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BEAM DIAGNOSTICS FOR LOW ENERGY ANTIPROTON BEAMS*

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Abstract

Beams of low energy antiprotons in the keV energy range are very difficult to characterize due to their low intensity of only 10^7 particles per shot, annihiliation, and low repetition rate. The project AVA [1] (Accelerators Validating Antimatter physics) is an Innovative Training Net-work within the H2020 Marie Skłodowska-Curie actions. It enables an interdisciplinary and cross-sector program on antimatter research across 3 scientific work packages. These cover facility design and optimization, advanced beam diagnostics and novel low energy antimatter exper-iments. This paper presents the AVA R&D into beam profile, position and intensity measurements, as well as detector tests which will provide an order of magnitude improvement in the resolution and sensitivity in closely related areas. It also summarizes the interdisciplinary training program that AVA will provide to its 15 Fellows, as well as to the wider antimatter and accelerator commu-nities.

INTRODUCTION

In July 1983, the very first ions were stored in the Low Energy Antiproton Ring (LEAR) at CERN in Geneva, Switzerland [2]. It was the first storage ring that was explicitly designed to address physics with low-energy antiprotons and opened the door to a field were several very fundamental questions in physics can be directly addressed. When this machine was prematurely shut down in 1996 to free resources for the Large Hadron Collider (LHC) project, an international user community pushed for the continuation of this unique research program. This led to the construction of the Antiproton Decelerator (AD) facility that became operational in 2000 [3]. This storage ring is presently the only facility in the world to allow the realization of experiments with low energy antiproton beams. It has led to the successful production of cold antihydrogen, which has been widely acknowledged in the scientific community, as well as in the public media. The successful storage of antihydrogen over an extended period [4] was selected as top physics highlight in 2010 by physics world. Other recent breakthroughs include successful two-photon laser spectroscopy of antiprotonic helium and the measurement of the antiproton-to-electron mass ratio [5], measurement of resonant quantum transitions in trapped antihydrogen atoms [6], one-particle measurement of the antiproton magnetic moment [7], the production of antihydrogen for in-flight hyperfine spectroscopy [8], direct measurements into the antihydrogen charge anomaly [9] and the comparison of antiproton-to-proton charge-to-mass ratio [10] in 2015. Due to the low intensity of only ~10^5 antiprotons/s and the availability of only pulsed extraction – one pulse every 85 seconds - the physics program is presently limited to the spectroscopy of antiprotonic atoms and antihydrogen formed in charged particle traps or by stopping antiprotons in low-density gas targets. Since the output energy of the AD (5 MeV kinetic energy) is far too high to be of direct experimental use, the standard deceleration cycle of the antiprotons consists of the following steps:

- Deceleration in the AD from 3.5 GeV/c down to 0.1 GeV/c;
- Degrading by a foil from 5 MeV kinetic energy down to a few keV;
- Electron and positron cooling of the particles trapped to meV energies.

The drawback of this procedure is the rather large increase of the beam divergence and momentum spread and the high loss rate of antiprotons in the degrader foil. These effects limit the capture efficiency to about 10^{-4} or even less. An improvement was achieved by the installation of a decelerating rf quadrupole structure (RFQ-D) used by the ASACUSA collaboration [11] that today provides beams at 100 keV energy. However, the rather large emittance ε=100 mm mrad and energy spread ΔE/E = 10% of the output antiproton beam require a large stopping volume and a high-power pulsed laser to induce transition for high precision spectroscopy. A cooled antiproton beam at such energy would greatly improve this situation and even CW laser spectroscopy may become feasible. The scientific demand for low-energy antiprotons at the AD continues to grow. By now there are six experiments at the AD, the most recent ones being AEgIS and BASE, and a seventh (GBAR) has recently been approved. These experiments, however, require significant improvements in the underpinning accelerator technology, beam cooling and handling techniques, novel instrumentation, as well as significant upgrades to the experiments themselves. The AD was not able to provide the required number of cooled antiprotons at lowest energies. CERN is currently finalizing the construction of a new Extra Low ENergy Antiproton ring (ELENA) [12] which promises a significant improvement over this situation. Commissioning of this machine started in 2016.

The *AVA* project focuses on R&D benefiting low energy antimatter facilities. The project will offer its Fellows the unique opportunity to make contributions to the ELENA machine development and physics R&D programs. Beyond the opportunities that ELENA will immediately provide it would be desirable to make experiments using the antiproton as a hadronic probe to study the nuclear structure [13] and to have RF bunching tools to switch between ns and long beam pulses for studies into the collision dynamics of matter and antimatter [14]. This range of experiments could be realized after appropriate

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future upgrades to ELENA or at the proposed Facility of Low energy Antiproton and Ion Research (FLAIR) that shall become part of the future international Facility for Antiproton and Ion Research (FAIR) in Germany. Following external evaluation of the FLAIR proposal, this facility has been part of the core FAIR project since 2007. Recent progress at FAIR, in particular the approval of the modularized start version (MSV) by the FAIR council in September 2015, the early installation of the CRYRING@ESR and commissioning of the HITRAP facility [15] now provide a possible route to the FLAIR physics program. Whilst *AVA* targets primarily ELENA and upgrade scenarios, it also lays the basis for an excellent long-tern perspective through work related to FLAIR.

RESEARCH

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

Facility Design and Optimization, addressing beam life time and stability in lowest energy storage rings, as well as beam cooling, deceleration and extraction through simulation and experimental studies, as well as innovative control systems;

Design, development and testing of novel **Beam Diagnostics** and establishment of a dedicated test stand, to fully determine the characteristics of an antiproton beam;

Design of novel low energy **Antimatter Experiments** through R&D into beyond state-of-the-art beam handling, storing and analysis techniques.

This paper gives an overview of the R&D which will be carried out in the beam diagnostics work package.

Transverse Profile Monitoring

A specific challenge of transverse beam profile monitoring is the detection of particles in the beam halo as these are particles that are likely to be lost and/or produce unwanted background noise in the experiment. This can be achieved with destructive devices such as wire scanners or scrapers [16] or secondary emission monitors which monitor particles produced when the beam interacts with residual or purposely injected gas [17]. A new high dynamic range, adaptive masking method to image the beam halo has recently been developed which uses a digital micro mirror-array device [18]. Ms Milena Vujanovic will be based at the University of Liverpool/Cockcroft Institute and adapt this method for advanced measurements that cannot presently be achieved with any other technique, namely *online, non-destructive high dynamic range beam profile measurements* using light generated by the primary beam. In a second step, measurements will be extended towards emittance and general 6D phase space diagnostics. This will be important for experiment optimization and in particular also for transferring the method to other applications, such as Free Electron Laser (FEL) facilities or the AWAKE experiment at CERN.

Instrumentation Test Stand

For the optimization of any detection technique towards low energy antiproton beams it is essential that detailed tests into the monitor characteristics can be carried out. Recent availability of keV antiprotons at AEgIS [19] has been used to carry out dedicated detector tests which have given important new results [20]. As the experiments mature, however, such opportunities of detector test disappear, while the need for a very low energy antiproton instrumentation test facility remains high. Mr Mattia Fani at CERN will design, build and establish a dedicated *diagnostics and detector test stand* at the AD and carry out investigations at different beam energies and intensities. A key aspect is that the setup needs to also contain the strong solenoidal magnets which are characteristic of all antiproton trapping devices. Consequently, multiple scattering in the degrading elements will result in very large beam divergence. In combination of simulations and technical design considerations the optimum geometry will be evaluated and whether e.g. a low momentum (weak field) magnetic filter would be beneficial. Space limitations, vacuum requirements, and tuneability of the degrader thickness will also be studied, to yield a polyvalent facility with great benefit in evaluating the performance of beam instrumentation for any low-energy antiproton facility.

Diamond Detector R&D

Diamond has been used for many applications in beam instrumentation [21]. Miha Cerv will be based at Austrian company CIVIDEC and study the use of *μm ultra-thin diamond layers as beam position and profile monitors* in low energy antiproton beam lines. He will develop a new type of beam monitor which is based on thin diamond membranes on the one hand and pixelized diamond electrode structures on the other. Initial simulations have indicated a position resolution in the sub-micrometer range and at extremely fast counting rates in the range of Gigahertz, fully exploiting the advances of diamond as radiation sensor material. The project will detail these simulations and prototype detectors will be established and thoroughly tested.

Beam Current Monitor

Beam current is one of the basic quantities in any accelerator and serves as an input for the optimization of machine performance as well as for experiments with the beam. The intensity of low energy antiproton beams is typically rather low, requiring sensitive devices with a detection threshold below 1 nA. Such threshold can be reached by a SQUID-based measurement of the beam's magnetic field [22]. However, this monitor still requires a second instrument to provide a meaningful dynamic range. Such *sensitive DC-transformer* is not commercial-

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ly available and will be developed at GSI. David Haider will first study appropriate materials and modern high-performance electronics as a basis for beam current measurements with extremely wide dynamic range. He will then model sensitive current measurement methods and hardware realizations for different configurations using the CST Particle Studio simulation suite. In a next step, experimental tests with prototypes that will be built in-house will be done at GSI. These will form the basis for the final technical design. Sensitivity and dynamic range of the devices will then be experimentally tested at CRYRING@ESR

Liquid Target Detectors for Particle Tracking

For beam monitoring purposes, parallel plate avalanche counters (PPAC) and segmented Si-detectors are currently used at the AD, however, this will no longer be possible at energies of 100 keV or below as required for ELENA and FLAIR. Dominika Alfs will be hosted by Forschungszentrum Juelich (FZJ) in Germany and study the use of small *liquid hydrogen and deuterium targets* which will trigger annihilation events and allow monitoring of the beam track via straw tubes or scintillators. Using the expertise at FZJ in target development she will first carry out Monte Carlo simulation studies on expected signal levels. She will then design and build a prototype and carry out experimental studies at the AD. Based on results from measurements a final design for optimum integration into experiments at a low energy antiproton facility will then be made. For the target development, several approaches will be followed, including gaseous target cells with very thin walls and solid targets prepared by condensation at a cold backing. In order to transport the cooling power nearly masslessly, heat pipe techniques will be considered. Finally, careful balance between track resolution and straggling induced by the detector materials will be sought through studies of Si-μ-strips, straw-tubes, scintillation fibers and GEM-foil detectors.

Cryogenic Particle Detectors

Finally, trap experiments used e.g. for precision determination of the antiproton magnetic moment [23] require amplifier technologies with superior sensitivity and ruggedness. Ilia Blinov based at German company Stahl Electronics will advance the technology of current *single particle detectors*, integrated *in a cryogenic environment*. He will link the expertise available at the company with the one at GSI and carry out measurements for detector characterization. He will also investigate optimum trap design in close collaboration with the Max Planck Institute for Nuclear Physics. Ultimately, the goal will be to establish a novel detection system which will be easier to operate, rugged under adverse conditions and feature much higher detection sensitivity, down to single particles, by using latest generation electronic detectors from Stahl Electronics. Moreover, resonators connected to the system shall be abandoned, yielding true broad-band detection technology.

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 is based on the successful ideas developed within the DITANET, oPAC and LA^{3}NET projects [24-26].

All Fellows will be given the opportunity to enroll into a PhD program. They will thus be embedded into a structured course program at their host university or, if their work contract is with an industry partner or a research center, with a collaborating university. Courses at the PhD awarding institution will include lectures on fundamental symmetries, precision experiments, electronics, detector design, as well as courses on the local language. It is widely recognized that best practice in researcher training involves cohorts of trainees rather than individuals. The ITN structure is ideal for this and to achieve the aspirations of the EU Principles for Innovative Doctoral Training AVA will take best advantage of industry participation and by providing regular network training to bring the Fellows together. Most network-wide events will also include external participation and will be open to the wider scientific community. The four AVA Fellows who had already started earlier in 2017 were invited to a researcher skills training at the University of Liverpool in April 2017 where they joined 15 Fellows from the OMA network [27]. This week-long School included sessions on project management, presentation skills, communication of research outcomes to diverse audiences, as well as IP rights and knowledge transfer. Two 1 week-long international Schools, open to all *AVA* Fellows and up to 50 external participants on Antimatter research, as well as on Fundamental Symmetries and Interactions will be organized. All Schools will be announced via the project home page [1]. To further promote knowledge exchange and ensure that all Fellows are exposed at highest possible level to the techniques and methodologies developed in the other WPs, three 2-day Topical Workshops covering two scientific WPs at a time will be organized. These will cover facility optimization via diagnostics, diagnostics in accelerators and experiments and questions related to the machine-experiment interface. In the last year of the project a 3-day international conference will be organized, with a focus on the novel techniques and technologies developed within *AVA*.

SUMMARY

An overview of the beam diagnostics R&D and oeverall training program within the recently *AVA* project was given. With 4M€ of funding the network is one of the largest Marie Curie ITNs and will train 15 early stage researchers over the next four years. Schools, Topical Workshops, an international conference and various outreach events will all be open also for participants from outside of the consortium.

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