PROCEEDINGS OF SCIENCE

3D simulation studies of mixed plasma confinement at $AE\bar{g}IS$

B.S.Rawat,[a,b,*] **N.Kumar,**[a,b] **B. Rienäcker,**[a,b] **C. P. Welsch,**[a,b] **S. Alfaro Campos,**[c,d] **M. Auzins,**[e] **M. Berghold,**[f] **B. Bergmann,**[g] **P. Burian,**[g] **R. S. Brusa,**[h,i] **A. Camper,**[y] **R. Caravita,**[i] **F. Castelli,**[j,k] **G. Cerchiari,**[c,d] **R. Ciuryło,**[l] **A. Chehaimi,**[h,i] **G. Consolati,**[j,m] **M. Doser,**[n] **K. Eliaszuk,**[o] **R. Ferguson,**[h,i] **M. Germann,**[n] **A. Giszczak,**[o] **L. T. Glöggler,**[n] **Ł. Graczykowski,**[o] **M. Grosbart,**[o] **F. Guatieri,**[f,h,i] **N. Gusakova,**[n,p] **F.P. Gustafsson,**[n] **S. Haider,**[n] **S. Huck,**[n,q] **C. Hugenschmidt,**[f] **M. A. Janik,**[o] **T. Januszek,**[o] **G. Kasprowicz,**[r] **K. Kempny,**[o] **G. Khatri,**[n] **Ł. Kłosowski,**[l] **G. Kornakov,**[o] **V. Krumins,**[e,n] **L. Lappo,**[o] **A. Linek,**[l] **S. Mariazzi,**[h,i] **P. Moskal,**[s,t] **M. Münster,**[f] **P. Pandey,**[s,t] **D. Pecak,**[u] **L. Penasa,**[h,i] **V. Petracek,**[v] **M. Piwiński,**[l] **S. Pospisil,**[g] **F. Prelz,**[j] **S. A. Rangwala,**[w] **T. Rauschendorfer,**[n,x] **V. Rodin,**[b] **O. M. Røhne,**[b] **H. Sandaker,**[b] **S. Sharma,**[s,t] **P. Smolyanskiy,**[g] **T. Sowiński,**[u] **D. Tefelski,**[o] **M. Volponi,**[n] **M. Zawada,**[l] **J. Zielinski,**[o] **N. Zurlo**[aa,ab] **and (AEḡIS collaboration)**

[a] *The Cockcroft Institute, Daresbury, Warrington WA4 4AD, UK*
[b] *Department of Physics, University of Liverpool, Liverpool L69 3BX, UK*
[c] *University of Siegen, Department of Physics, Walter-Flex-Strasse 3, 57072 Siegen*
[d] *Universität Innsbruck, Institut für Experimentalphysik,Technikerstrasse 25/4, 6020 Innsbruck, Austria*
[e] *University of Latvia, Department of Physics, Raina boulevard 19, LV-1586, Riga, Latvia*
[f] *Heinz Maier Leibnitz Zentrum (MLZ), Technical University of Munich, Lichtenbergstraße 1, 85748, Garching, Germany*
[g] *Institute of Experimental and Applied Physics, Czech Technical University in Prague, Husova 240/5, 11000, Prague 1, Czech Republic*
[h] *Department of Physics, University of Trento, via Sommarive 14, 38123 Povo, Trento, Italy*
[i] *TIFPA/INFN Trento, via Sommarive 14, 38123 Povo, Trento, Italy*
[j] *INFN Milano, via Celoria 16, 20133 Milano, Italy*
[k] *Department of Physics "Aldo Pontremoli", University of Milano, via Celoria 16, 20133 Milano, Italy*
[l] *Institute of Physics, Faculty of Physics, Astronomy, and Informatics, Nicolaus Copernicus University in Toruń, Grudziadzka 5, 87-100 Toruń, Poland*
[m] *Department of Aerospace Science and Technology, Politecnico di Milano, via La Masa 34, 20156 Milano, Italy*
[n] *Physics Department, CERN, 1211 Geneva 23, Switzerland*

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0) All rights for text and data mining, AI training, and similar technologies for commercial purposes, are reserved. ISSN 1824-8039 . Published by SISSA Medialab.

https://pos.sissa.it/

PoS(EXA-LEAP2024)076

[o] *Warsaw University of Technology, Faculty of Physics, ul. Koszykowa 75, 00-662, Warsaw, Poland*
[p] *Department of Physics, NTNU, Norwegian University of Science and Technology, Trondheim, Norway*
[q] *Institute for Experimental Physics, Universität Hamburg, 22607, Hamburg, Germany*
[r] *Warsaw University of Technology, Faculty of Electronics and Information Technology, ul. Nowowiejska 15/19, 00-665 Warsaw, Poland*
[s] *Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland*
[t] *Centre for Theranostics, Jagiellonian University, Kraków, Poland*
[u] *Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL-02668 Warsaw, Poland*
[v] *Czech Technical University, Prague, Brehová 7, 11519 Prague 1, Czech Republic*
[w] *Raman Research Institute, C. V. Raman Avenue, Sadashivanagar, Bangalore 560080, India*
[x] *Felix Bloch Institute for Solid State Physics, Universität Leipzig, 04103 Leipzig, Germany*
[y] *Department of Physics, University of Oslo, Sem Sælandsvei 24, 0371 Oslo, Norway*
[aa] *INFN Pavia, via Bassi 6, 27100 Pavia, Italy*
[ab] *Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, via Branze 43, 25123 Brescia, Italy*

E-mail: bharat.rawat@cockcroft.ac.uk

The $AE\bar{g}IS$ (Antimatter Experiment: Gravity, Interferometry and Spectroscopy) project, based at CERN's Antiproton Decelerator (AD) facility seeks to probe the Weak Equivalence Principle (WEP) for antimatter. It has undergone significant enhancements, capitalizing on the increased quantity of colder antiprotons made available by the Extra Low Energy Antiproton Ring (ELENA) decelerator. These improvements aim to create a horizontal pulsed beam of antihydrogen atoms and enable a direct investigation into the impact of gravity. The $AE\bar{g}IS$ experiment consists of a Penning Malmberg trap comprising cylindrical electrodes within a 5 T and a 1 T axial magnetic field region. The 5 T field captures cold antiprotons, while the 1 T field is used for further trapping which ultimately leads to antihydrogen production. To maximize the antihydrogen formation, it is crucial to have a detailed understanding of the properties of trapped antiprotons, which can be achieved by realistic 3D simulation studies for the dynamics of particle confinement. Previous studies indicated antiprotons exhibit greater stability in a shallower potential well [1]. In this work, we examine the dynamics of antiprotons by varying the outer electrode potentials while maintaining constant potentials at the inner electrodes of the electrostatic trap, utilizing an Electrostatic Particle-In-Cell (ES-PIC) solver in the CST (Computer Simulation Technology) studio. We extended the studies on the temporal evolution of a mixed plasma generated with the introduction of electrons inside the trap along with the antiprotons by observing the effect of their properties: density, and temperature. Additionally, we provide an overview of the results obtained for the energy evolution of antiprotons using a Rotating Wall (RW) electrode at different RW frequencies. Finally, we summarize our plans to develop a full digital twin of the $AE\bar{g}IS$ experiment for the next two years, providing valuable insights into the parameters required for optimized experiments.

International Conference on Exotic Atoms and Related Topics and Conference on Low Energy Antiprotons (EXA-LEAP2024)
26-30 August 2024
Austrian Academy of Sciences, Vienna.

PoS(EXA-LEAP2024)076

1. Introduction

The $AE\bar{g}IS$ (Antimatter Experiment: Gravity, Interferometry, and Spectroscopy) experiment consists of a series of cylindrical electrodes used to trap non-neutral antimatter plasma using axial magnetic fields, forming a Penning Malmberg trap [2, 3]. The cylindrical electrodes create an electrostatic potential well preventing the plasma loss in the axial direction whereas the axial magnetic field helps to avoid the radial plasma losses. To optimize the trap for the experiments, it is very important to study how the plasma behaves under different trap conditions. This work studies the dynamics of the trapped particles using the ES-PIC solver in the CST studio. The paper is divided as follows first the trap geometry in the simulation setup for the 1 T trap is discussed, followed by a discussion on the electrostatic trap simulation with electrons and antiprotons, followed by the discussions of results from the Rotating Wall electrode simulations. In conclusion, we summarize the contribution and our further plans to develop a full Digital Twin of the $AE\bar{g}IS$ experiment in the course of the next two years which will help us in providing some valuable insights for performing optimized experiments.

2. Simulation setup

Various plasma simulation codes in the area of particle accelerators are available to model plasma behavior like WARPX, XOOPIC, and CST Studio [4–6]. CST Studio offers the flexibility to perform 3D PIC using electromagnetic and electrostatic solvers. The electromagnetic solver utilizes maxwell's equations and time-stepping techniques to predict particle evolution, accounting for self-generated magnetic fields. However, this approach is computationally demanding. Alternatively, the Electro-Static (ES) solver is suitable for cases where self-generated magnetic fields due to particle motion can be neglected, making it computationally less intensive. The ES solver calculates charge distribution by solving Poisson's equation and updates the fields at each time step based on particle positions. For the present simulation studies, the ES-PIC solver in CST Studio is used and we plan to do full PIC simulations in the future which will consider the interactions due to the self-generated magnetic field of the particles.

One of the key challenges in PIC modeling for large models is the spatial scales that dominate the plasma dynamics. It is not numerically feasible to resolve electron motion for a density of around $1 \times 10^{12}\ m^{-3}$ and T = 55 K on a 1:1 scaled computer model because the debye length for such parameters is around 0.05 mm and the mesh generated for a 1:1 scaled model takes an impractical amount of computational space. Thus, a 1:50 scaled-down model of the trap was used to overcome the computational limitations. Such scaling techniques have been usually used to simulate the physics of ion beam neutralization using electrons in hall thrusters models [7]. Figure 1 (a) shows the actual Penning Malmberg trap of the $AE\bar{g}IS$ experiment (scale:1:1), while Figure 1 (b) shows the corresponding scaled-down (1:50) 3D model of only a part of the 1T section created in CST Studio. If the time step exceeds 1ns, the electrons do not spend enough time within the simulation domain and tend to escape. On the other hand, if the time step is smaller than 1ns, it significantly increases the computational requirements. Therefore, a time step of 1ns is chosen as a balanced value, adequate for studying the energy and density evolution of electrons within the trap. The constant 1 T axial magnetic field is applied using the analytic field import definition in

PoS(EXA-LEAP2024)076

CST studio and each 100 μs simulation takes several hours to complete running on a 12 core CPU system.

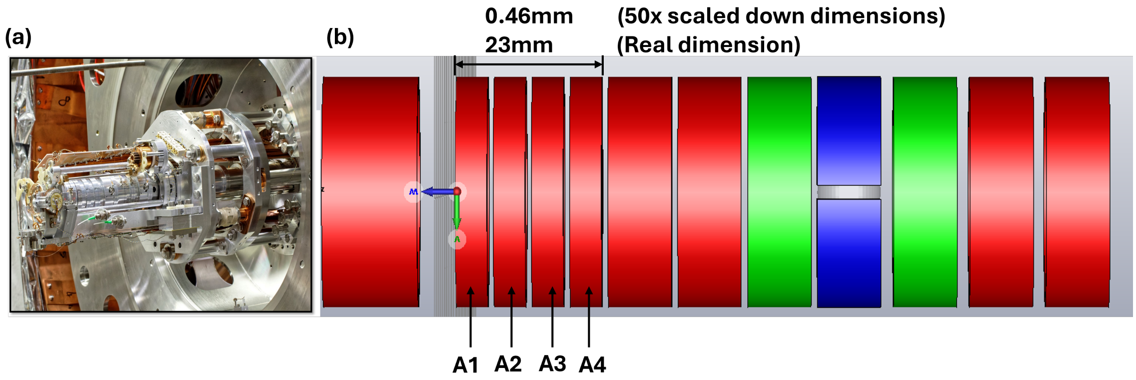

Figure 1: (a) The $AE\bar{g}IS$ Penning Malmberg trap[2]. (b) The 3D CST model of the $AE\bar{g}IS$ Penning Malmberg trap (Scale:1:50).

3. Electrostatic trap simulations with electrons and antiprotons

The present simulation focuses on four electrodes, labeled A1, A2, A3, and A4. This region plays a key role in the trap, as positronium emitted from the converter targets interacts with the stored antiprotons in this area, making it crucial for analysis. Figure 2 (a) shows the potential profiles between electrodes A1-A4 when they are set to -5 V and A2 and A3 are set to 0 V. A 2D particle monitor is set in the x,z plane between A1-A4 to store different particle properties (like coordinates, kinetic energy, etc) during the simulation. Assuming a spherical source of diameter 3 mm, with an initial temperature T=55 K (7.1 meV), the density of 1×10^{10} m^{-3} in a Maxwellian distribution, the variation of the density of electrons and the antiprotons between A1-A4 electrodes are shown in Figure 2 (b). To understand how the mean kinetic energy of antiproton changes for the different trap voltages a parametric sweep is performed on A1 and A4 electrodes by varying their value from -20 V to -5 V. No loss of particles was observed even for the shallowest potential well in the trap for the given simulation time.

In the next set of simulations, different energy electrons were used to perform a parametric sweep by varying the electron temperatures and observing their impact on the mean energy of antiprotons as a function of simulation time. Figure 3 (a) shows the number of electrons in the trap as a function of time for different electron temperatures at a fixed trap potential. It is quite intuitive that for the fixed trap potential the colder electrons tend to have a slower loss rate . All of these losses occur axially in the trap and no radial losses are observed for any of the cases. These simulations were carried out with 2000 electrons and 2000 antiprotons in the trap.

4. Rotating Wall (RW) electrode simulations

The Rotating Wall (RW) electrode consists of four segmented sectors on which a phase-shifted sinusoidal signal $V(t) = A_{\mathrm{RW}} \sin(\omega_{\mathrm{RW}} t + \phi)$ is applied to create a rotating electric field. The

PoS(EXA-LEAP2024)076

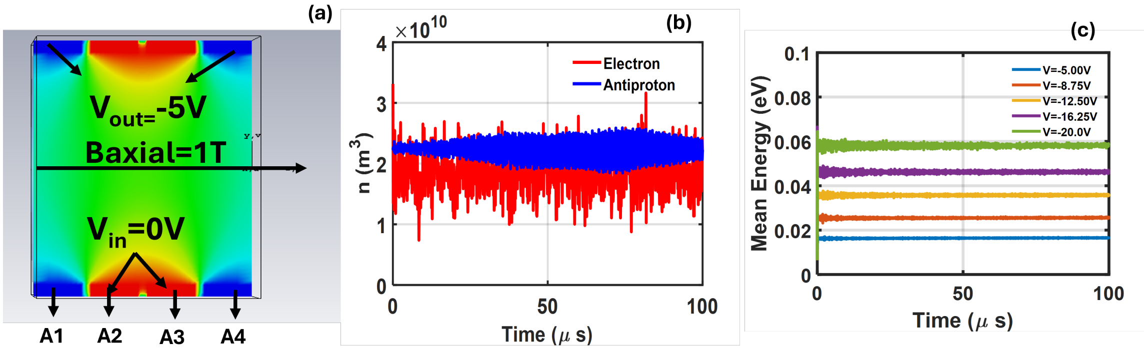

Figure 2: (a) Potential profiles of the electrostatic trap A1-A4. (b) The variation of mean density as a function of time for antiprotons and electrons between the A1-A4 electrode. (c) Variation of mean energy of antiprotons as a function of time for different potentials applied to the electrodes A1 and A4.

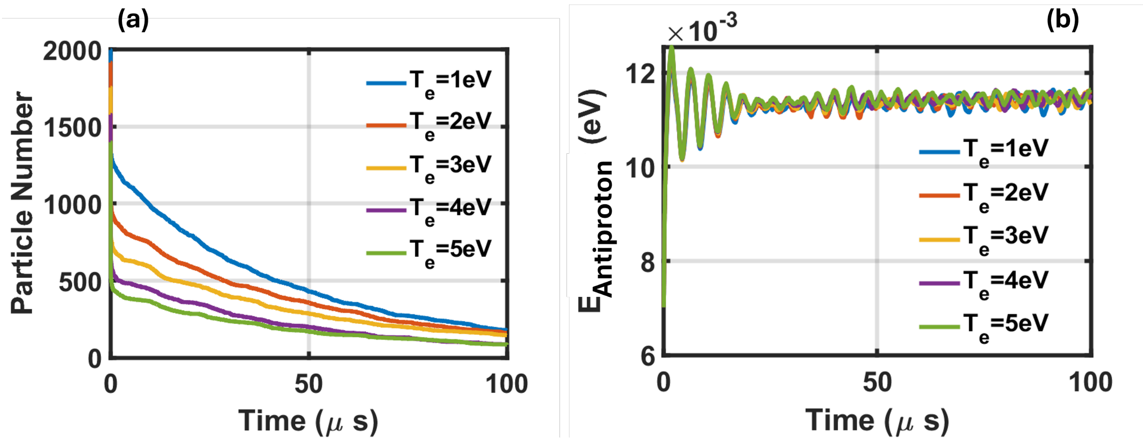

Figure 3: Effect of electron temperature on (a) Number of electrons in the trap and (b) Mean energy of antiprotons for different electron temperatures.

sine signal is shifted in phase by 90 degrees for each segment in the electrode. Depending on the frequency of the RW and the rotating frequency of plasma various manipulation processes such as compression, centrifugal separation, etc can be achieved [8].

The electrodes next to the RW electrode are kept at a potential of -20 V. The simulations are performed by loading cold antiprotons with T = 55 K, and the variation in their mean energy as a function of time is studied for different RW frequencies ranging between 160 kHz to 480 kHz as shown in Figure 4 (a). The mean number of antiprotons in the RW trap electrode is estimated for each RW frequency, which helps to select the right frequency for a particular density, temperature, and trap voltage. Such types of parametric sweep can be used to further optimize the loading conditions to achieve the coldest antiprotons in the trap to maximize the probability of charge exchange with positronium. Figure 4 (b) shows the average number of antiprotons for each RW frequency and has maximum storage at around 320 kHz for the given input conditions.

PoS(EXA-LEAP2024)076

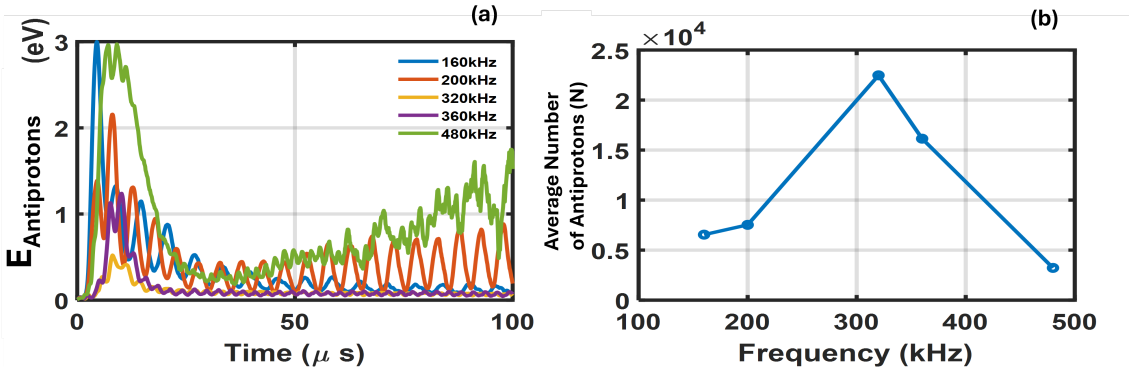

Figure 4: (a) Mean energy of antiprotons as a function RW frequency. (b) The average number of antiprotons in the trap as a function of RW frequency.

5. Conclusion and Future work

3D ES-PIC simulations of the 1T trap region of the $AE\bar{g}IS$ experiment have been performed to explore particle trapping schemes, focusing on how electrode voltages and electron temperatures affect particle density, energy, and loss rates. Initial simulations demonstrate various study possibilities related to the optimization of the trap, with future work aiming to use more realistic experimental parameters. RW simulations for cold antiprotons, without electrons, were performed across a 160-480 kHz range, showing that at 320 kHz the antiprotons have the maximum storage inside the trap for the given simulation conditions.

Future developments will extend the to simulate the real-scale Digital Twin [9] (see prototype $AE\bar{g}IS$ Digital Twin in Figure 5), which will include the 5 T and 1 T electromagnets and corrector coils with realistic 3D magnetic fields. Additionally, a Geant4-based Digital Twin focused on nuclear interaction studies is also planned, aimed at optimizing antiproton capture and manipulation for future experiments.

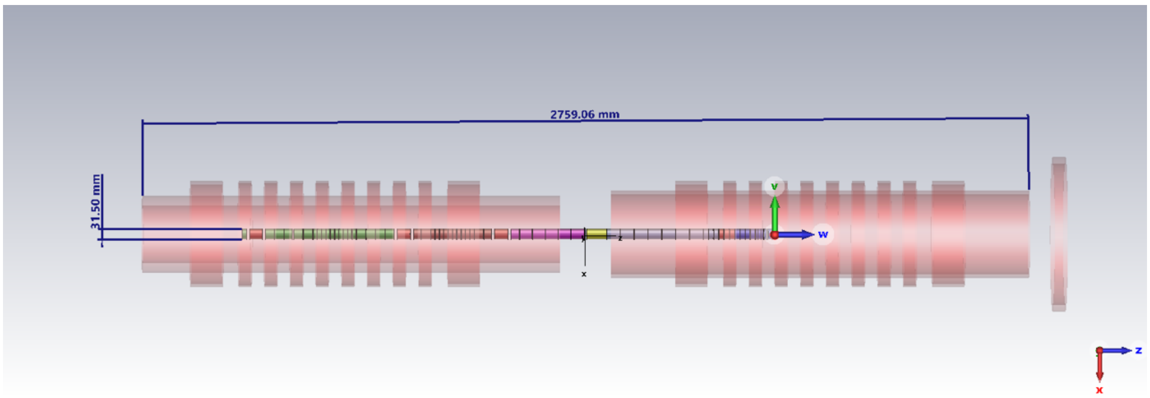

Figure 5: 3D model of $AE\bar{g}IS$ Digital Twin in CST studio.

6. Acknowledgements

This work is supported by EPSRC under grant agreement EP/X014851/1.

PoS(EXA-LEAP2024)076

References

[1] Rawat, B., *et al.*, "Simulation Studies for the Confinement of Antiprotons for the AEgIS Experiment", in *Proc. IPAC'24*, Nashville, TN, pp. 2684-2687, May 2024. 10.18429/JACoW-IPAC2024-WEPR75

[2] Volponi, M., "Towards the Formation of a Forward-Boosted Beam of Neutral Antihydrogen for Gravitational Studies", PhD Thesis, Università di Trento, Italy, 2024. https://cds.cern.ch/record/2911109

[3] Doser, M., *et al.*, (AEgIS Collaboration). "Exploring the WEP with a Pulsed Cold Beam of Antihydrogen", Classical and Quantum Gravity, vol. 29, p. 184009, 2012. 10.1088/0264-9381/29/18/184009

[4] Thevenet, M., *et al.*, "WarpX: Toward Exascale Modeling of Plasma Particle Accelerators". https://www.exascaleproject.org/.

[5] Usui, H., *et al.*, "Development of 1D Object-Oriented Particle-In-Cell Code (1D-XOOPIC)", IEICE Transactions on Electronics, The Institute of Electronics, Information and Communication Engineers, 2000.

[6] CST Studio Suite, https://www.3ds.com/products-services/simulia/products/cst-studio-suite/solvers

[7] Brieda, L., "Multiscale Modeling of Hall Thrusters", PhD Thesis, The George Washington University, USA, 2012. https://ui.adsabs.harvard.edu/abs/2012PhDT........45B

[8] Aghion, S., *et al.*, "Compression of a Mixed Antiproton and Electron Non-neutral Plasma to High Densities", The European Physical Journal D, Vol. 72, p. 76, 2018. 10.1140/epjd/e2018-80617-x

[9] Jones, D., *et al.*, "Characterising the Digital Twin: A Systematic Literature Review", CIRP Journal of Manufacturing Science and Technology, vol. 29, pp. 36-52, 2020. 10.1016/j.cirpj.2020.02.002

PoS(EXA-LEAP2024)076