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ADVANCES IN LOW ENERGY ANTIMATTER BEAM GENERATION AND MANIPULATION *

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Abstract

The Accelerators Validating Antimatter physics (AVA) project has enabled an interdisciplinary and cross-sector R&D program on low energy antimatter research. The network comprises 13 universities, 9 national and international research centers and 13 partners from industry. Between 2016 and 2021, AVA 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. This paper presents several research highlights that originated within or on the basis of AVA: Results from studies into carbon nanotubes as field emitters for cold electron beams with superior beam quality, the design of a low energy negative ion injection beamline for experiments with antiprotonic atoms, and studies into realistic simulations of antiproton deceleration in foil degraders.

INTRODUCTION

The project Accelerators Validating Antimatter physics (AVA) has enabled 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. During the project duration it 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, they received a wider network-based training, including scientific schools, workshops, as well as training in complementary skills, enhancing their future employability. In the following section examples of research results in or on the basis of the AVA project that are presented at this year's IPAC conference are given, along with a summary of the scientific events that have been organized by the AVA consortium to date.

RESEARCH OUTCOMES

The AVA partners carried out a closely connected R&D program that span across three scientific work packages:

- **Facility Design and Optimization**;
- Design, development and testing of novel **Beam Diagnostics**;
- Design of novel low energy **Antimatter Experiments**.

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 positronium via 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 accelerator-related research results from selected projects.

Stability and Lifetime Studies of Carbon Nanotubes for Electron Cooling in ELENA

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 Bruno Galante was to identify new ways to produce a mono-energetic and relatively intense electron beam. Based at CERN, he carried out optimization studies into the electron gun of the ELENA cooler with a focus on using a cold cathode based on carbon nanotubes (CNTs).

A cold cathode has good potential to bring a number of benefits in terms of the achievable electron beam energy and the overall simplicity of the gun itself. CNTs can emit relatively high currents while being mechanically stable and chemically inert [6, 7]. A honeycomb-like array was studied in detail [8] and CNT samples were characterized in terms of their stability, lifetime and overall performance during current switching.

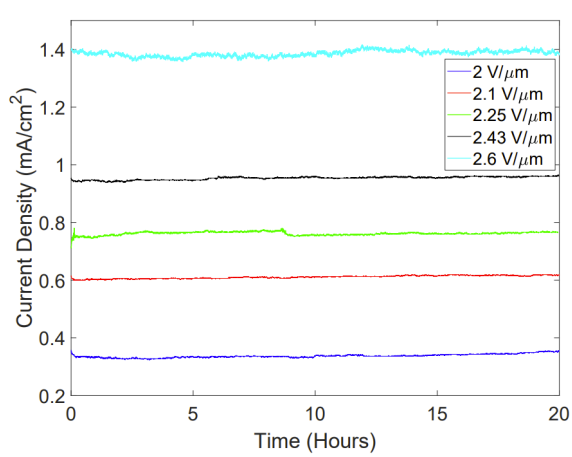

Figure 1: Current density as a function of time (hours) and electric field (V/μm). Five different measurements of 20 hours each at five different applied electric fields [8].

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Figure 1 shows results from measurements carried out over a period of 20 hours and at five different applied electric fields. For each case, the overall standard deviation of the current density output and the coefficient of variation were calculated, showing that a CNT cathode can stably emit even when increasing the emission current. A lifetime of more than 1,500 hours was successfully demonstrated with an emission stability better than 1%. This helped identify a CNT-based cathode as a suitable candidate for the ELENA electron cooler [8]. It should be highlighted that no signs of current deterioration were noticed and excellent output stability was found in current switching mode.

Low-Energy Ion Injection Beamline for Experiments with Antiprotonic Atoms at AEgIS

The AEgIS collaboration [9] recently proposed an experimental scheme allowing to perform an experiment with antiprotonic bound systems. The production of ions will be done in situ via additional Paul trap and/or sputter sources. The current experimental beamline shall be enhanced so that it allows the simultaneous usage of three different beams. To this end, a new beamline concept was developed and realistic simulations of the ion injection into the AEgIS experiment were carried out.

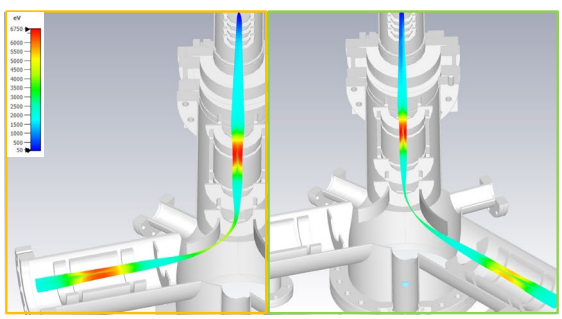

Figure 2: Tracking of 2 keV iodine beam in CST. Focusing in both deflection cases, 75° (left) and 45° (right), occurs close to the middle of the bending electrode.

Ion beam tracking through the entire beamline for two different angles has been carried out, and the results are shown in Fig. 2. A 2 keV iodine beam with a radius of around 10 mm was utilized. The potentials were applied to one of the two arms sides at a time. In practice, the deflection chamber will be able to operate in both, DC and bunched beam mode. The Einzel lens after the bending was kept at around 5.5 kV. For more energetic anion beams all voltages can simply be scaled up by a given linear factor. Three sets of correctors, the first after the deflector, the second after the last Einzel lens, and the last one further downstream, will help keep the orbit close to the design orbit in the presence of magnetic stray fields. In order to test the performance of the correctors, the magnetic field from previous studies [10] was included into tracking simulation, taking into account only the closest 5 T solenoid. The amplitude of the field close to the deflection chamber was ≈ 0.01 T. More details about the scheme can be found in [11].

Realistic Simulations of Antiproton Deceleration in Foil Degraders

Experiments with low energy antiprotons in traps require beam energies in the sub 10 keV range to trap the antiprotons efficiently. To achieve this, different experiments routinely use destructive degrader foils which significantly impact the number of available antiprotons in the traps.

AVA Fellows Volodymyr Rodin and co-workers under the lead of Steve Padden have successfully modelled degrader foils using density functional theory in combination with molecular dynamics [12] to fine-tune foil degrader thickness, maximizing the number of antiprotons available for trapping. The beam transfer line ELENA to the ALPHA (Antihydrogen Laser PHysics Apparatus) experiment was used as a case study and simulated in G4Beamline [13]. A specific focus was put on a new method of rapidly prototyping realistic simulations from existing MAD-X [14] models which use lattice based structures, into one which models a voxelized world space whereby electromagnetic fields determine the motion of particles. Electromagnetic fields are generated by realistically modelled structures, with quadrupole field gradients calculated directly from integrated field strengths returned from MAD-X. Whilst current work focuses on the ALPHA transfer line, with some user modification the method presented is extensible for any transfer line that uses repeated optical structures. By utilizing Enge style functions to model fringe fields [15], quadrupoles are modelled in a more realistic manner. The impact of these is seen as an increase in the quadrupole's effective length in G4Beamline simulations, causing a discrepancy between the beta values returned by MAD-X and those from G4Beamline. Similarly with sufficient modelling, the impact of any stray fields can be included and suitably accounted for [16]. The effects of fringe fields are reduced by development of a beta matching minimization algorithm, resulting in significantly greater agreement between the two models, see Fig. 3.

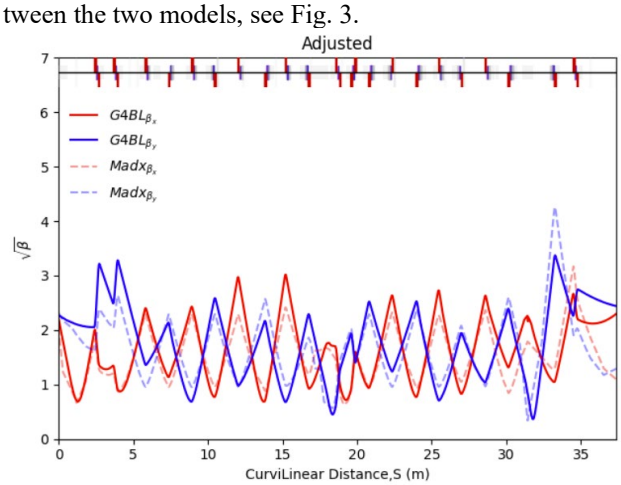

Figure 3: Beta matching after Markov Chain Monte Carlo adjustments. After 8,000 iterations, matching was greatly improved along the entire beamline, providing improved agreement between MADX models and G4Beamline models in the presence of fringe fields [12].

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A new approach to rapidly modelling accelerator beamlines has been demonstrated to be quick and effective at prototyping MAD-X simulations into simulations in which particle movement is determined by electromagnetic fields. This allows for the inclusion of fringe fields as well as any stray magnetic fields. The effects of fringe fields has been accounted for by the development of a beta matching minimization algorithm resulting in an improvement between the two simulations of approximately 30%.

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 [17-19].

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 [20], followed by Topical Workshops on Diagnostics and Detectors at CIVIDEC in 2018 [21] and Low Energy Facility Design and Optimization at GSI in early 2019 [22]. 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 [23]. A workshop on Machine-Experiment Interface in 2019 [24] and an international School on precision physics in 2020 [25] 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 [26]. 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 is expected to benefit wider low energy ion experiments and applications in general. The potential of the new technologies that were developed during the project lifetime 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 under the influence of realistic electromagnetic fields, as well as the electron cooling process in storage rings, are expected to find application beyond the field of antimatter research.

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