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NEW OPPORTUNITIES IN LOW ENERGY ANTIPROTON RESEARCH*

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Abstract

Experiments with low energy antiprotons are at the cutting edge of science and offer unique opportunities to test some of the fundamental laws of physics. The experiments are, however, very difficult to realize. They critically depend on high performance numerical tools that can model realistic beam transport and storage and also require advanced beam monitors and detectors that can fully characterize the beam. Finally, novel experiments need to be designed that exploit the enhanced beam quality that the new ELENA ring at CERN provides.

This paper presents some selected findings from the pan-European AVA network's three scientific work packages. It shows results from studies into electron cooling at the new ELENA storage ring, research into carbon nanotubes as cold electron field emitters for electron cooling and how antiproton-atom collision experiments can be optimized using GEANT4. Finally, the paper gives an overview of the network's interdisciplinary training program.

INTRODUCTION

The project Accelerators Validating Antimatter physics (AVA) enables an interdisciplinary and cross-sector R&D program on antimatter research at the AD and the future FLAIR facility in Germany [1]. The network comprises 13 universities, 9 national and international research centers and 13 partners from industry.

The project has successfully trained 16 early-stage researchers that were based at universities, research centers and companies across Europe where they carried out cutting edge research into low energy antimatter physics and related technologies.

Each Fellow also benefited from a comprehensive training program. In addition to research-based training at their host institution, the Fellows received a wider network-based training. This training included scientific schools, workshops that provided them with skills and knowledge in wider R&D, beyond their core research project, as well as training in complementary skills, enhancing their future employability. This paper gives a few examples from research outcomes presented at this year's IPAC conferences, as well as the events that have been organized to date.

SELECTED RESEARCH RESULTS

The AVA partners carry out a closely connected R&D program across three scientific 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 [2], the production of long-lived 2 ^{3}S positronium via 3 ^{3}P laser excitation in magnetic and electric fields [3], and the measurement of sympathetic cooling of protons and antiprotons with a common endcap Penning trap [4]. The following sections summarize the directly accelerator-related research results from selected projects.

Optimization of Electron Cooling

The Extra Low ENergy Antiproton (ELENA) ring at CERN [5] will provide cooled, high quality beams of antiprotons with kinetic energies of 100 keV at intensities exceeding those achieved at the Antimatter Decelerator by a factor, depending on the experiment, of between ten to one hundred. The aim of studies by AVA Fellow Bianca Veglia was to investigate the performance of rings, such as ELENA, by means of beam dynamic simulations, and where available compared with existing measurements. This included careful modelling all relevant physics phenomena for this kind of machine which included, but was not limited to: scattering on residual gas, space charge effects, intrabeam scattering (IBS), and interactions with the electron cooler. A particular challenge for low energy storage rings, such as ELENA, is the beam life-time and beam stability. To address this question, the long-term beam dynamics in ELENA was studied considering different effects which limit the minimum emittance achievable through electron cooling. The lattice structure of ELENA was used to perform computations in MAD-X [6] and multiparticle tracking was done in BETACOOL [7]. This required modeling various effects acting on the circulating beam and combining their action to calculate anticipated heating/cooling rates and the evolution of beam characteristics.

The cooling process can be described by two approaches: dielectric theory and binary collision approximation [8]. However, neither of these models provide a closed solution for the resulting cooling force. It is therefore necessary to find appropriate numerical approximations. In BETACOOL, the standard approach is to use the semi-empirical expression of the cooling force proposed by Parkhomchuk [9]. There are many effects contributing to the longitudinal temperature root mean square (rms) velocity

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spread [10] which is a parameter in the Parkhomchuk formula and it determines the location of the maximum of the longitudinal component. These quantities require measurements at ELENA which are not currently available. Therefore, the Erlangen model [8] was opted for in the simulations, since it allows to evaluate the intensity of the force without the need of empirical parameters.

Figure 1 shows the evolution of the horizontal and vertical emittance in the presence of cooling, IBS and scattering on the residual gas [11]. The simulation was compared with measurements obtained by intercepting the circulating beam with a blade (scraper) [12] before and after the electron cooler was switched on. A very good agreement between the simulations and experimental data was found, suggesting that the model includes all relevant effects influencing the beam emittance.

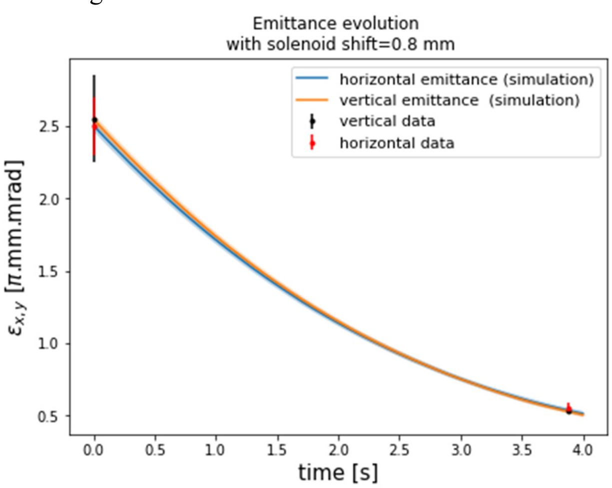

Figure 1: Simulated evolution of the horizontal and vertical emittance at 100 keV compared with scraper measurements after 3.88 s of electron cooling [11].

Carbon Nanotubes as Electron Field Emitters

Closely linked to the studies into the electron cooling process mentioned in the previous section is the question of how to best produce a high quality cold electron beam in the ELENA electron cooler.

Currently, a thermionic gun is used at CERN, however, its performance is limited due to the relatively high transverse energy of the emitted beam, $E_{trans}>100$ *meV*. AVA Fellow Bruno Galante has been investigating carbon nanotubes (CNTs) as electron field emitters, potentially providing cold electron beams for the cooler.

Field emission (FE) has become a florid research field because of the rise of 2D nano-structures, which can greatly enhance the FE properties, allowing to extract high currents at low applied electric fields. They are considered as the most promising FE material, allowing to reach high current densities while having good chemical and emission stability. Several groups have reported promising results using arrays of vertically aligned CNTs, minimizing screening effects which can severely affect FE performances [13, 14].

Two different array types have been characterized thus far: a honeycomb-like array and a squared-islands array. These have been tested with regards to their emitted current as a function of the applied electric field, emission stability, lifetime and beam energy. Detailed results along data from conditioning tests are presented elsewhere at this conference [15].

In addition, measurements of the samples' work function during thermal annealing were carried out to investigate whether air exposure affects the work function. The annealing was conducted in 4 steps: 180 ºC for 30 mins, 180 ºC for 120 mins, 250 ºC for 240 mins and finally 300 ºC for 180 mins.

Figure 2 shows that the work function for all samples stays within the measurement uncertainty W=4.4 ± 0.1 eV. This finding is also supported by RGA measurements that were done throughout the process. It should be pointed out that the measurements were done on an area of about 5 mm x 5 mm, meaning that local contaminations may still lead to changes in the work function in localized areas. This could play a role in stability variations during the first stages of beam emission.

The tests have indicated a good stability and promising lifetime honeycomb-like arrays. In terms of the maximum current that can be achieved, all samples have reached the target value of 5 mA. In fact, it was shown that samples can reach up to 2 mA/cm^2. However, it was noticed that stability and lifetime improve at low emission currents. This behavior suggests that the use of a large area cathode would be beneficial for optimizing the overall performance for operational use. This will be subject to further studies.

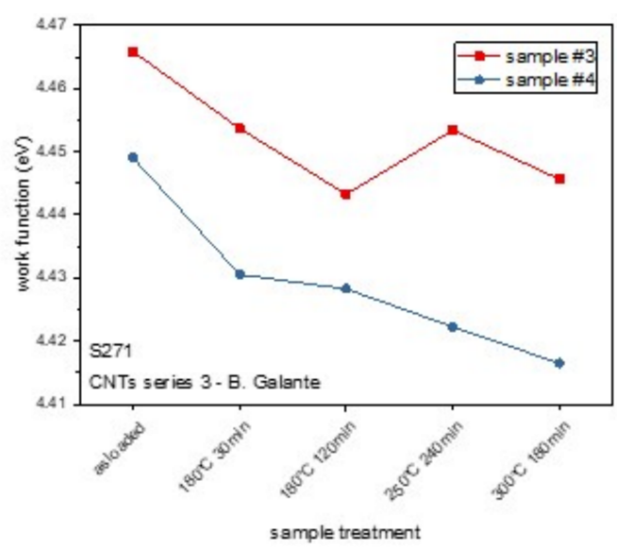

Figure 2: Work function measurements for 2 different CNT samples [15].

Antiproton-atom Collision Studies

The study of the collision dynamics of correlated quantum systems can be done by interaction with a low density atomic or molecular gas-jet target with a beam of low energy antiprotons. Low-energy antiprotons are the ideal and perhaps the only tool to study in detail correlated quantum dynamics of few-electron systems in the sub-femtosecond time regime. However, for the precise detection of products

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of the reaction, this requires a small beam size (~2 mm) and a substantial time reference point.

Research carried out by AVA Fellow Volodymyr Rodin aimed at the development of an experimental setup for these studies for ELENA/FLAIR conditions. His work included the identification of methods to realize compact, ultra-short antiproton beam pulses as required for investigations into the correlation effects in quantum systems. Compression was based on higher order harmonic bunching and longitudinal phase space 'gymnastics' which was previously used to study compression in the ultra-low energy storage ring USR [16], but also included, for the first time, a full 3D description of bunch motion in the storage ring, including all relevant effects on the beam. 6D tracking simulations of antiproton bunch compression in ELENA were done, based on velocity bunching, as wells as bunch splitting technique [17].

Figure 3 shows a realistic bunch compression within an electrostatic transfer line from the storage ring to one of the experiments, including the effect from fringe fields and space charge, as well as other field errors [18]. After reaching the longitudinal focal point, the compressed bunch was ready for the passage of particles through a gas or a solid target, providing a sharp focus and thus a suitable trigger signal for kinematically complete cross section measurements.

On the basis of the results from this study, several improvements can be considered to improve the overall performance: 1) Decreasing the single bunch intensity using high harmonic splitting with two rf systems; 2) Extending simulations to include the combined effects from 3D space charge and intrabeam scattering; 3) Optimizing the reaction microscope design for optimum detection of recoil ions and secondary electrons.

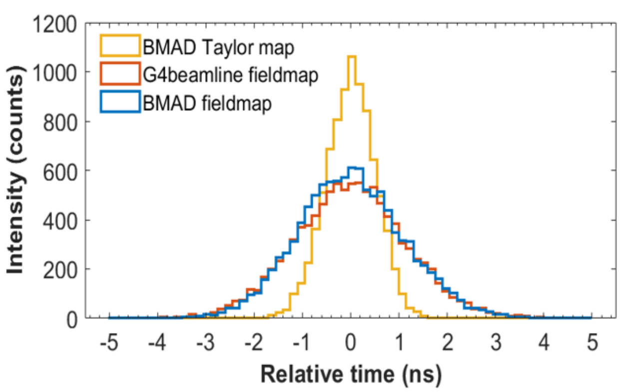

Figure 3: Bunch length obtained from G4beamline and BMAD [18].

RESEARCHER TRAINING

Training within AVA consisted of research-led training at the respective host in combination with local lectures, as well as participation in a network-wide training program that was also open to external participants. This training concept built on the successful ideas developed within the DITANET, oPAC and LA^{3}NET projects [19-21].

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 organized international schools, workshops and conferences that provided specific training and gave extensive networking opportunities. A week-long international Schools on Antimatter Research was held at CERN between in 2018 [22], followed by Topical Workshops on Diagnostics and Detectors at CIVIDEC in 2018 [23] and Low Energy Facility Design and Optimization at GSI in early 2019 [24]. The project also organized an International Symposium on Accelerators for Science and Society in summer 2019 at the ACC in Liverpool with the other major training initiatives OMA (Optimization of Medical Accelerators) and LIV.DAT (Data Science). All talks were live-streamed and are now available on-demand via the event homepage [25]. A workshop on Machine-Experiment Interface in 2019 [26] and an international School on precision physics in 2020 [27] complemented the program. In addition, the scientific events, the Fellows and all partners contributed to a multi-facetted outreach and public engagement program. This was exceptionally successful and has reached millions of people around the world. Amongst the activity was a video about the project, produced by the AVA Fellows and network partner Carbon Digital [28]. The video became the most-viewed video on the EC's official science short film playlist and was commended as "good communication" practice. Parts of the video have also been re-used in a science film on DAMPE produced for Discovery Channel.

SUMMARY AND OUTLOOK

The AVA network facilitated international collaboration and an exchange of knowledge, and benefited from significant industry involvement. This in turn helped increase the competitiveness of the researchers and institutions involved, contributing to the principles of the European Research Area.

In terms of research impact, several of the detector solutions developed by AVA Fellows show great promise for pushing the state-of-the-art and allowing better measurements in the future. This will be of great use not "only" for measurements with low energy antimatter particles, but also for low energy ion experiments and applications in general. The involvement of industry ensures that patents on the basis of AVA technologies will be actively sought and that routes to market will continue to be developed.

The potential of these technologies has been further underlined by several grant applications that were based on AVA Fellows' work and that were submitted to e.g. the European ATTRACT call focusing on novel detectors with a view to societal impact or a successful grant application to STFC on adaptive optics-based monitors for beam imaging purposes. Furthermore, the simulation tools that have been developed to describe the motion of charged particle beams, as well as the electron cooling process in storage rings, are expected to find application well beyond the AVA network.

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