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Plans for the creation and studies of electron–positron plasmas in a stellarator

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Abstract. Electron–positron plasmas are unique in their behavior due to the mass symmetry. Strongly magnetized electron–positron, or pair, plasmas are present in a number of astrophysical settings, such as astrophysical jets, but they have not yet been created in the laboratory. Plans for the creation and diagnosis of pair plasmas in a stellarator are presented, based on extrapolation of the results from the Columbia Non-neutral Torus stellarator, as well as recent developments in positron sources. The particular challenges of positronium injection and pair plasma diagnostics are addressed.

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1. Introduction

Electron–positron plasmas (also called pair plasmas) are unique because of the perfect mass symmetry and perfect charge anti-symmetry. In contrast, many of the fundamental features of an ordinary electron–ion plasma are due to the large mass asymmetry between the negative and positive species. One example is the ion acoustic wave that is driven by a combination of the electron pressure (supplying the restoring force) and the ion mass (supplying the inertia). Even in the absence of collisions, this wave propagates in an electron–ion plasma, because the particles move collectively in response to the electric field that is generated by the electron pressure, as the electrons outrun the ions and space charge builds up. In an equal temperature electron–positron plasma, no such electric field develops since the two species escape a high-pressure region at the same rate because they have the same mass. Since the collisional mean free path is usually large, no regular acoustic wave appears; the plasma simply relaxes and eliminates the pressure perturbation through free streaming of the particles. The ion acoustic wave response along the magnetic field is an important component in most drift wave instabilities. Since this wave is absent in an electron–positron plasma, the physics of drift wave instabilities, ubiquitous in magnetized electron–ion plasmas, is also fundamentally different.

The mass symmetry also implies that electromagnetic waves traveling along the magnetic field do not experience Faraday rotation, contrary to the situation in electron–ion plasmas. Therefore, while electron–positron plasmas also allow the propagation of electromagnetic and electrostatic waves, the situation is quite different from that in an electron–ion plasma. It should, at least in principle, be much simpler, as many wave types that are distinct in an electron–ion plasma coalesce into just a few wave types in an electron–positron plasma. For example, the lack of Faraday rotation can be thought of as the disappearance of the distinction between the dispersion relations for left-hand polarized (L) waves and right-hand polarized (R) waves.

Another related example is that the low-frequency shear Alfvén wave does not exist in an electron–positron plasma. All three waves have the same dispersion relation and are indistinguishable. Some of the unique features of pair plasmas are described in a seminal article

from 1978 on electron–positron plasmas by Tsytovich and Wharton [1], which was the first paper to propose experimental studies of electron–positron plasmas. Since then, a large body of analytic and numerical work has been published exploring the unique physics of these plasmas, including explorations of basic wave physics [2], reconnection [3–5] and nonlinear phenomena such as solitons [6, 7].

However, no experimental study of pair plasma has been carried out so far. Such an investigation would not only reveal fundamental plasma physics, but also be of direct relevance for understanding a number of astrophysical objects. The energy density around, for example, neutron stars and active galactic nuclei is so large that copious pair production occurs (gamma radiation interacting with matter). Consequently, pair plasmas appear, for example in the relativistic jets that are observed around these objects. That some relativistic jets are in fact dominated by pair plasma has been observationally confirmed [8, 9]. The ability to study and manipulate pair plasmas in the laboratory should significantly enhance our ability to understand those astrophysical phenomena that involve pair plasma.

Astrophysical pair plasmas are often strongly magnetized. It would therefore be particularly interesting if one could create and study a strongly magnetized (small Larmor radius), small Debye length pair plasma. Recently, a proxy for a pair plasma was created, allowing studies of weakly magnetized almost equal mass plasma physics using fullerenes [10]. Such a plasma has many interesting pair plasma properties, but due to the large mass and the nonzero asymmetry in masses, the issues of confinement and stability of a strongly magnetized small Debye length pair plasma were not addressed. Also, the fact that the constituents of the fullerene plasma do not have exactly equal mass raises the possibility for acoustic waves. Thus, the physics of a magnetized pair plasma is yet to be investigated experimentally. We have previously proposed a stellarator as a suitable trap for such a plasma [11], and published a general plan on how to create it [12]. After nearly a decade of research since then, a more detailed plan has been developed, one that relies on modest extrapolations from experimental results that have been obtained in the meanwhile. We present this plan here.

2. Method of creation of electron–positron plasmas in a stellarator

2.1. Two simultaneous developments: A Positron–Electron Experiment (APEX) and Positron Accumulation Experiment (PAX)

The proposed experiments will be conducted in a dedicated stellarator experiment, the ‘A Positron–Electron Experiment’ (APEX). However, for the success of the research program, it is also required that a ‘Positron Accumulation Experiment’ (PAX) be developed. The importance of the PAX comes from the relative weakness of existing positron sources and from the fact that we now predict the confinement in APEX to be of the order of 1 s, rather than 1000 s as assumed earlier [12]. The APEX project will be housed at the FRM-II facility in Garching, Germany, which is home to the NEPOMUC positron source, arguably the brightest source of slow positrons in the world, 9×10^8 positrons s^{-1} with an energy spread well below 5 eV [13], with rates as high as 3×10^9 positrons s^{-1} on the near-term horizon. By comparison, a small heated filament is trivially capable of thermionic emission of electrons at rates above $10^{15} s^{-1}$, illustrating the significant challenge we face. At the same time, the NEPOMUC source rate will in fact be more than adequate for our purpose, since we will have the PAX, described in section 2.3. The two experiments will be developed in parallel and then combined together.

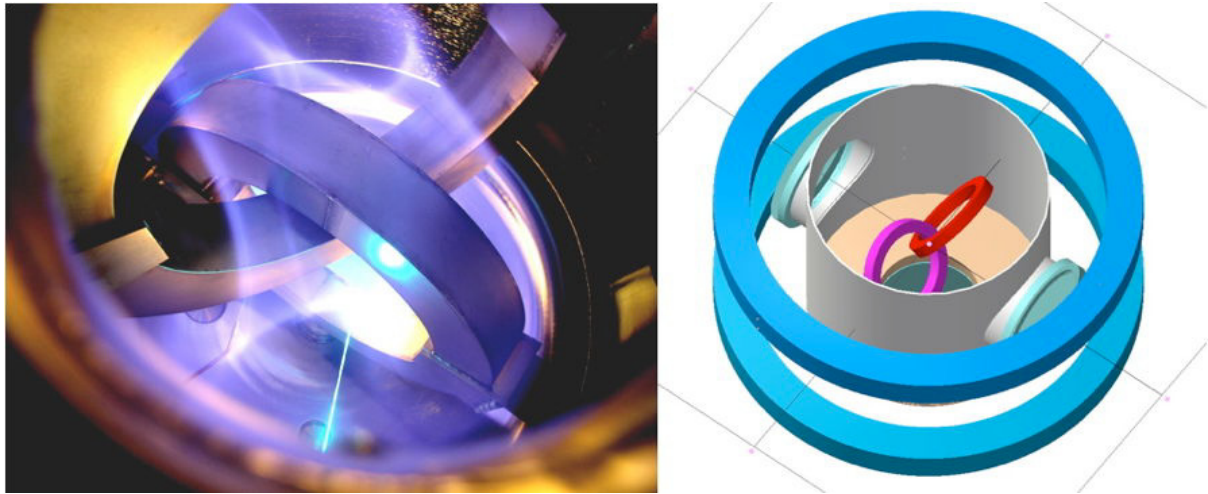


Figure 1. Left: a view through a vacuum port of CNT shows the blue/purple glow of plasma in the shape of magnetic surfaces. Right: a simplified CAD drawing of APEX. APEX will be conceptually similar to CNT but more than a factor of two smaller and with an order of magnitude higher magnetic field strength.

2.2. Design, construction and initial operation of the APEX stellarator

APEX will be a relatively small, superconducting stellarator. Its design is based on the Columbia Non-neutral Torus (CNT), which was built and operated at Columbia University. Figure 1 shows the CNT and a CAD drawing of APEX. The new experiment will consist of four circular coils, two of which will be interlocked (the interlocking (IL) coils). The magnetic field strength at the magnetic axis will be 2 T. The IL coils of APEX will be at an angle of 64° to each other—the same angle as that of CNT during its first operational phase, one that was characterized by a very low aspect ratio (a large volume relative to the surface area and experimental footprint), excellent magnetic surface quality and an unusually high error-field resilience [14, 15]. APEX will be significantly smaller than CNT—the major radius will be $R \approx 15$ cm and the minor radius $a \approx 7$ cm. The two IL coils will be placed inside the vacuum chamber, and the two larger poloidal field (PF) coils will be placed outside of the vacuum chamber. The chamber will be 316L stainless steel with copper (CF) flanges, bakeable and outfitted with a large UHV compatible cryopump allowing a base pressure of $p_n < 10^{-10}$ torr. Compared with CNT, the following differences are expected in APEX:

1. APEX will be smaller: the volume of the confinement region will be about 10 liters as compared with 100 liters in CNT
2. APEX will have higher B -field: APEX will operate with $B = 2$ T in steady state, as compared with 0.2 T achieved for 10 s pulses, or 0.06 T achieved in steady state in CNT.
3. APEX will have a better vacuum ($p_n < 1 \times 10^{-10}$ torr achievable during plasma operation, as compared with $p_n = 2 \times 10^{-10}$ torr, achieved only in the empty vacuum chamber in CNT, or $p_n = 1.1 \times 10^{-9}$ torr, achieved during pure electron plasma experiments.

Table 1 shows a comparison between the achieved parameters in CNT (for plasmas without internal objects) and the expected parameters in APEX.

Table 1. Comparison between achieved parameters in CNT and expected parameters in APEX.

Device	B -field (T)	R (cm)	a (cm)	T (eV)	n_e (m^{-3})	n_p (m^{-3})	N_e	N_p	τ (s)	p_n (Torr)	λ_D (cm)
CNT	0.2	30	16	2–20	3×10^{12}	0	3×10^{11}	0	0.09	1×10^{-9}	1.0
APEX	2	15	7	0.2–2	10^{13}	10^{13}	10^{11}	10^{11}	1	1×10^{-10}	0.1–0.3

The changes in APEX compared to CNT are primarily based on experimental results from CNT, which are briefly discussed in section 4.

However, the decision to make APEX smaller than CNT is due to the special challenge we face in attempting to create a pair plasma: that sources of positrons are relatively weak, making high plasma density a challenge, yet the Debye length (which decreases with increasing pair plasma density) must be small compared to the system size.

A simple scaling argument shows why, in this case, smaller is better: let the minor radius of the pair plasma be a and the major radius R . Then define the aspect ratio as $A = R/a$, and the volume of the plasma

$$V = \pi a^2 \times 2\pi R = 2\pi^2 Aa^3. \quad (1)$$

In a stellarator, there are subtleties in such definitions, since the plasma shape is topologically toroidal but it is not a simple torus, rather it is a twisted torus, and a and R can be defined in more than one way. However, in the following, such details are not important. One can simply assume that equation (1) holds for adequately defined a and R —it is the scaling that is important here. We want to find the size of the plasma that yields the maximum number of Debye lengths given a definite number of positrons $N = V \times n = 2\pi^2 Aa^3 n$. Here n is the positron density. Assuming that the plasma temperature T is independent of the size of the plasma, the number of Debye lengths in the device will scale as follows:

$$\frac{a}{\lambda_D} = a \sqrt{\frac{ne^2}{\epsilon_0 T}} = \sqrt{\frac{Ne^2}{\epsilon_0 T 2\pi^2}} \times \frac{1}{\sqrt{aA}}. \quad (2)$$

With our assumption that T is independent of a , we find that minimizing a and A will be optimal. This means one should build a small, low aspect ratio stellarator. CNT in its 64° configuration is the smallest aspect ratio stellarator ever built, $A = 1.9$ [14]. So again choosing the 64° configuration of CNT as the configuration not only makes sense because of the coil simplicity and the existing experience with this configuration, but also because it will maximize the number of Debye lengths. Additionally, one sees that making the device smaller helps just as much as making the aspect ratio smaller. There are, however, practical limits on the miniaturization. The smaller the experiment, the harder it will be to find space for diagnostics. The smaller the plasma and the Debye length, the smaller the macroscopic waves/modes will be. This may make detailed diagnosis harder. Smaller copper coils are harder to cool (if one keeps the required magnetic field constant), and water-cooled copper coils producing a given B -field become impractical below a certain size. The size chosen for APEX is a trade-off between these requirements, one that for example allows the PF coils to be steady-state capable water-cooled copper coils.

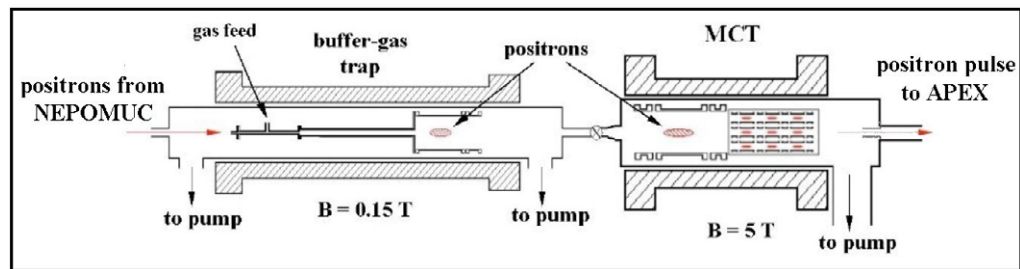


Figure 2. Positrons from the NEPOMUC source will enter a buffer gas trap, where they are collisionally slowed down and trapped. They are then transferred to the master cell of the MCT and from there loaded into the individual long term storage cells. Once a large enough number is accumulated in the storage cells, they can be injected into APEX.

The IL coils will be liquid-helium-cooled coils likely wound from NbTi superconducting wires. They will be operated with a maximum field of 4 T at the magnets (and, as mentioned, 2 T on the magnetic axis). This operating point is 35% below the critical current at the highest magnetic field point in the coil.

The initial physics phase for the APEX stellarator will consist of field line mapping, to confirm the existence of nested closed magnetic flux surfaces, and basic studies of pure electron plasmas. The goal will be to confirm very long-lived pure electron plasmas. As mentioned above, the projected confinement time is just above 1 s.

2.3. Accumulation of positrons in the PAX multicell Penning trap

With a plasma volume of 10 liters, a plasma minor radius of $a \approx 7$ cm, and an expected electron and positron temperature of 1 eV, the APEX pair plasma will have approximately 10 Debye lengths, $a/\lambda_D \approx 10$, enough to expect collective (plasma) behavior, if one has successfully injected $N \approx 10^{10}$ positrons (and electrons). One would, in other words, need a confinement time of more than 10 s if one were to use the NEPOMUC source in steady state to fill the trap. As described in section 4, the best confinement times achieved in CNT for positron-relevant conditions is two orders of magnitude lower. The higher B -field and better vacuum will likely improve confinement of pure electron plasmas up to just above 1 s, if one relies on the rather large linear extrapolation from CNT to APEX parameters. Therefore, we consider it too risky to rely on at least 10 s confinement time in APEX. Instead, we propose to accumulate of the order of 10^{11} positrons in a multicell Penning trap, the PAX. This trap would then be filled from NEPOMUC in a few minutes, and could be emptied into APEX in just a few milliseconds. Even if confinement in APEX (contrary to our expectations) would be somewhat worse than in CNT, APEX would still be able to create and study pair plasmas with a small Debye length.

The PAX experiment will be based on the buffer gas trap and Penning trap positron manipulation and storage techniques already developed [16, 17]. A multicell trap (MCT) system similar to that proposed some years ago is envisioned [18, 19]. An existing 5 T solenoidal magnet, previously used for studies of atomic clusters [20–22], will be used to provide the confining magnetic field for PAX. A schematic diagram of the setup is shown in figure 2.

Experiments will start with electron trapping, and once experience has been gained and successful long-term trapping of electrons has been achieved, PAX will be relocated to the NEPOMUC source for positron accumulation and trapping experiments. At first, loading and unloading of positrons will be performed, in parallel with the research program on APEX. The positron content will be measured by emptying the traps onto metal plates, and measuring the 511 keV annihilation photons with annihilation detectors as described in section 3. Once significant storage has been achieved, the ability to empty the trap rapidly and accurately will be established. Already at the level of 10^{11} stored cold positrons, PAX will have the world's largest accumulation of cold positrons. This should be a sufficient amount if 10% injection efficiency can be achieved in a way that allows the temperature to stay at or below 1 eV. The final goal is the simultaneous trapping of 10^{12} positrons [23].

2.4. Initial experiments in APEX

APEX will start its experimental campaign after field line mapping confirms nested closed flux surfaces. Initially, pure electron plasmas created from a removable heated filament will be studied, as has been done in CNT [26].

APEX will then begin experiments with positrons. The positron beam coming directly from NEPOMUC will be used for the development of schemes for the injection of positrons into APEX. Two different approaches are currently being considered. The first approach relies on special drift orbits that can be created and removed using electrostatic potentials. We have recently shown numerically that it is possible to use such drift orbits to inject positrons deep into the confined region of CNT, and then to close the orbits again, on time scales of 10^{-5} s by changing the voltages on biased sections [25]. APEX will be built with this capability. With this injection scheme, an electron plasma is first created using thermionic emission [24], the filament is retracted [26], and the positrons are drifted into the initially pure electron plasma, which will then start to accumulate positrons. During this experimental phase, it is unlikely that confinement will be sufficiently good that a small Debye length pair plasma will be created, since the NEPOMUC source only supplies of the order of 10^9 positrons s^{-1} . It will not only be necessary to switch the pattern of the electrostatic perturbation on and off, to avoid that the positrons drift out the same way they drifted in, but the patterns themselves will likely need to change as the plasma starts to neutralize. However, one should be able to build up a small but non-negligible population of positrons at that stage. This will also allow initial testing of the diagnostic system *in situ*. A much more massive injection of positrons coming from the PAX device should then lead to the successful creation of an electron–positron plasma. During this phase, it is likely that a glimpse of pair plasma physics will be seen: an electron plasma interacting with a small but non-negligible population of positrons.

The second injection scheme is fundamentally different: positrons will be guided onto specially prepared single-crystal Si surfaces, which have recently been shown to produce close to 100% conversion rate of positrons to 0.16 eV positronium (the neutral atom consisting of an electron–positron pair) [27]. An alternative scheme, which could be pursued if problems arise with the Si conversion scheme, is to guide the positrons onto a hot metal plate. Such plates are also known to create neutral positronium with very high efficiency [28, 29]. The positronium, which will be born in the ground state $n = 1$, will be excited to $n = 2$ to avoid prompt annihilation by a laser with wavelength 243 nm and pumped from there with a second infrared laser into a Rydberg state [30]. The positronium Rydberg atoms will then ballistically

drift across the magnetic field. The plate will be placed within 1 cm of the magnetic surfaces, in such a way that the positronium will drift into the confining magnetic field region (the closed magnetic surfaces) in 10^{-8} s. There, the positronium will be photo ionized by a third tunable infrared laser. Compared to the drift orbit scheme listed above, the positronium–laser injection scheme has two important advantages:

1. The plasma will be born neutral since each ionization exactly creates one electron and one positron.
2. The plasma temperature will be adjustable by the wavelength of the second laser.

So far, no clear disadvantages of this scheme have been identified. The scheme is based on a very recent work by Cassidy *et al* [27, 31].

3. Pair plasma diagnostics

Compared with quasineutral electron–ion laboratory plasmas, the pair plasmas we expect to create will be of very low density—3–9 orders of magnitude lower. Due to this low density, many non-perturbative diagnostics developed for fusion plasmas such as reflectometry or Thomson scattering, despite being in principle appropriate for diagnosis of pair plasmas, would be very challenging. Non-neutral plasmas typically have densities similar to those envisioned here, but the diagnostics developed for these plasmas roughly fall into two categories: either they are perturbative, requiring either a termination of the plasma or an internal probe [32], or they are non-perturbative but rely on external electrostatic measurements. Since the electric fields of a non-neutral plasma are large because of the space charge, these techniques have been very successful. However, a large space charge electric field is not expected in a quasineutral electron–positron plasma. The ambipolarity condition for such a symmetric situation will guarantee that the electric fields will be very small in an equal temperature pair plasma.

While the above observations should not be taken to indicate that none of the existing quasineutral plasma diagnostic techniques developed for other plasmas will work, they show that it is a non-trivial challenge to develop diagnostics for a pair plasma. However, there is one process in a pair plasma that should allow very good measurements to be carried out: annihilation.

Even though the electron–positron annihilation rate is so small that this loss channel is unlikely to limit the lifetime of the electron–positron plasma, there will be enough annihilation events to make them useful as a diagnostic. For a pair plasma with densities of the order of $n \approx 10^{13} \text{ m}^{-3}$ ($N = 10^{11}$ positrons injected into APEX), and electron and positron temperatures in the $T \approx 1 \text{ eV}$ range, the lifetime of the plasma, if limited by electron–positron annihilation processes, would be in the 10^5 s range (i.e. over a day) [33]. Still, with 10^{11} positrons and electrons simultaneously confined, there will be about one bulk annihilation event every μs , most likely creating two 511 keV photons—although higher photon numbers are possible [34]. Coincident two-photon γ -detection has been extensively used in gamma spectroscopy [35, 36] and positron emission tomography [37]. We will use a system inspired by these existing techniques. A ring of γ ray detectors will be installed around the plasma, and photons from each annihilation event will be detected within a coincidence time window ($\lesssim 10 \text{ ns}$) to diagnose our plasma. Coincidence detection determines the line along which each annihilation occurs, and if sufficiently fast detectors are used, the time of flight of the photons in a coincident event can provide more precise information on the position where the annihilation took place. The

Table 2. Physical properties of different scintillator materials as specified by Saint–Gobain Ceramics and Plastics, Inc.

	Density (g cm ⁻³)	Light yield (photon keV ⁻¹)	τ_{decay} (ns)	Energy resolution (FWHM; %)
NaI(Tl)	3.67	38	250	6
BaF ₂	4.88	1.8	0.7	9
BGO	7.13	9	300	12
LYSO	7.10	32	41	8
LaBr ₃	5.08	63	16	2.9

511 keV photons detected in coincidence will also experience a Doppler shift (ΔE_γ) which can be used to study the energy distribution of the positron–electron pair before the annihilation. ΔE_γ is given by [36, 38]

$$\Delta E_\gamma \approx \frac{1}{2}cp_L,$$

where c is the speed of light in vacuum, and p_L is the longitudinal component of the momentum of the center of mass for the electron–positron pair in the laboratory frame.

For gamma ray detectors with high-energy resolution, it will be possible to measure temperatures of the pair plasma. Scintillators are commonly used to detect positron–electron annihilations, but the energy resolution of these detectors is more than one order of magnitude worse than required in order to measure temperatures of the order of a few eV (table 2). High-purity Ge detectors (HPGe detectors) typically have an energy resolution of $\Delta E_\gamma \approx 1.2$ keV, which will allow the measurement of temperatures above 2 eV. If the plasma is colder than 2 eV, these detectors will at least be able to provide an upper bound on the temperature of 2 eV, which should allow confirmation that the Debye length is small.

The diagnostic scheme foreseen for APEX consists of a set of coincident HPGe detectors, and a densely populated matrix of scintillator detectors also working in coincidence. The scintillator system will be used to verify the successful accumulation of positrons. Most annihilation events will be recorded in the set of scintillators, so that the average plasma density is determined. If the density is known, the temperature of the plasma can be estimated based on the annihilation rate (also measured with the scintillators) and cross-checked with the value of temperature obtained in the HPGe detectors by measuring the Doppler shift. LaBr₃ scintillators present attractive properties (high density, light output and fast time constant, table 2) and will be used in combination with avalanche photodiodes (APDs), which are compatible with high magnetic fields [39, 40].

Thus, a set of three measurements (Doppler shift of the annihilation photons, the number of annihilations and annihilation rate) will be available at APEX to determine the average density and temperature of the pair plasma. In addition, measurements with very high spatial resolution will be carried out by injection of pellets with a diameter of 0.2 mm. These pellets will be injected at a velocity of the order of 200 m s⁻¹, driven by a neutral gas (likely helium), and they will act to localize the annihilation rate of positrons to the pellet. For the calculation of the annihilation rate of positrons on the pellet, it is important to keep in mind that for an equal temperature ($T_e = T_p$) quasineutral ($n_e = n_p$) pair plasma, there is no sheath around a material object since it does not charge up—electrons and positrons arrive at the surface at the same rate when the object is at the same potential as the plasma, so no sheath appears. If the pellet

is made of a material that does not convert positrons into positronium, but rather captures the positron, and if the positron then annihilates on a time scale less than 1 ms, then the positron annihilation rate dN_a/dt can be equated with the positron arrival rate on the pellet and therefore can be estimated as

$$\frac{dN_a}{dt} = 2\pi r_{\text{pellet}}^2 n_p \sqrt{\frac{T_p}{2\pi m_p}}. \quad (3)$$

Here, r_{pellet} is the radius of the pellet (assumed spherical in shape), n_p is the positron density, and we have assumed that the positrons and electrons are strongly magnetized (Larmor radius much smaller than pellet radius), so the effective area of collection is the area projected along the magnetic field in both directions, $2\pi r^2$. As can be seen from the above formula, the annihilation rate on a small material object is proportional to $n_p \sqrt{T_p}$ and thus not uniquely related to density or to temperature. With the aforementioned parameters ($n_p = 10^{13} \text{ m}^{-3}$, $T_p = 1 \text{ eV}$, $r_{\text{pellet}} = 2 \times 10^{-4} \text{ m}$), the annihilation rate is approximately $4 \times 10^{11} \text{ s}^{-1}$, i.e. at least four orders of magnitude above the bulk annihilation rate. Therefore, one can safely assume that the annihilations detected during the pellet's transit through the plasma all originate on the pellet. The pellet will traverse the plasma (approximately 10 cm from edge to edge) in $500 \mu\text{s}$, causing a total of 2×10^8 annihilations, i.e. it will only remove a fraction of 2×10^{-3} of the pair plasma inventory. Therefore, many pellets can be introduced sequentially or simultaneously and still act as localized non-perturbative objects. The pellets can be tracked with high-speed video cameras to monitor the exact paths.

3.1. Initial goals for the pair plasma physics phase

As good diagnostic tools are developed, plasmas will be studied in order to determine confinement times, heat and particle transport rates, to diagnose any observed instabilities, and detection of turbulence (if present). Macroscopic drift wave instabilities are not expected to occur, nor are microscopic instabilities, as investigated numerically previously [12]. The results show that at densities well below the Brillouin density limit ($n_B = \epsilon_0 B^2 / 2m_e$ [41]), finite Debye length damping should eliminate microscopic turbulence. If a macroscopic drift wave type instability appears nonetheless, it should be easily detectable by rotating patterns of annihilation on objects limiting the plasma, patterns that would presumably rotate poloidally and would give rise to annihilation modulations with frequencies that can be estimated in an order of magnitude sense as

$$f \approx mT / (2\pi eLaB) \quad (4)$$

with $L \approx 5 \text{ cm}$ a characteristic scale length of the gradients in B and gradients in plasma pressure p , and the minor radius of the plasma a of the same order of magnitude. Here m is the poloidal mode number which we assume is relatively low, 1–10. For $B = 2 \text{ T}$, this yields in the range 30–300 Hz. Interchange modes will be in the same frequency range and will also be easily detectable.

As can be seen from the approximate formula, the predicted low frequency range for these modes is the result of a combination of the relatively low temperature and the high magnetic field strength. If one can find a way of determining the plasma frequency, this will also yield information about the plasma density:

$$\omega_p^2 = \frac{(n_e + n_p)e^2}{\epsilon_0 m_e}. \quad (5)$$

Moreover, if the propagation speed of these waves can be measured, the plasma temperature can be deduced.

4. Important enabling research results from the Columbia non-neutral torus stellarator

The research program on the creation and confinement of electron–positron plasmas builds directly on research results achieved in the CNT stellarator, as also mentioned in our first paper on the prospects for creation of electron–positron plasmas in a stellarator [12]. The difference between the plans described here and the plans previously proposed are to a large degree due to the results that were obtained in CNT. We therefore summarize the most important results here. Most of these results have already appeared in the peer reviewed literature [11, 14, 24, 42, 43].

The CNT stellarator experiment received funding in 2002 and went into operation in 2004. Field line mapping confirmed the existence of large, high-quality magnetic surfaces [14]. Pure electron plasmas with a small Debye length and up to 20 ms confinement time were then confirmed later [24], and diagnostics were developed for these plasmas [32]. Detailed measurements, modeling [44] and experimental improvements allowed confinement, with internal electron sources, to reach 320 ms [45]. Since a retractable electron emitter was installed, capable of retraction in 20 ms [26], we expected already in 2007 to be able to start the study of plasmas without internal objects. This turned out to take longer than that, but we have now measured plasmas that gradually disappear with decay time scales as long as 0.09 s, clearly demonstrating that plasma remains after retraction.

Although the 0.09 s decay time is more than long enough for positron injection, it is still shorter than the confinement time record of 0.32 s achieved with internal electron sources. The shorter time scale is understood; after retraction, the plasma charge collapses due to ion buildup. Therefore, the confinement time is very much dependent on the neutral pressure (lower is better), the neutral species (neutrals hard to ionize, e.g. He, are much less detrimental than neutrals easier to ionize, such as N₂ or O₂) and the electron temperature (lower is better). When the ionization collapse is avoided, either through a lower temperature or a high ionization potential, the electron decay time (confinement time) scales approximately linearly with the magnetic field strength; otherwise the B -field dependence is weak. A more detailed description of these results is presented in an upcoming paper [46]. The important points here are that pure electron plasmas without internal objects have now been made and that the APEX experiment should have a high B -field, a neutral pressure as low as possible and a low electron temperature. A simple extrapolation of the data indicates that confinement times above 1 s can be expected for pure electron plasmas at $B = 2$ T, as long as the ion contamination collapse is avoided. At $B = 2$ T, cyclotron cooling [47] will allow the electrons (and positrons) to radiate off a significant fraction of their perpendicular kinetic energy on a 1 s time scale.

5. Summary

The ingredients for making pair plasmas on the Earth appear to be in hand. The NEPOMUC source of moderated positrons combined with a multicell Penning trap PAX should allow at least 10^{11} and perhaps up to 10^{12} simultaneously stored positrons, with a fill time of up to 15 min. Recent results from CNT show that pure electron plasmas without internal objects can be produced and that confinement times of such plasmas are expected to reach 1 s with the experimental parameters foreseen for APEX. Diagnostics for the initial operation of APEX rely

on the detection of the positron annihilation photons and should allow measurements of the bulk density, bulk temperature and also density profiles. Low-frequency drift wave-like instabilities should also be detectable. Two different injection schemes will be pursued; experimental and numerical results indicate that both could work.

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References

- [1] Tsytovich V and Wharton C B 1978 *Comments Plasma Phys. Control. Fusion* **4** 91
- [2] Zank G P and Greaves R G 1995 *Phys. Rev. E* **51** 6079
- [3] Bessho N and Bhattacharjee A 2005 *Phys. Rev. Lett.* **95** 245001
- [4] Blackman E G and Field G B 1994 *Phys. Rev. Lett.* **72** 494
- [5] Yin L, Daughton W, Karimabadi H, Albright B J, Bowers K J and Margulies J 2008 *Phys. Rev. Lett.* **101** 125001
- [6] Berezhiani V I and Mahajan S M 1994 *Phys. Rev. Lett.* **73** 1110
- [7] Cattaert T, Kourakis I and Shukla P K 2005 *Phys. Plasmas* **12** 012319
- [8] Wardle J F C, Homan D C, Ojha R and Roberts D H 1998 *Nature* **395** 457
- [9] Hirotani K *et al* 2000 *Astrophys. J.* **545** 100
- [10] Oohara W and Hatakeyama V 2003 *Phys. Rev. Lett.* **91** 205005
- [11] Pedersen T S and Boozer A H 2002 *Phys. Rev. Lett.* **88** 205002
- [12] Pedersen T S, Boozer A H, Dorland W, Kremer J P and Schmitt R 2003 *J. Phys. B: At. Mol. Opt. Phys.* **36** 1029
- [13] Hugenschmidt C, Löwe B, Mayer J, Piochacz C, Pikart P, Repper R, Stadlbauer M and Schreckenbach K 2008 *Nucl. Instrum. Methods Phys. Res. A* **593** 616
- [14] Pedersen T S, Kremer J P, Lefrancois R G, Marksteiner Q, Sarasola X and Ahmad N 2006 *Phys. Plasmas* **13** 012502
- [15] Pedersen T S, Kremer J P, Lefrancois R G, Marksteiner Q, Pomphrey N, Reiersen W, Dahlgren F and Sarasola X 2006 *Fusion Sci. Technol.* **50** 372
- [16] Surko C M, Leventhal M and Passner A 1989 *Phys. Rev. Lett.* **62** 901
- [17] Greaves R G and Surko C M 2000 *Phys. Rev. Lett.* **85** 1883
- [18] Surko C M and Greaves R G 2003 *Radiat. Phys. Chem.* **68** 419
- [19] Danielson J R, Weber T R and Surko C M 2006 *Phys. Plasmas* **13** 123502
- [20] Schweikhard L *et al* 1995 *Phys. Scr.* **T59** 236
- [21] Schweikhard L, Krückeberg S, Lützenkirchen K and Walther C 1999 *Eur. Phys. J. D* **9** 15
- [22] Martinez F, Marx G, Schweikhard L, Vass A and Ziegler F 2011 *Eur. Phys. J. D* **63** 255
- [23] Danielson J R, Weber T R and Surko C M 2009 *Non-Neutral Plasma Physics VII, 9th Int. Workshop on Non-Neutral Plasmas* ed J R Danielson and T S Pedersen, pp 199–206
- [24] Kremer J P, Sunn Pedersen T, Lefrancois R G and Marksteiner Q 2006 *Phys. Rev. Lett.* **97** 095003
- [25] de Gevigney B D, Pedersen T S and Boozer A H 2011 *Phys. Plasmas* **18** 013508
- [26] Berkery J W, Pedersen T S and Sampedro L 2007 *Rev. Sci. Instrum.* **78** 013504
- [27] Cassidy D B, Hisakado T H, Tom H W K and Mills A P 2011a *Phys. Rev. Lett.* **106** 133401
- [28] Canter K F, Mills A P and Berko S 1974 *Phys. Rev. Lett.* **33** 7

- [29] Mills A P and Pfeiffer L 1979 *Phys. Rev. Lett.* **43** 1961
- [30] Cassidy D B, Hisakado T H, Tom H W K and Mills A P 2012 *Phys. Rev. Lett.* **108** 043401
- [31] Cassidy D B, Hisakado T H, Tom H W K and Mills A P 2011b *Phys. Rev. Lett.* **107** 033401
- [32] Kremer J P, Sunn Pedersen T, Marksteiner Q, Lefrancois R G and Hahn T 2007 *Rev. Sci. Instrum.* **78** 013503
- [33] Crannell C J, Joyce G, Ramaty R and Wertz T 1976 **210** 582
- [34] Ore A and Powell J L 1949 *Phys. Rev.* **75** 1696
- [35] Stadlbauer M, Hugenschmidt C, Schreckenbach K and Böni P 2007 *Phys. Rev. B* **76** 174104
- [36] Lynn K G, MacDonald J R, Boie R A, Feldman L C, Gabbe J D, Robbins M F, Bonderup E and Golovchenko J 1977 *Phys. Rev. Lett.* **38** 241
- [37] Valk P, Delbeke D, Bailey D, Townsend D and Maisey M 2006 *Positron Emission Tomography: Clinical Practice* (Berlin: Springer)
- [38] Iwata K, Greaves R G and Surko C M 1997 *Phys. Rev. A* **55** 3586
- [39] Ziegler S 2005 *Proc. IEEE* **93** 763
- [40] Bergeron M *et al* 2009 *IEEE Trans. Nucl. Sci.* **56** 10
- [41] Brillouin L 1945 *Phys. Rev. Lett.* **67** 260
- [42] Marksteiner Q, Pedersen T S, Berkery J, Hahn M, Mendez J and Himura H 2008 *Phys. Rev. Lett.* **100** 095003
- [43] Pedersen T S, Berkery J W, Boozer A H, Brenner P W, de Gevigney B D, Hahn M S, Himura H and Marksteiner Q R 2008 *J. Plasma Fusion Res.* **3** S1022
- [44] de Gevigney B D, Pedersen T S and Boozer A H 2009 *Phys. Plasmas* **16** 122502
- [45] Brenner P W, Pedersen T S, Sarasola X and Hahn M S 2010 *Contrib. Plasma Phys.* **50** 678
- [46] Brenner P W and Pedersen T S 2012 Pure electron plasmas confined for 90ms in a stellarator without electron sources or internal objects *Phys. Plasmas* submitted
- [47] Anderegg F, Hollmann E M and Driscoll C F 1998 *Phys. Rev. Lett.* **81** 4875