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APEX – Newly Implemented Functionalities Towards the First Magnetically Confined Electron-Positron Pair Plasma

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Abstract. The APEX (A Positron Electron eXperiment) collaboration aims to magnetically confine a low-temperature electron-positron pair plasma. By using a pair of ExB plates, positrons generated by the NEPOMUC facility are drift-injected into the confinement field created by a supported permanent magnet. Fine-tuning the fields generated by electrodes and magnetic coils increased the injection efficiency to 100% and positron confinement times to more than 1s. A newly installed electron gun has been used to inject electrons, guided alongside the positron beam, into the confinement volume. This contribution describes the recent upgrades required for the first dual species experiments.

INTRODUCTION

Creation of a magnetically confined electron-positron pair plasma is the aim of the APEX collaboration [1]. For the realization of such matter-antimatter plasmas, we plan to develop a superconducting (SC) levitated dipole experiment operated at the NEPOMUC positron beam facility. Challenging issues include the realization of efficient injection of positrons into the closed field lines, followed by stable simultaneous trapping of both species. Prior to the SC experiment, we have been conducting basic experiments with a permanent magnet dipole device focusing on the injection and trapping properties of positrons and electrons.

EXPERIMENT SETUP

Low energy positrons provided by the NEPOMUC source are guided into a confinement chamber after passing a diagnostic chamber where various measurements are conducted. In the confinement chamber, both positrons and electrons are drift injected and trapped in a dipole magnetic field generated by a permanent magnet (NdFeB).

Diagnostic Chamber

Appropriate diagnostics of the positron beam is essential for successful injection and confinement. While its mean kinetic energy is basically chosen by the electrostatic potential of the remoderation crystal, the shape and position of the beam is influenced by various static electric and magnetic fields required to guide the positrons towards the instrument. As the injection process of positrons into our confinement device is quite sensitive to the

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initial beam location, precise centering of the beam improves the reproducibility of the measurements over various beam times [2]. For this and other diagnostic purposes the setup is equipped with a diagnostic chamber which the beam passes prior to entering the confinement volume. Its main component is a multi-functional structure (Fig. 1b) containing a microchannel plate (MCP), a target plate and an electron gun. These components are arranged linearly and, by using a motorized linear translator, can be either placed individually in the center of the chamber to intersect the beam, or fully retracted to provide an unperturbed propagation of the beam.

The copper target plate has a solid section serving two major purposes: when it is grounded, the annihilation gamma rays from positrons hitting the plate are detected by a BGO scintillation detector located outside the chamber. This provides a rough estimate of the beam path and is mainly used for the initial beam positioning. Further, the positron flux at the plate can be measured directly by using a charge-integrating amplifier. Two apertures in another part of the plate, with diameters of 15 mm and 3 mm, are used to verify the beam centering, as they indicate in combination with the BGO scintillation detector whether the beam is passing the apertures or hitting the plate.

When the positrons hit the MCP they generate secondary electrons which are subsequently amplified and accelerated onto a phosphor screen. The phosphor screen image is reflected in a 45° mirror towards a camera, providing access to the beam shape and position. To prevent electric stray fields from perturbing the incoming beam either due to applied biases or due to charge-up effects, a copper shield plate mounted onto the front element of the MCP assembly covers all potentially disturbing structures facing the beam.

Electrons are emitted parallel to the positron beam by an electron gun assembly mounted underneath the solid area of the target. Generating high numbers of electrons is, in contrast to positrons, a straightforward process through thermionic emission from a tungsten filament. To preserve the reproducibility of our previous experiments that were operated solely with positrons, effects of electrostatic stray fields induced by the operating electron gun on the positron beam must be minimized. For this purpose, the electron gun comprises a minimal design with its outer diameter (30 mm) being smaller than the width of the target plate (40 mm) covering it. The electron gun is embedded in a stainless-steel case which is, like the target plate, grounded during operation. It consists of a V-shaped tungsten filament and a Wehnelt electrode of 5 mm thickness, mounted with a distance of 5 mm to the output aperture (3 mm diameter). The electron beam propagates parallel to the centered positron beam, with an offset distance of less than 2 cm, into our confinement chamber by using the same adiabatic guiding fields (0.55mT to 1.26mT). Simulations indicate that this very simple structure is capable of manipulating the beam (Figure 1c). However, as the electron gun is located within the magnetic field of the beam line, the actual particle trajectories differ from this simulation, as it does not include the adiabatic guiding. Nevertheless, the measured current of electrons injected into the dipole trap is affected by changing the electric bias on the Wehnelt electrode.

Confinement chamber

After passing through the diagnostic region but before entering the confinement chamber, the beam position can be optimized for injection by two pairs of steering coils (position shown in Fig. 1a) in order to improve the injection. The main component of the confinement chamber is a supported cylindrical permanent magnet with a field strength of 0.6T at its poles, embedded into a copper case which can be electrically biased against the vacuum chamber. Above the magnet, a pair of ExB plates and a shield plate placed perpendicular to them are mounted. The complete confinement setup is surrounded by a cylindrical wall divided into 10 horizontally and vertically segmented electrodes in two layers. The bottom layer consists of 8 identical electrode segments surrounding the magnet, while the top layer consists of two electrodes surrounding the ExB plates: a 1/8 segment is adjacent to the injection port while the remaining 7/8 of circumference denotes the second electrode. These electrodes can be biased individually either with static potentials or with time-varying fields capable of compressing the orbits by applying a rotating wall technique [4].

For diagnostic purposes, two BGO scintillation detectors are used to measure the annihilation events. One of them detects events of positrons that are not successfully injected and annihilate near the injection region, while the other one observes a target probe, insertable on the equatorial plane of the magnet at the side opposite to the injection region. When fully inserted, all positrons performing a 180° toroidal precession around the magnet will hit either the probe or its supporting rod. Measuring the annihilation counts as a function of the target position provides information on the distance between the positron cloud and the magnet. Furthermore, the positron flux can be measured directly with a charge-integrating amplifier, and injected electron currents can be measured with a source meter.

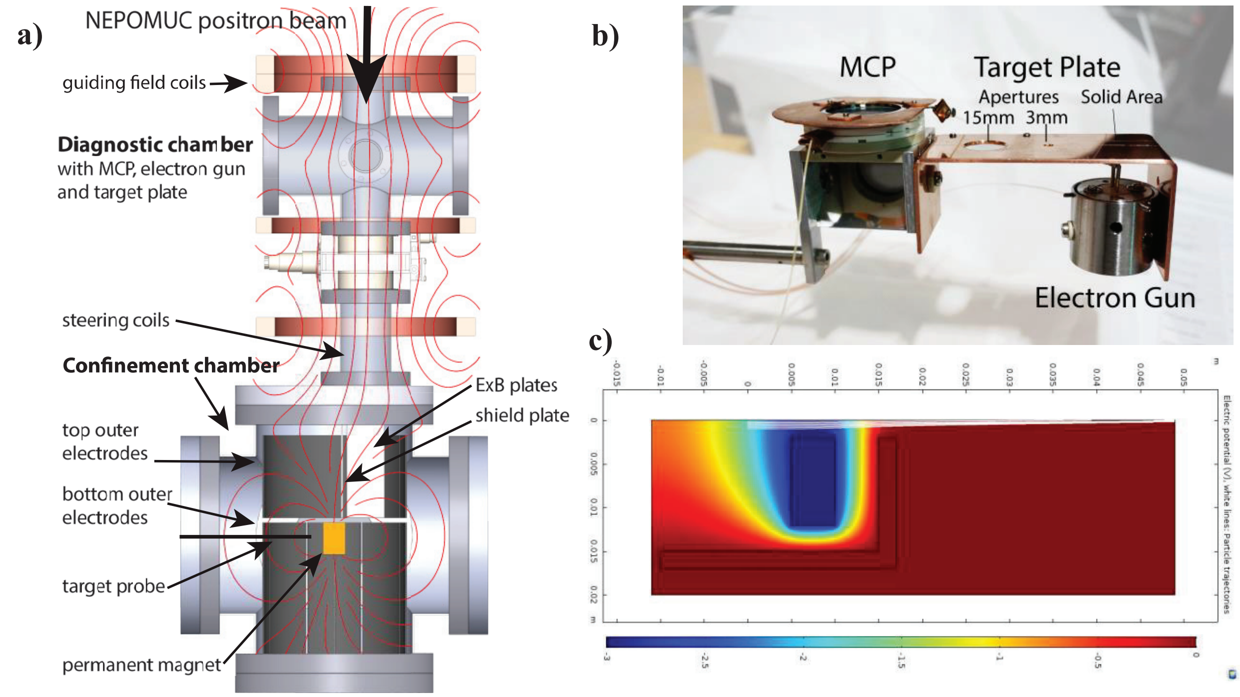

Figure 1:
(a) Sketch of the APEX setup [3]. Magnetically guided positrons enter the confinement chamber, where they are drift injected into the confinement field created by a supported permanent magnet, after passing the diagnostic chamber.
(b) Photograph of the diagnostic assembly inside the diagnostic chamber. The complete structure can be moved horizontally to centrally position the individual sections under the incoming positron beam. From left to right: MCP placed above a 45° mirror to image the beam and check its positioning, followed by a copper target plate consisting of two apertures (15 and 3mm) and a solid section. An electron gun is placed underneath the target plate's solid area.
(c) Simulation of the electric field in rotational symmetry of the electron gun. The field of the negative biased Wehnelt electrode is restricted within the case, while the electron trajectories (white stripes) indicate the focusing capabilities of this minimalistic design.

ELECTRON INJECTION USING POSITRON CONDITIONS

Injecting electrons or positrons into a magnetic dipole field is not a straightforward process [4]. Incoming positrons following the magnetic field lines from the beam line would be lost either by magnetic mirroring or by annihilation at the magnet's top pole. To reach the confinement region, the particles need to drift across magnetic field lines. This process is induced by a set of ExB plates (Fig. 1a). Injected positrons then magnetically mirror into the trap directly or after being electrostatically reflected by the positively biased segments of the outer electrode. When trapped, the particles perform a rapid gyromotion around the magnetic field lines, a bounce motion while being reflected magnetically or electrostatically between the two poles of the magnet and a slow toroidal drift motion around the magnet.

Even though injecting electrons employs the same principles as used for positron injection, the realization of simultaneous injection of both species is not trivial. The applied static electric field configurations are optimized for an efficient positron injection, which is achieved by applying repulsive positive potentials to the magnet and certain outer wall segments. Consequently, high numbers of electrons are lost because of these positive electrode biases and the shifted beam position. Nevertheless, as electrons can easily be generated in very high numbers, the injected numbers still exceed their positron counterpart by orders of magnitudes.

For this measurement, we demonstrate the feasibility of electron injection in our set up. The electron gun was placed at the same position a positron beam would be placed. The nominal bias voltages in the confinement device are +8V to the magnet, +14V to the outer electrode next to the ExB plates and +22V to its bottom equivalent. Electrons were emitted using a -18V bias on the filament, while +/-240V are applied to the ExB plates.

Figure 2 depicts a two-dimensional electron injection scan of the electron current measured at the fully inserted target probe (after 180° precession) versus the currents applied to the two pairs of steering coils. The y-axis can be interpreted as the radial beam displacements (closer or further away from the magnet) while the x-axis would correspond to azimuthal displacements (in between the ExB plates). The coloring changes from red to blue with increasing electron current. The narrow and nearly one-dimensional shape of this "position map" indicates a very high dependence on the tangential component of the position. The shape of this injection map can be explained qualitatively by the fact that positrons in our experiment require the repulsive potentials of the magnet and the outer wall electrodes to prevent collisions with them. Electrons in contrast, can only be injected within a narrow spatial window that is coupling them onto field lines which are not intersecting the outer wall and which further enable them to be solely magnetically mirrored by the permanent magnet despite its attractive potential.

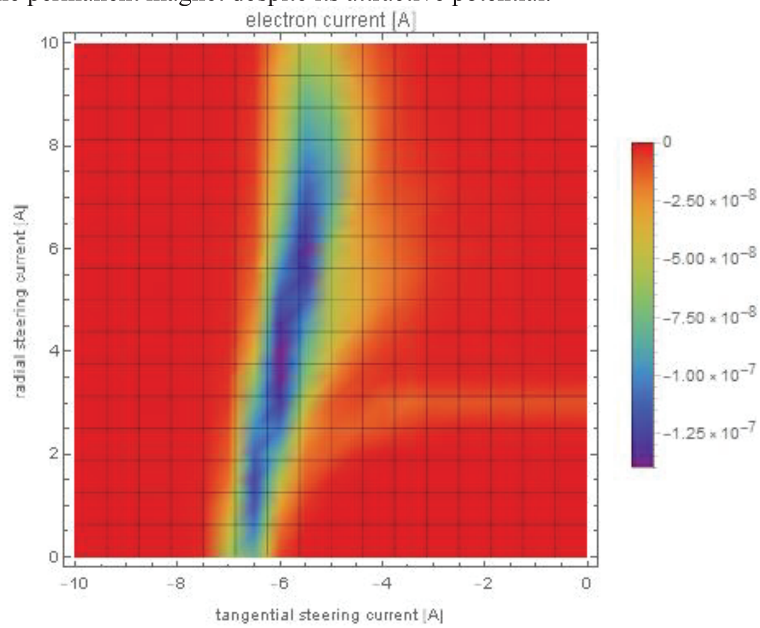

Figure 2: Measured electron current on the target probe as a function of the beam starting point: the y-axis represents the current of the coil affecting the radial position of the beam (i.e. closer to the magnet or closer to the outer wall), while the x-axis represents the current of the other pair of guiding coils manipulating the position between the ExB plates.

SUMMARY AND OUTLOOK

On the way towards creating a magnetically confined laboratory pair-plasma we have achieved various milestones such as 100% [5] injection efficiency and long (>1 s) [6] confinement of positrons. Measurements with the newly added electron gun indicate that electrons can be injected successfully even while the applied settings are optimized for positron injection. As a next step, experiments on simultaneous injection of electrons and positrons will be conducted, before we will apply our experience in ExB drift injection to other confinement geometries, such as a levitated superconducting coil which are expected to allow long time dual species confinement.

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