ACCELERATORS VALIDATING ANTIMATTER PHYSICS (AVA)*

C. P. Welsch†, University of Liverpool/Cockcroft Institute, UK

Abstract

Antimatter experiments are at the cutting edge of science. They are, however, very difficult to realize and have been limited by the performance of the only existing facility in the world, the Antiproton Decelerator (AD) at CERN. The Extra Low Energy Antiproton ring (ELENA) will be a critical upgrade to this unique facility and commissioned from autumn 2016. This will significantly enhance the 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, life time and interaction, beam diagnostics tools and detectors to characterize the beam's properties, as well as in novel experiments that exploit the enhanced beam quality that ELENA will provide. *AVA* is a new European research and training network between universities, research centers and industry that will carry out R&D into ELENA and related facilities [1]. This paper gives an overview of the *AVA* research program across its 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 [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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 721559.
#c.p.welsch@liverpool.ac.uk

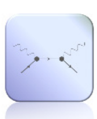
range of experiments could be realized after appropriate future upgrades to ELENA or at the proposed Facility of Low energy Antiproton and Ion Research (FLAIR) that shall become part of the future international Facility for Antiproton and Ion Research (FAIR) in Germany. Recent progress at FAIR, in particular 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.

RESEARCH

To fully exploit the potential of ELENA and FLAIR, the *AVA* partners propose to 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.

Facility Design and Optimization

ELENA at CERN's AD and FLAIR will provide cooled beams of antiprotons at lower energies than currently achievable anywhere in the world. It will be crucial to have detailed knowledge about the achievable stability of the beam in the storage ring and the expected beam life times. Existing low energy storage rings, operating at keV beam energies, found strong limitations on beam intensity and reduced life time in experimental studies [16]. The nature of these effects had not been fully understood for a very long time and only recently causes of these limits to beam current and life time were identified and reproduced in simulations [17]. A Fellow based at the University of Liverpool/Cockcroft Institute will build up on these studies and investigate all effects impacting on *beam stability* and establish realistic models of beam storage and cooling. She will also develop new simulation tools that enable start-to-end simulations of antiproton pulses through electrostatic low energy beam lines. These tools will then be applied for an optimization of beam handling towards requirements of future antimatter experiments.

Electron cooling of the antiproton beam will be essential to reduce or eliminate the emittance blow-up caused by the deceleration process and obtain the small emittance antiproton beam needed for further deceleration and extraction to the trap experiments. The electron gun must produce a cold ($T_\perp < 0.1$ eV, $T_\parallel < 1$meV) and intense electron beam ($n_e \approx 1.5\text{x}10^{12}$ m^{-3}). At CERN a Fellow will study options for a *cold electron source* [18], including expected performance and limitations and improve the understanding of cold electron beam generation.

Crucial for any accelerator based research facility is an efficient integration of all experiments, beam handling and transport systems, and the various diagnostics into a powerful control system [19]. An early stage researcher at COSYLAB will develop a *versatile control system* that will link across all WPs and enable enhanced communication between all devices. The Fellow will focus on a flexible machine control system, hard real-time feedback and precise timing system. Finally, it is critical for beam storage and energy ramping in a storage ring and efficient beam transport from a ring to the experiments that power supplies with a stability of better than 10^{-4} , which can be ramped over more than one order of magnitude in output voltage in 1 s over a linear ramp and that can be smoothly integrated into the accelerator control system are available. A Fellow at FOTON will design, build and test such *high precision power supplies*.

Beam Diagnostics and Particle Detection

The second scientific work package addresses 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. 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 [20] or secondary emission monitors which monitor particles produced when the beam interacts with residual or purposely injected gas [21]. 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 [22]. A Fellow at the University of Liverpool/Cockcroft Institute will adapt this method for advanced measurements that cannot presently be achieved with any other technique, namely online, non-destructive 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* which will be important for experiment optimization.

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 [23] has been used to carry out dedicated detector tests which have given important new results [24]. 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. A Fellow at CERN will design, build and establish a dedicated *diag-*

ISBN 978-3-95450-182-3

nostics and detector test stand at the AD and carry out investigations at different beam energies and intensities.

Diamond has been used for many applications in beam instrumentation [25]. CIVIDEC's Fellow will study the use of *μm ultra-thin diamond layers as beam position and profile monitors* in low energy antiproton beam lines. 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 [26]. However, this monitor still requires a second instrument to provide a meaningful dynamic range. Such *sensitive DC-transformer* is not commercially available and will be developed at GSI.

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. A Fellow will be hosted by FZJ 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. Finally, trap experiments used e.g. for precision determination of the antiproton magnetic moment [27] require amplifier technologies with superior sensitivity and ruggedness. A Fellow based at company STEL will advance the technology of current *single particle detectors*, integrated *in a cryogenic environment*.

Antimatter Experiments

The study of the *collision dynamics of correlated quantum systems* can be done by crossing a gas jet target with a beam of low energy antiprotons. Antiproton (projectile) energies between 20 keV and some MeV correspond to interaction strength between a weekly perturbed system (where approximation theories can be applied) and strong perturbation (where all details of the interaction need to be taken into account in theoretical models) [28]. However, this requires beam compression to a diameter of around 1 mm and a pulse length of 1-2 ns or a highly optimized compact recycler ring [29]. A Fellow at University of Liverpool/Cockcroft Institute will develop an experimental setup for these studies. To make precision experiments for tests of CPT invariance independent of accelerator-beam time cycles and shut-down periods it would be highly desirable to have an additional controllable source of antiprotons. A Fellow at GSI in Germany will develop, build and test a '*reservoir trap*' [30] which can deliver a well-defined number of antiprotons, and even a single particle, into adjacent precision traps for periodic measurement cycles over extended periods of time. This reservoir trap will make experiments independent of accelerator beam-times and shut-down periods and will provide beams at different energies. A Fellow at Max Planck Institute for Nuclear Physics will combine the advances in *laser cooling of trapped ions* with precision (anti)proton spectroscopy [31] and antihydrogen ground state hyperfine splitting spectroscopy to perform stringent tests of CPT invariance. Sympathetic cooling of antiprotons will be achieved by coupling them to laser-cooled ions [32]. This will provide the coldest antimatter particles and plasmas ever observed and will improve precision in single antiproton spectroscopy by orders of magnitude. Building up on previous experience in spectroscopic measurements of the host group at Stefan Mayer Institute in Vienna, a *Ramsey technique* will be implemented into an existing setup at the AD to measure the ground-state hyperfine structure of antihydrogen with an improved precision by a factor of 10, compared to the precision which can be achieved with the currently used setup, and thus provide one of the most sensitive tests of CPT invariance ever performed. Finally, a Fellow at the University of Manchester/Cockcroft Institute will study the optimization of *degrader integration, improved beam injection, and high precision magnetic field measurements*. These techniques and associated hardware developments will allow performing antihydrogen experiments with significantly higher efficiency and thus benefit all trap-based developments within *AVA*.

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 [33-35]. 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 R&D and training program within the recently approved *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. The consortium consists of universities, research centers, clinical centers, and industry partners and will also organize many training events. This includes Schools, Topical Workshops, an international conference and various outreach events which will all be open also for participants from outside of the project.

REFERENCES

[1] *AVA*, `http://www.ava-project.eu`
[2] The LEAR Team, "Performance of LEAR", *IEEE Transactions on Nuclear Science*, Vol. 3. No. 5 (1985).
[3] S. Baird et al., "The Antiproton Decelerator: AD", *Proc. Part. Acc. Conf.* (1997).
[4] G. B. Andersen, et al., *Nature Physics*, 7, 558 (2011).
[5] M. Hori, et al., "Two-photon laser spectroscopy of antiprotonic helium and the antiproton-to-electron mass ratio", *Nature* 475 (2011).
[6] C. Amole, et al., "Resonant quantum transitions in trapped antihydrogen atoms", *Nature* 483, 439 (2012).
[7] J. DiSciacca, *Phys. Rev. Lett.* 110, 130801 (2013).
[8] N. Kuroda et al., *Nature Communications* 5, 3089 (2014).
[9] C. Amole, et al., *Nature Communications* 5, 3955 (2014).
[10] S. Ulmer, et al., *Nature* 524, 196-199 (2015).
[11] W. Pirkl, et al., "First operating experience with the CERN deceleraing RFQ for antiprotons", *Proc. Part. Acc. Conf.*, Chicago, USA (2001).
[12] V. Chohan, et al., *ELENA TDR*, CERN (2014).
[13] A. Trzcinska, et al., *Nucl. Phys. A* 692 (2001) 176c.
[14] T.N. Rescigno, et al., *Science* 286 (1999) 2474. M. Baertschy, et al. and A.S. Kadyrov, et al., *Phys. Rev. Lett.* 91 (2003) 253202-1.
[15] F. Herfurth, et al., "The Low Energy Storage Ring CRYRING@ESR", *Proc. COOL*, Murren, Switzerland (2013).
[16] S.P. Møller et al., *Proc. Europ. Part. Acc. Conf.*, Vienna, Austria (2000), p.788-790.
[17] A. Papash, et al., *Phys. Rev. STAB* 16, 060101 (2013) and J. Resta-Lopez, et al., *JINST* 10 E08001 (2015).
[18] K. Roberts, et al., *SSSEPB* (2013) and H. Sik Kim, et al., *Anal. Chem.* (2012), 84, 3635-3619.
[19] L. Catani, et al., *Phys. Rev. STAB* 15, 112804 (2012).
[20] J.D. Gilpatrick, *AIP Conf. Proc.* 693, 122 (2003).
[21] P. Cameron, et al., "The RHIC Ionization Beam Profile Monitor", *Proc Part. Acc. Conf.*, New York, USA (1999).
[22] H. Zhang, C.P. Welsch, et al., "Beam halo imaging with a digital optical mask", *Phys. Rev. STAB* 15, 072803 (2012).
[23] A. Kellerbauer et al., *Nucl. Instr. Meth. B* 266 (2008) 351.
[24] N. Pacificoa, et al., *Nucl Instr Meth. A* (2014), A. Sosa, et al., Hyp. Inter. (2014) and S. Aghiona, et al., *JINST* 8 P08013 (2013).
[25] C. Weiss, et al., *Nucl. Instr. Meth. A* 732 (2013) 190–194 and C. Guerrero, et al., *Eur. Phys. J. A* (2013) 49:27 (2013).
[26] M. Fernandes, et al., "Non-perturbative measurement of low-intensity charged particle beams", *Superconductor Science and Technology* 30, Number 1.
[27] Mooser et al., *Phys. Rev. Lett.* 110, 140405 (2013) and S. Ulmer et al., *Phys. Rev. Lett.* 106, 253001 (2011).
[28] C.P. Welsch, et al., *AIP Conf. Proc.* 1037 (2008), p.318-332.
[29] O. Karamyshev, et al., *Nucl. Instr. Meth.* A Vol 700 pp 182-187 (2012).
[30] S. Sturm, et al., *Nature* 506, 467–470 (2014) and C. Smorra, et al., *J Mass Spectrometry* 389, 10-13 (2015).
[31] S. Sturm, et al., *Nature*, 13026 (2014) and A. Mooser, et al., Nature, 13388 (2014).
[32] D. J. Heinzen, et al., *Phys. Rev. A* 42, 2977 (1990); A. Kellerbauer, etl al., *New J. Phys.* 8, 45 (2006) ; P. Yzombard et al., *PRL* 114, 213001 (2015).
[33] DITANET, `http://www.liv.ac.uk/ditanet`
[34] oPAC, `http://www.opac-project.eu`
[35] LA^{3}NET, `http://www.la3net.eu`

ISBN 978-3-95450-182-3