ACCELERATORS VALIDATING ANTIMATTER PHYSICS*

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Abstract

The Extra Low Energy Antiproton ring (ELENA) will be a critical upgrade to the unique Antiproton Decelerator facility at CERN and is currently being commissioned. ELENA will significantly enhance the achievable beam quality and enable new experiments. To fully exploit the discovery potential of this facility, advances are urgently required in numerical tools that can adequately model beam transport, lifetime and interaction, beam diagnostics tools and detectors to fully characterize the beam properties, as well as in novel experiments that exploit the enhanced beam quality that ELENA will provide. These three areas form the scientific work packages of the new pan-European research and training initiative AVA (Accelerators Validating Antimatter physics). The project has received around 4M€ of funding and brings together universities, research centers and industry to train 15 Fellows through research in this area. This contribution presents the research results across AVA's three scientific work packages.

INTRODUCTION

In July 1983, the very first ions were stored in the Low Energy Antiproton Ring (LEAR) at CERN in Geneva, Switzerland [1]. It was the first storage ring that was explicitly designed to address physics with low-energy antiprotons and opened the door to a field where 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 [2]. 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 [3] 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 [4]
- measurement of resonant quantum transitions in trapped antihydrogen atoms [5]
- one-particle measurement of the antiproton magnetic moment [6]
- the production of antihydrogen for in-flight hyperfine spectroscopy [7]
- direct measurements into the antihydrogen charge anomaly [8]
- the comparison of antiproton-to-proton charge-to-mass ratio [9]

Due to the low intensity of only $\sim 10^5$ 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 [10] that today provides beams at 100 keV energy. However, the rather large emittance ε=100 mm mrad and energy spread $\Delta E/E=10\%$ 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 will, 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) [11] 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

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antiproton as a hadronic probe to study the nuclear structure [12] and to have RF bunching tools to switch between ns and long beam pulses for studies into the collision dynamics of matter and antimatter [13]. This range of experiments could be realized after appropriate 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 [14] 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-term 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 lifetime and stability in lowest energy storage rings, as well as beam cooling, deceleration and extraction.
- 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.

The sections below gives some examples from across the three AVA work packages..

Facility Design and Optimization

At the low energies that ELENA will provide, it is important to correctly evaluate the long term beam stability. To provide a consistent explanation of the different physical phenomena affecting the beam, AVA Fellow Bianca Veglia, based at the University of Liverpool/Cockcroft Institute, uses the BETACOOL program [15] to simulate particle dynamics in storage rings under the action of the electron cooling force and in presence of intrabeam scattering [16]. Her studies will predict the evolution of particle motion invariants under different conditions with good accuracy and under different models. The effect on the friction force from different density distributions of the electrons were analyzed, along with studies on possible imperfections of the electron cooler. The main goal of the electron cooler is to reduce the emittance and increase the energy resolution of the circulating ion beam. This makes taking any performance-limiting factors into account extremely important. Several simulations including beam shift and misalignment of the electron cooler have been completed and compared against analytical results.

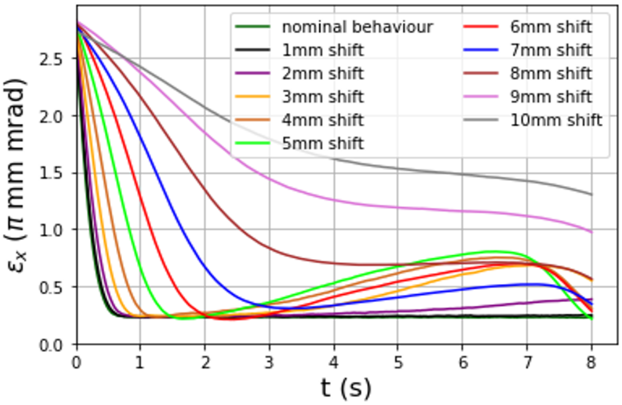

Figure 1: Evolution of horizontal emittance of the antiproton beam in ELENA in presence of an offset between electron cooler axis and circulating beam [16].

Figure 1 shows the evolution of horizontal beam emittance as a function of vertical beam offset. Further studies are now planned involving the effects of magnetic field imperfections and non-linearities.

Beam Diagnostics

The main scientific goal of the AEgIS experiment is the direct measurement of the Earth's local gravitational acceleration on antihydrogen [17]. The weak equivalence principle is a foundation of General Relativity. It has been extensively tested with ordinary matter but very little is known about the gravitational interaction between matter and antimatter. Antihydrogen is to be produced in AEgIS via charge exchange reactions between Rydberg-excited positronium and cooled down antiprotons. All the activities inside the Collaboration are strongly directed towards this milestone. AVA Fellow Mattia Fani is working on the design of a dedicated instrumentation and detector test stand. His work concerns the physics and technology of ultra-cold plasmas, detector technologies and detection and manipulation of excited atomic systems. He has successfully defined a procedure for efficient compression of a mixed antiproton-electron non-neutral plasma up to high antiproton peak densities in the Penning trap in operation in AEgIS. Thus far, experimentalists have used a rather simple set of formulae to predetermine the compression rate and efficiency inside a trap with limited theoretical underpinning. The compression of a mixed antiproton and electron plasma can be achieved at a fixed frequency if the compression of the electron cloud is slow enough, using low amplitudes. It was found that the speed of compression is not the key parameter and that, on the contrary, full compression of the electron cloud, including its low density radial tails, is central in achieving high radial antiproton compression. The antiproton compression dynamics seems to be solely dependent on the electron dynamics and can thus be optimized outside of the antiproton beam time [18]. At present, test measurements aimed to improve the sensitivity of positronium detection in the time region of interest for antihydrogen production are being carried out. This could result in the possibility of development and implementation of a new detection system in the final stage of the apparatus.

The project by Miha Cerv, based at CIVIDEC in Vienna, Austria, targets ultra-thin diamond detector for antiproton characterization. Measurements have already been performed in the Grace beam line of AEgIS using a 500 µm Diamond Knopf Detector with 470 nm thick metallization (250 nm Au + 120 nm Pt + 100 nm Ti), the CIVIDEC C2 current amplifier and ROSY readout system [19-21]. As the metallization of the detector was too thick for low energy antiprotons to reach the diamond sensor, most of the annihilation was expected to happen in the electrode. The measured waveforms first showed a flash of pions followed by individual pulses from individual low energy antiprotons. Sometimes huge pulses were measured, which saturated the amplifier. These are suspected to be caused by antiprotons that annihilated inside the diamond sensor, see Fig. 2.

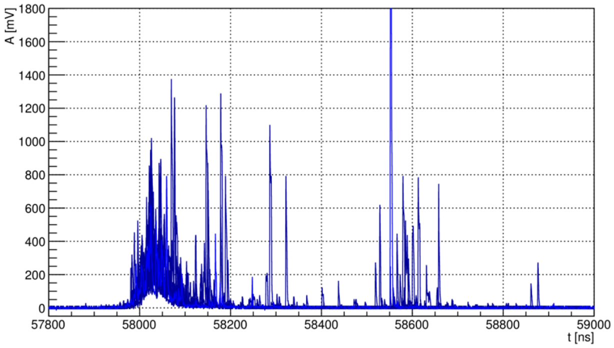

Figure 2: Antiproton signal measured with Diamond Knopf detector in AEgIS Grace beam line.

The measurement is planned to be repeated in 2018, when a diamond sensor with a very thin metallization will be used, so that more antiprotons can reach the diamond and annihilate in it. This way, significantly more annihilation signals are expected for an in-depth analysis.

Novel Antimatter Experiments

Using advanced Penning-trap methods, the BASE collaboration has recently determined the magnetic moments of the proton and the antiproton with a relative precision of 0.3 p.p.b. and 1.5 p.p.b., respectively [22, 23]. State-of-the-art experiments rely on sub-thermal cooling of the particle's modified cyclotron mode using feedback-cooled tuned circuits. Particle temperatures as low as ~0.5 K can be reached. This time-consuming process is ultimately required to identify single spin quantum transitions with high detection fidelity, a major prerequisite to apply multi-trap methods that are essential for p.p.b. measurements. In order to advance state-of-the-art techniques and drastically reduce the measurement time, the BASE collaboration involving AVA Fellow Markus Wiesinger, based at Max Planck Institute for Nuclear Physics in Heidelberg, is implementing methods to sympathetically cool protons and antiprotons by coupling them to laser-cooled beryllium ions, using a common endcap method [24]. BASE has developed and built a new apparatus featuring a common endcap double Penning trap [25]. Based on these calculations it is expected that the new apparatus will enable preparation of single protons and antiprotons with energies close to the Doppler limit of laser cooling within tens of seconds, which will ultimately reduce particle preparation times in the experiments of the BASE collaboration by a factor of at least 50. Protons and beryllium ions have been trapped in the new apparatus and first experiments to characterize the new apparatus been carried out.

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 [26-28].

All Fellows were given the opportunity to enroll into a PhD program. They are thus 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 include lectures on fundamental symmetries, precision experiments, electronics, detector design, as well as courses on the local language. In addition, network-wide events will be organized that are also open to external participation. All AVA Fellows have already completed a dedicated Researcher Skills Training school at the University of Liverpool. This week-long school included sessions on project management, presentation skills, and communication of research outcomes to diverse audiences, as well as IP rights and knowledge transfer. Two week-long international Schools, open to all AVA Fellows and up to 50 external participants, on Antimatter Research and Fundamental Symmetries & Interactions will be organized with the first taking place at CERN between 25-29 June 2018 [29]. In addition, a new Media Training school was offered to all AVA Fellows at MediaCityUK, Manchester in 2018 in close collaboration with experts from Carbon Digital. The Fellows learned the essential skills of video production and produced their own project video, now available on YouTube [30]. 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 diagnostics in accelerators and experiments in Vienna in October 2018, facility optimization via diagnostics, and questions related to the machine-experiment interface. An Outreach Symposium will be held in Liverpool on 28 June 2019 and 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. All events will be announced via the AVA home page [31].

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