Document: **Final report (17 October 2014)**

Proposition: **LABEX P2IO R&D (08-November-2011)**

Project title: **A novel antiproton-decelerator concept**

Partners: **Service de Physique de Particules (SPP), IRFU/CEA (Saclay) and Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM) IN2P3-CNRS, Université de Paris Sud (Orsay)**

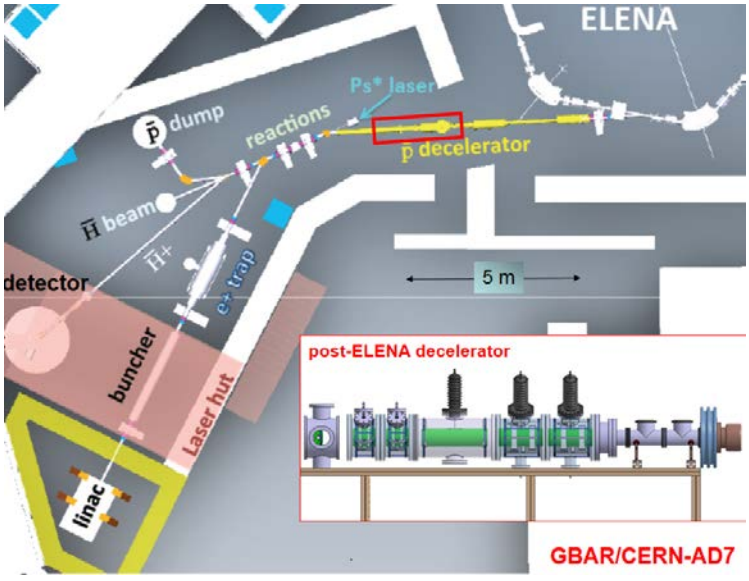
Coordinator: **david.lunney@csnsm.in2p3.fr**

Amount: **96 k€**

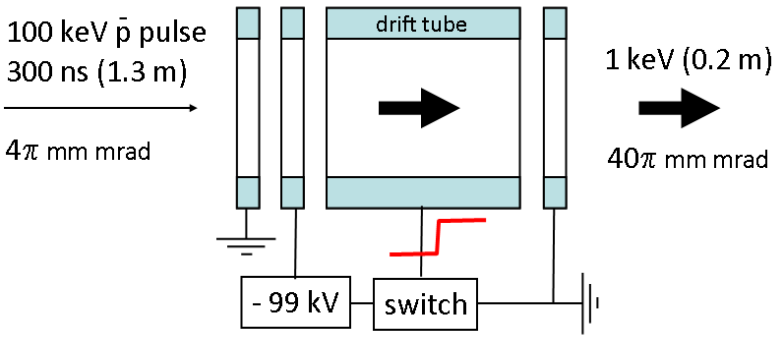
1. Project Goals: The aim of this project was the realization of a novel decelerator concept for the production of antimatter. The project is a subtask of the CERN AD7 experiment GBAR (Gravitational Behavior of Antimatter at Rest). The ingredients of antihydrogen are necessarily created at high energy with particle accelerators whereas efficient synthesis requires slowing them down. Current techniques using a foil are very inefficient causing losses of 99.99% of the antiprotons. Applying atomic physics techniques that have been used successfully for handing exotic radioactive species, we proposed an electrostatic decelerator setup to furnish low-energy antiproton beam pulses of less than 1 keV. This development relies on the very fast switching of a drift tube from 100 keV to ground, plus additional beam optics for preparing the antiproton beam. The granted P2IO funds were used for building and testing such a decelerator. The constructed instrument will be installed at the CERN AD antiproton facility. Coupled to the ELENA storage ring, the decelerator will be used to help with the commissioning of ELENA. While specifically conceived for the recently proposed GBAR experiment, the new decelerator will benefit all experiments that plan to use the ELENA facility.

2. Description of work achieved

To illustrate the context of the antiproton decelerator project, the overview of the GBAR experiment as planned for CERN is shown in the figure opposite (right). After cooling in the ELENA (extra-low energy antiproton) storage ring, the antiprotons (travelling clockwise) will be extracted (from right to left) through an electrostatic beam line (in yellow) at 100 keV to the decelerator setup (red rectangle and inset). After the energy transformation (to 1 keV) the antiprotons are deflected into a reaction chamber. Prior to the arrival of the antiproton pulse, a cold cloud of positrons (produced by electrons from a linac) has been prepared in the trap. The positrons create a dense cloud of positronium, which the antiprotons transit to create antihydrogen ions by successive charge-exchange reactions (enhanced by laser excitation of the positronium). The antihydrogen ions enter the detection chamber for further preparation and neutralization before being "dropped" to measure *g*.



The schematic concept of the antiproton decelerator is illustrated in the figure opposite (right). The incident 100-keV antiproton beam pulse is decelerated by cylindrical electrodes, held at potentials reaching -99 kV. When the pulse enters the drift tube electrode, the voltage is rapidly (100-200 ns) switched from -99 kV to ground. Inside the conductor, the antiprotons feel no potential gradient and remain at 1 keV energy when exiting the drift tube.



In the course of the project we performed: simulations, design, construction, and experimental tests. The simulations were performed using the SIMION software package and some of the results are shown in the following figure.

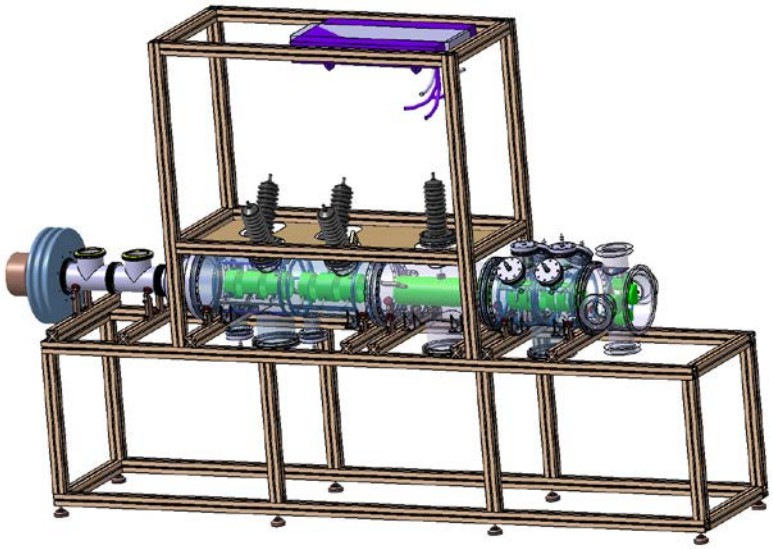
Trajectory simulations showing (right) the single-stage version shown as a potential surface (the effect of pulsing the voltage on the drift tube can be seen) and (left) in 2D showing a new, two-stage deceleration geometry (two sets of three electrodes) followed by the pulsed drift tube cavity (long tube), followed by a modular Einzel lens for focusing the antiproton beam into the antihydrogen formation chamber.

New simulations were necessary halfway through the project since the specifications of the antiproton beam furnished by ELENA became ten times worse (0.1%). This led us to the more optimized, two-stage geometry (shown in the above figure, right). This work was performed as a Masters project of T. Ke (M1 – Nuclear Energy, Paristech) from April – August, 2014. The initial engineering drawings have been made for this system (see figure below) and the material has been ordered. All of the electrodes have been machined and mounted within a KF-based vacuum system, constructed from standard-sized modular components. This is to validate the decelerator geometry before installing it in a custom-made CF (high vacuum) system made with 316LN non-magnetic steel.

The fast high-voltage switch has been purchased (the delivery took one year!) and the installation is in progress. Using a lower-voltage switch from the same manufacturer, we have successfully tested the system with 10-keV beams, achieving switching times within 100 ns.

A program of tests with proton beam energies up to 10 keV has been achieved and we have successfully decelerated 10 keV pulses to 1 keV within 200 ns. These are important results that allow us to scale up to 100 keV with no worries. The results were achieved within the framework of the ENSTA-Paristech M2 internship project of A. Pandey (From April to August 2013).

The 100-kV isolation transformer has been positioned under a high-voltage platform and the safety elements have been assembled. This work, plus other installation tasks and measurements, were performed during the DUT-*measures physique* stage of Y. Zhang, (IUT d'Orsay) from April – June, 2014.



CAD drawing of the new, two-stage deceleration system for 100 kV: The proton source is on the far left, followed by four sets of steering electodes, the two sets of three deceleration electrodes, the pulsed drift tube electrode and finally the reacceleration and focusing electrodes. The large feedthroughs are rated for 100 kV. On top is the structure for the high-voltage switch, which is connected to the pulsed drift tube.

Photographs of the proton-decelerator test bench: (left) one of the two sets of deceleration electrodes; (right) part of the beamline showing the three chambers that house the electrodes; feedthroughs are mounted on insulators for the final deceleration electrode and pulsed drift tube (under the high-voltage protective covers).

3. Publications

The decelerator concept was presented at the last International Conference of Low Energy Antiproton Physics (LEAP), which was held in Uppsala (Sweden) in July 2013. The conference proceedings, consisting of authors from both partner institutes (CSNSM/IN2P3 and SPP/IRFU) has been published:

> D. Lunney et al., "Beam preparation for studying the Gravitational Behavior of Antimatter at Rest (GBAR)," Hyperfine Interactions 229, 1 (2014).

The paper is appended to this report. Once the final tests and commissioning are finished, we will publish those results in a full paper.

Four students participated in the realisation and tests of the decelerator project and wrote reports:

2012: S. Delpine, M1 (U. Blaise Pascal, Clermont Ferrand)
2013: A. Pandey, M2 (Paristech, Saclay)
2014: T. Ke, M1 (Paristech, Saclay)
2014: Y. Zhang, DUT2 (IUT, Orsay)

4. Relevance and specific added value for P2IO

The GBAR experiment addresses questions of fundamental physics, specifically the symmetry between matter and antimatter, which is central to the two infinities of P2IO. GBAR is approved and a Memorandum of Understanding has now signed by CERN and the 17 Collaborating institutes. P2IO has played an extremely important and catalysing role for GBAR. The investment of P2IO has provided the needed equipment to build (and test) the decelerator prototype. This would have been impossible otherwise!

Development of GBAR is in full swing, with support from a new ANR project and two doctoral students - one from the LABEX P2IO (see section 7). There will therefore be further benefits from the investment made in this project. Moreover, the project enabled strengthening the ties between SPP/IRFU and CSNSM/IN2P3, which surely played a role in the success of the ANR grant. This collaboration is also very important in the local context of the new Université Paris-Saclay.

In terms of education, the project was the subject of four internships, ranging from IUT to the M2 level.

5. Valorization

Although the concept put forward by this project could be of great interest for the other experiments studying antimatter, it is hard to say if the technique could be commercialized. If ever low-energy antiprotons could be shown to be of interest for material characterization (like positrons) then there would be a possible interest in a patent.

6. Expenses

The single most expensive purchase during the project was the ulta-fast high-voltage switch, which was purchased from the Behlke High Voltage Company (in Germany). Behlke has a monopoly on such fast high-voltage switches so they are relatively expensive. We purchased a push-pull (bi-polar) version in order to use it with both antiprotons and protons. We also purchased a cheaper push version as a text device and as a spare. These purchases, plus power supplies and other electronics-related expenses, accounted for 56% of the granted P2IO funds. Working with antimatter requires ultra-high vacuum components, which are extremely expensive. Thanks to the P2IO grant, we were able to purchase some of the high vacuum components as well as an ion pump and controller. These items accounted for 23% of the total spending. Many parts were machined and many of them had to be sent to external companies. The insulating parts were particularly expensive to buy and machine. Total spending on mechanical parts was 12%. The remaing 9% of the funds was spent on software, cables, gas, etc. The summary from the CNRS administration software platform GESLAB is shown.

LABORATOIRE : A06412 CSNSM
COMMANDES PAR ENTITE DEPENSIERE
Toutes les commandes du 01/01/2012 au 31/12/2014

Le : 13/10/2014
Exercice : 2014
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Entité 12D5DL R & D - Décélérateur antiproton/Dave

Crédits reçus : 96,000.00
Disponible sur réalisé : 5,655.38

N° commande	Souche	Libellé commande	Date création	Raison sociale fournisseur	Montant engagé	Montant réalisé	Montant facturé	Code origine	Nature	Statut	Cdegpée
32065		REPARATION CONTROLLEUR TURBO	10/05/12	AGILENT TECHNOLOGIES FRANCE			1,640.00				
31270		REALISATION MECANIQUE	16/05/12	ISTO			1,762.00				
31301		ENSEMBLE SUPPORT MAYTEC	22/05/12	APORE			1,990.99				
31404		GRATIFICATION DE STAGE	25/05/12	SEBASTIEN DELPHINE			2,213.17				
31428		COMMUTATEUR-HAUTE TENSION 6KV	07/06/12	PULSE MC2			11,132.00				
31436		DISC EXTERNE	08/06/12	MAGASIN IPN			84.74				
31591		RACCORD	03/07/12	ADIXEN VACUUM PRODUCTS			1,148.50				
31679		ALIMENTATION-COFFRET	13/07/12	RADIOSPARES COMPOSANTS			92.39				
32014		ECROU 1/2 LUNE	27/09/12	APORE			135.00				
32149		INSTRUMENTATION ELECTRONIQUE	22/10/12	NATIONAL INSTRUMENTS			2,029.83				
32236		SUPPORT POUR PLATEFORME	09/11/12	APORE			904.93				
32255		BROCHE DROITE ALIMENTATION	13/11/12	RADIOSPARES COMPOSANTS			59.47				
32785		OP-AMP RAPIDE	25/02/13	RADIOSPARES COMPOSANTS			19.23				
32808		CF TEE ISO 100	27/02/13	ADIXEN VACUUM PRODUCTS			321.58				
32910		CONICAL REDUCER	03/12/13	ADIXEN VACUUM PRODUCTS			224.70				
33126		COMMUTATEUR	15/04/13	PULSE MC2			22,565.00				
33457		ALIMENTATION	28/05/13	YELLOZ COMPONENTS			2,300.00				
33513		REPARATION/EXCHANGE TRISCROLL	06/06/13	AGILENT TECHNOLOGIES FRANCE			4,387.00				
33517		REPARATION DE 2 ALIMENTATIONS	06/06/13	YELLOZ COMPONENTS			780.00				
33580		COAXIAL PULSED AMPLIFIER	17/06/13	MINI CIRCUITS EUROPE			235.14				
33662		LICENCES	27/06/13	BCP INSTRUMENTS			2,440.00				
33725		Embout DN	07/09/13	ADIXEN VACUUM PRODUCTS			190.93				
34476		Tube Aluminium	19/11/13	CHAUVIERE ACIERS			396.00				
35195		Chambre à vide	17/03/14	MDC VACUUM PRODUCTS SARL			1,708.92				
35196		Recharge pour canon à ion	17/03/14	HYPERTECH			3,575.00				
35222		POMPE IONIQUE VACION	19/03/14	AGILENT TECHNOLOGIES FRANCE			10,262.70				
35290		ELEMENTS CHAMBRE VIDE	27/03/14	ADIXEN VACUUM PRODUCTS			831.90				
35581		Ensemble réalisation mécanique	14/05/14	STIM			5,377.50				
35853		COMMUTATEUR	07/02/14	PULSE MC2			11,536.00				
				Total entité R & D - Décélérateur antiproton/Dave :			90,344.62				

7. Future of the project after P2IO funding

In 2014 two important events occurred that will guarantee the future of the funded instrument: a new (four-year) grant from the ANR (called ANTION – coordinated by IRFU-Saclay with CSNSM-Orsay and LKB-Paris as partners) was received. The ANR will provide further equipment and manpower to continue this work. Moreover, two new doctoral students have started working on the experiment (one of them was funded through the P2IO program for interdisciplinary studies).

The plans for the next three years will include a first measurement of the matter-analog charge exchange reactions – using part of the setup that was built with the funds from this P2IO project. The decelerator itself will be moved to CERN in 2016 to help commission the ELENA storage ring. The added value of P2IO will be exceptional here since it will have provided the first instrument connected to ELENA and as such will play a critical role in the commissioning experiments!