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ENHANCING EXPERIMENTAL PROSPECTS WITH LOW ENERGY ANTIPROTONS*

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Abstract

The Extra Low Energy Antiproton ring (ELENA) is a critical upgrade to the Antiproton Decelerator (AD) at CERN and saw first beam in 2018. ELENA will significantly enhance the achievable quality of low energy antiproton beams and enable new experiments. To fully exploit the potential of this new facility, advances are required in numerical tools that can adequately model beam transport, life time and interaction, beam diagnostics tools and detectors to fully characterize the beam's properties, as well as in novel experiments that take advantage of the enhanced beam quality that ELENA can provide. These research areas are in the heart of the pan-European research and training network AVA (Accelerators Validating Antimatter physics) which started in 2017. This paper presents research results within AVA on the performance of ultra-thin diamond membranes, beam tracking and optimization of the ELENA beam lines, as well as efficient integration and performance optimization of cryogenic detectors.

INTRODUCTION

The AVA (Accelerators Validating Antimatter physics) project is an Innovative Training Network (ITN) that has received 4 Million Euro of funding within the H2020 Marie Skłodowska Curie Actions [1]. The project enables an interdisciplinary and cross-sector program on antimatter R&D . The network includes most of the European expertise in antimatter research and joins 4 universities, 8 national and international research centers and 13 partners from industry and government. Within AVA, partners carry out research across three scientific work packages.

Fifteen early stage researchers have been recruited to established scientific teams. They are based at institutions across Europe. A structured combination of local and network-wide training is offered to them. This includes hands-on training at state of-the-art accelerator facilities, as well as an international training program consisting of schools, topical workshops and conferences that is open to all AVA Fellows, as well as the wider scientific community. In the center of several project has been ELENA, a small storage ring designed to decelerate the 5.3 MeV antiprotons from the AD even further. The ring was commissioned in 2018 to improve the conditions for antimatter experiments dramatically. Amongst others, it will reduce antiproton energies to below 0.1 MeV which will help enhance antiproton trapping efficiency by 10 and 100 times. On the long term, a potential Facility for Low energy Antiproton and Ion Research (FLAIR) [2] might provide additional research opportunities.

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RESEARCH

To fully exploit the potential of ELENA and FLAIR, the AVA partners carry out a closely connected R&D program in the following three work packages:

- **Facility Design and Optimization**, addressing beam lifetime and stability in storage rings, as well as beam cooling, deceleration and extraction;
- Design, development and testing of novel **Beam Diagnostics** to fully determine the characteristics of low energy antiproton and ion beams;
- Design of novel low energy **Antimatter Experiments** to explore fundamental symmetries and interactions.

The research within AVA has already led to a number of high impact physics results: This includes the measurement of ultralow heating rates of a single antiproton in a cryogenic Penning trap [3], the production of long-lived 2 ^{3}S positronium via 3 ^{3}P laser excitation in magnetic and electric fields [4], and the measurement of sympathetic cooling of protons and antiprotons with a common endcap Penning trap [5]. The following sections summarize the directly accelerator-related research results from selected projects.

Diamond membranes for low energy beams

There are several ways of detecting particles, including gaseous and solid-state detectors. For solid state detectors one uses semiconducting materials, usually either silicon, germanium or diamond. Silicon and germanium detectors have traditionally been widely used, but lately diamond detectors have gained some popularity [6]. Their advantages are radiation hardness, lower leakage current, low thermic noise, fast response and they also require no cooling. The aim of this project at CIVIDEC is to produce and characterize ultra-thin diamond detectors and use them for particle detection, in particular for antiproton measurements. During his project, AVA Fellow Miha Cerv has so far:

- Developed different VHDL implementations for real time signal analysis, particle identification, spectroscopy, rate monitoring and phase measurements;
- Tested and calibrated diamond detectors in laboratory experiments;
- Carried out measurements with antiprotons in the GRACE beam line at CERN.

Initial measurements gave interesting results: Waveforms showed a first flash of particles - a result of antiprotons annihilating in the beam pipe and on the electrons – which was followed by signals caused by single particles identified as low energy antiprotons. Most of these signals were recorded in full, but a small number of them contained huge pulses that completely saturated the detector. These

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big signals are believed to be antiprotons, annihilating in the detector. The rarity of these events was likely due to the electrode being too thick. This meant that most of the annihilation happened in the electrode. A thinner electrode would allow for more antiprotons to reach the diamond. For the next measurement campaign, a new detector was produced, see Fig. 1.

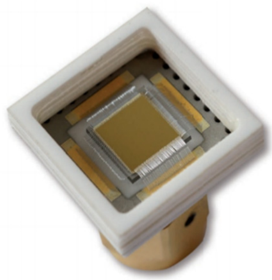

Figure 1: Photograph of diamond Knopf-detector, used for tests at CERN.

The thickness of the diamond was chosen again to be 500 μm, but this time the electrode was made much thinner, only 100 nm in thickness and made of titanium with a gold ring for wire bonding. The voltage range of the measurement was also adjusted so that signals from annihilation in the diamond can be recorded. A second series of measurements was carried out in October and November 2018. All data was taken in the GRACE beam line of the AEgIS experiment. Initial problems with triggering and ringing on the measuring channel were quickly overcome and a lot of useful data was recorded, see Fig. 2 as an example. Full data analysis is still being done, but initial results showed that much more annihilation events happened inside the diamond.

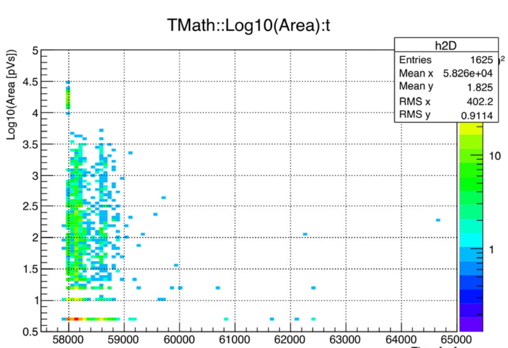

Figure 2: Example signals from measurements in GRACE beam line at AEgIS.

It should be pointed out that both measurement campaigns had a rather low total count rate, as data was taken "parasitically" to other studies at AEgIS. In addition, the rate of antiprotons coming from the Antiproton Decelerator is very low anyway, with only shot of 10^7 antiprotons provided every 110 seconds. All shots were shared between several experiments. It is planned to next use diamond detectors in combination with real-time signal processing to better understand the full capabilities of this detector. Studies will then also include a pixelated electrode which might give further insight into the beam.

Beam Tracking Studies

Some of the envisaged experiments at ELENA and FLAIR require beam compression to a diameter of around 1 mm and a pulse length of only 1-2 ns. In order to identify ways of how this can be achieved, a more comprehensive approach to beam propagation simulations inside low energy rings and transfer lines had to be developed. AVA Fellow Volodymyr Rodin combined several existing simulation tools into one versatile toolkit: G4Beamline, BETACOOL, MADX, BMAD and CST Particle Studio.

Results of different codes were benchmarked against each other and also against analytical results at different stages of the simulation process to ensure that the physics of beam transport was correctly represented, see Fig. 3. This was also important to identify the individual weaknesses and limitations of the various codes.

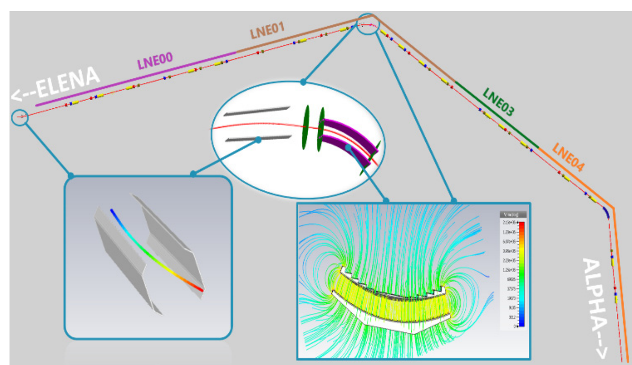

Figure 3: Simulation results from 3D tracking studies through ELENA beam line to ALPHA.

To simulate the ELENA transfer lines properly, the G4Beamline code was modified, allowing an easy implementation of electrostatic optics. As opposed to particle tracking codes such as MADX, particles in this code are propagated through a realistic 3D environment where they may be subject to additional forces and effects based on boundary conditions that can be set by the user. At such low beam energies, even small electrostatic field imperfections can have a significant impact on the orbit and quality of the beam. Hence, any simulation should take a number of factors into account, including parameterized shapes of inhomogeneous and fringe fields, stray magnetic fields, residual gases, heating effects, space charge effects and other scattering and collective effects.

As part of this work, a novel way of measuring the real electrostatic field distribution with state-of-art MEMS sensors, was developed [7]. Initial data taken at CERN and more detailed measurements on individual electrostatic elements at TU Vienna gave excellent results [8]. This data was then used as input to describe the beam line.

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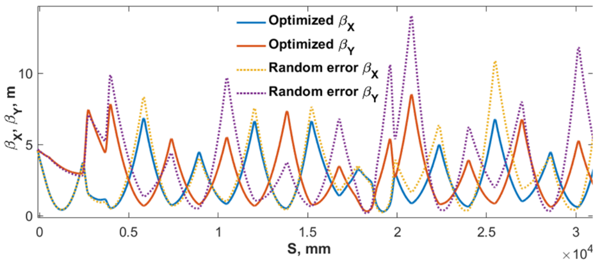

Figure 4: Transfer line before and after tuning.

In order to then maximize transmission and obtain various desired characteristics, the full beamline must be tuned. For this optimization non-dominated sorting genetic algorithm II (NSGA-II) is often used [9]. However, it requires many iterations before providing meaningful results. *Paretosearch* is a new multi-objective algorithm added in recent version of Matlab [10]. An example of optimized beam transport using this method through a full transfer line is shown in the Fig. 4 above. More details can be found elsewhere in these proceedings [11].

Cryogenic Detectors

Image charge detection has proven to be a reliable tool for non-destructive particle detection. This holds especially for cryogenic Penning Traps, in which the highly precise determination of a trapped particle's motion is the key element not only for its detection but also for determination of key particle properties such as mass, charge and magnetic moment.

The recent advent of a new transistor technology promises a significant increase of detection efficiency and a more reliable way to build the critical and delicate detectors. The evaluation of the novel components and their implementation into easy-to-use control electronics, providing a simple and efficient tool for the experimentalists, is an interesting challenge.

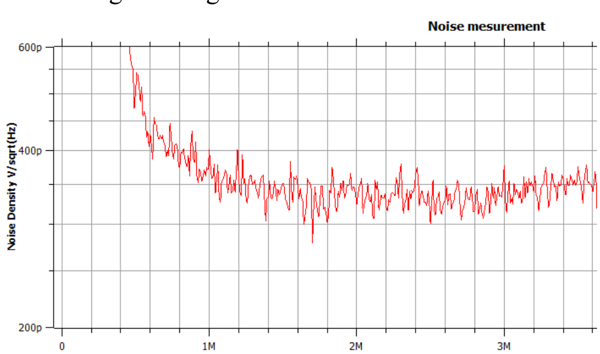

Figure 5: Noise measurements of cryogenic detector as function of frequency.

For ion trap experiments, amplifier technologies are required with superior sensitivity and ruggedness. Also, amplifiers have to be suitable for using directly inside a cryogenic vacuum setup with strong magnetic fields up to several Tesla.

The project of AVA Fellow Ilia Blinov at Stahl Electronics, Germany targets the advancement of single particle detectors, integrated into a cryogenic environment. He has designed and characterized a new prototype of cryogenic amplifier. The amplifier is based on custom-made GaAs transistor and uses an improved layout with 50% lower input capacitance than the previous model series. First tests were done in collaboration with GSI where the amplifiers were installed in the HILITE setup for charge counting purposes. These measurements show a greatly improved sensitivity of almost a factor of 3 which marks a major step forward in this field, especially for single-pass particle detection in beam lines. The sensor was also analyzed in detail with regards to its noise sensitivity as a function of frequency, see Fig. 5. Future studies will focus on further improving the technology readiness level of the sensor so it can become an off-the-shelf device for use in different environments.

TRAINING EVENTS

Training within AVA consists of research-led training at the respective host in combination with local lectures, as well as participation in a network-wide training program that is also open to external participants. This training concept builds on the successful ideas developed within the DITANET, oPAC and LA^{3}NET projects [12-14].

All Fellows were given the opportunity to enroll into a PhD program and follow the postgraduate training of the university where they are registered. In addition, AVA organizes international schools, workshops and conferences that provide specific training and give extensive networking opportunities. A week-long international Schools on Antimatter Research was already held at CERN between 25-29 June 2018 [15], as well as Topical Workshops on Diagnostics and Detectors at CIVIDEC 15-17 October 2018 [16] and Low Energy Facility Design and Optimization at GSI on 6-7 February 2019 [17]. The project will next hold an International Symposium on Accelerators for Science and Society on 28 June 2019 at the ACC in Liverpool, UK where all talks will also be live-streamed [18]. This will be followed by a Workshop on Machine-Experiment Interface on 10-11 October 2019 with COSYLAB as local host, details will be announced via the project home page [1]. More details about the network can also be obtained through the project video, produced by the AVA Fellows and network partner Carbon Digital [19].

CONCLUSION

Research in the AVA project has already produced a number of remarkable results. Some selected accelerator R&D outcomes were summarized in this paper. It is expected that these results will find much broader application than "only" at low energy antiproton facilities as the resulting benefits will also enhance the performance of other low energy ion beam facilities. The training program of the network is now also running at full speed with first events already held at venues across Europe and many more in the planning.

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