect material properties like hardness, permittivity, grain structure or nitride concentration. At temperatures below 300ºC, there is almost no outgassing because the thermal energy is too low. Between 500ºC and 900ºC, there is the formation of M23C6 and possibly s-phase intergranular corrosion and grain disintegration. A vacuum annealing treatment, which leads to a low outgassing rate with constant hardness, appears challenging. Finally, a new material called 'Alloy 50' was presented as an alternative due to its superior hardness limits, low permittivity, good weldability.

Ivo Wevers (CERN) described the outgassing rate of four common polymers used in accelerators: PEEK, Kapton, Mylar and Vespel. The description was based on theoretical models and experimental results, and the measurements are well fitted with a 3-step model. At room temperature, the outgassing is initially very high but decays rapidly after a certain amount of time $\tau/2$, depending mainly on the thickness. Higher moisture content causes higher outgassing rates during all stages of the pump-down, while a greater diffusion coefficient (although increasing the initial outgassing rates) results in overall lower outgassing rates, particularly for pumping times beyond $\tau/2$. Finally, it was shown that storing polymeric parts with dried silica gel granules can effectively reduce their outgassing rates, but exposure to air during installation must be minimized.

Coming from a private company, Klaus Bergner (company VACOM) shared his experience of adequately defining the quality requirements. The focus was set on surface cleanliness in the manufacturing of vacuum components. In this regard, the specifications should be given for the total outgassing rate in the assembly and quantitatively so that the user can test and validate them. Thus, continuous communication between user and supplier is essential.

NEW TECHNOLOGIES & COMPONENTS

Gerhard Schneider (CERN) reported on his experience with viewports and mirrors. About 250 window flanges are installed on the CERN accelerator complex, either made of borosilicate glass (Kodial) or fused silica (quartz) glass. CERN has experienced failures of brand-new window flanges, mainly with fused silica material. Investigating the cause, they found out that window flange manufacturers used elastomer seals during leak tests, different from the use-case with non-annealed copper gaskets. The failure analyses led to a new technical specification requiring 100% of the window flanges to be tested with CERN supplied gaskets and baked to the nominal temperature. Metal flange parts and windows are usually procured by the window flange manufacturer from a sub-contractor. The real expertise of the manufacturer is solely the connection from the glass window to the weld ring and the welding of the ring to the base flange material. Weld rings must carefully be chosen, considering radiation and magnetic parameters and possible oxidation and low differential thermal expansion coefficient versus the optical window.

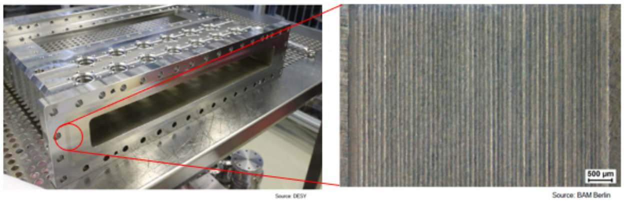
Slava Grishin (ESS ERIC) shared his experience on 16 years of collaborative work between CERN and IHEP (Protvino), where more than 5000 beam loss monitor (BLM) detectors of various types have been produced. The manufacturing process was under the responsibility of IHEP, using industry-produced components [22, 23]. For the success of such a collaborative project, crucial points are generally design optimisation and organisation of the collaboration between both partners particularly for specification and selection of industrial suppliers and components. The production of prototypes (with a pre-series for a large number of items), continuous material verification, continuous monitoring of the production schedule, several tests before, during and after production, final installation, and final control of detector performance are all key to success. Driven by the system complexity, no compromise should be allowed in some details, however, a high focus should be placed on quality assurance.

Ben Jensen (company Surrey NanoSystems) presented coatings for UHV instrument stray light suppression. Such coatings should have high absorbance at specific instrumentation wavelengths, both good Total Integrated Scattering (TIS) values and spectral Bidirectional Reflectance Distribution Function (BRDF) and low outgassing at chamber operational temperatures. They should be compatible with UHV bake-out and experience no degradation from long term UV exposure, be tolerant to radiation exposure, thermally stable and electrically conductive. Based on company experience in space technology applications, super-black coatings were developed (brand name Vantablack). Two such coatings were discussed, which were already tested at CERN: S-VIS and CX2 (a beta phase development coating). While both materials are spray applied, S-VIS requires vacuum post-processing (activation) to create the required absorbing cavities. This coating shows good UV-THz performance and seems to be well suited for applications in an accelerator environment.

Additive Manufacturing (AM) in Beam Instrumentation was presented by Ana Miarnau (CERN): A brief description of the techniques of AM was given. The "Selective Laser Melting" technique is used at CERN for the production of vacuum parts. Some mechanical constraints such as roughness, tolerances and vacuum constraints like impurities and porosity were reported. However, outgassing tests at CERN showed a typically clean and unbaked metal pump-down curve without significant contamination. Some examples from CERN were discussed [24].

The Easy Alignment System (EASy) was described by Ufuk Akkaya (DESY). New High-Precision 6-Axes-Positioning devices, the EASy-family, was developed at DESY to meet the needs of accelerators/experiments for high precision and stiffness. It has the advantage of combining compactness and a carrying capacity between 10 kg to > 5000 kg with a precision of weight-dependent positioning 1 to 20 µm. A standardised motor control unit will ensure integration in control systems whilst manual operation is also possible.

A sealing technology for high precision wide open vacuum flanges and waveguide connections was presented by Martin Lemke (DESY). The traditional metal sealing technology for large vacuum flanges requires a mirror-like surface. The new concept introduces small grooves on the sealing surface with about 50 µm depth and distance from each other of about 25 µm; an example is depicted in Fig. 4. This concept also reduces the requirements of the flange surface by some factors. No vacuum leaks were discovered during tests and installations at DESY and BESSY.



Source: DESY

Source: BAM Berlin

Figure 4: A large flange vacuum chamber with the grooves. The zoom shows a high magnification photo of one of the first test pieces.

CONCLUSION

The workshop took place with a lively atmosphere even despite the absence of a face-to-face contact. Each session was followed by a breakout room session, with one virtual room per speaker. This gave a more informal environment where detailed questions and discussions could be held and proved very successful, with some discussions, in particular those not discussed in regular conferences, lasting for an hour after the end of the programme.

Raymond Veness (CERN) chaired the final wrap-up session. He summarised some subjects of general interest to be followed-up by the community. These included:

- The use of nanotubes (carbon, boron nitride) for beam intercepting and other instrumentation uses
- Particle-free and low particle count devices and environments
- Development of a new generation of precision linear wire scanners
- The usage of magnetically coupled drives for UHV applications
- Novel methods of black coatings for optical light absorption.

Beam instrumentation experts from laboratories around the world were keen to share knowledge and best-practice in these areas, and it was agreed to make e-mail groups for the interested parties.

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