From levitated dipole trap to neutron star's magnetospheres
Proposal for a guiding center PIC simulation

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ABSTRACT

Neutron stars are rotating objects with a strong magnetic field. The consequent induced field in the rotating reference frame is expected to support the creation of pair plasma in the vicinity of the neutron star. Presumably, electrons and positrons reside in separated domains above the poles and around the equator [1]. This model is supported by several fully kinetic particle-in-cell (PIC) simulations [2][3]. However, the magnetic field needs to be scaled down by several orders of magnitude in these simulations, such that the gyromotion can be resolved. We propose to use the guiding center approximation to overcome this difficulty. In a **first step**, the simulation would be **benchmarked against experimental results** obtained by the APEX collaboration. The APEX collaboration has the goal to create a pair plasma in a **levitated dipole trap** [4]. In a **second step** we plan to gradually **introduce the properties** that distinguish the lab experiment from the **neutron star's magnetosphere**. This involves for example the extreme magnetic field which leads to radiative processes with consequent pair creation as well as ultra-relativistic velocities.

	Radio Pulsar Magnetosphere [8]	APEX Levitated Dipole
Magnetic Field	$10^8\ T$	$1\ T$
Density	$10^{17}\ m^{-3}$	$10^{13}\ m^{-3}$
Energy	$10^5\ eV$ ($\gamma \approx 10$ for secondary particles)	$1\ eV$
Cyclotron Frequency	$10^{19}\ s^{-1}$	$10^{12}\ s^{-1}$
Plasma Frequency	$10^9\ s^{-1}$	$10^7\ s^{-1}$
EXB Drift	$10^5\ ms^{-1}$	$10^5\ ms^{-1}$
System Size	$10^4\ m$	$1\ m$
Debye Length	$10^{-1}\ m$	$10^{-2}\ m$
Larmor Radius	$10^{-13}\ m$	$10^{-6}\ m$

NEUTRON STAR MAGNETOSPHERE

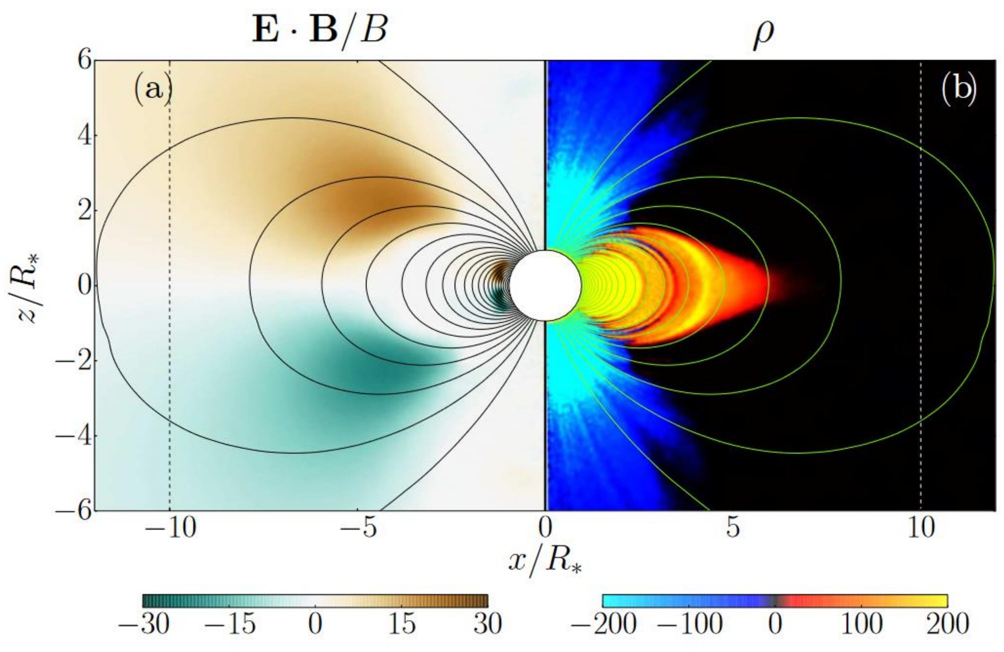

Fig. 1 2D fully kinetic PIC simulation of a neutron star's magnetosphere. (a) Parallel electric field (b) charge density. The rotation frequency/magnetic field is not high enough to sustain pair creation beyond the initial formation phase.
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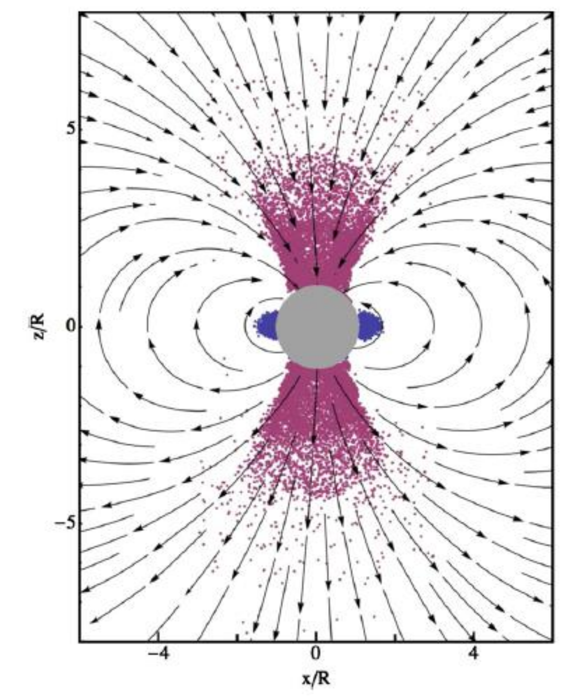

Fig. 2 3D fully kinetic PIC simulation of a neutron star's magnetosphere Electrons are blue, positrons are red
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The induced electric field in the rotating frame (Fig. 1a) extracts charged particles from the surface. Curvature and synchrotron radiation cause a cascade of pair creation. Electrons and positrons separate into a "disc and dome" distribution in an effort to shield the induced electric field (Fig. 1b & 2) .

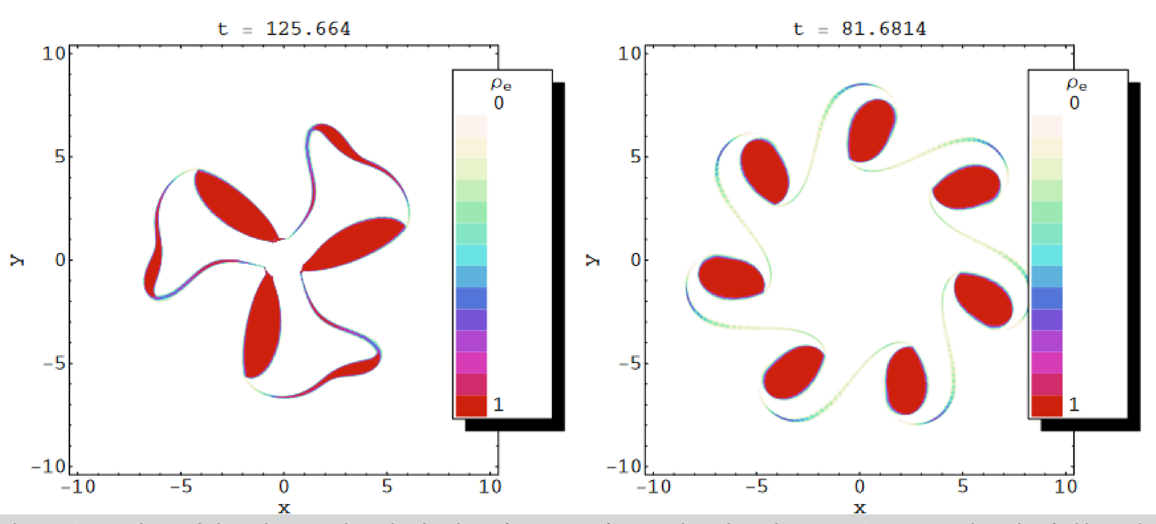

Fig. 7 Snapshot of the charge density in the plasma column showing the m = 3 pattern (on the left) and the m = 7 pattern (on the right). The chosen time corresponds to the transition between the linear phase and the beginning of the non-linear regime, associated with the total electrostatic energy curves. [6]

A guiding center PIC simulation of the equatorial plane of a neutron star's magnetosphere (Fig. 7) shows the same vortex structure that is observed in the non-linear phase of the diocotron instability in a Penning-Malmberg trap (Fig. 9).

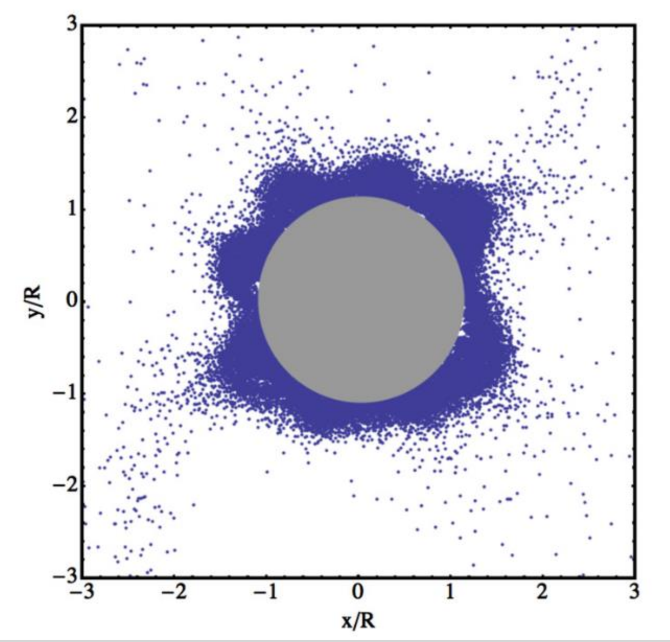

Fig. 8 Diocotron instability in the equatorial plane of the charge-separated aligned rotator. The instability leads to non-axisymmetric charge modulations and radial expansion of the disk.
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A global, fully kinetic PIC simulation of a neutron star's magnetosphere shows a mode structure that might be a diocotron mode in the equatorial plane (Fig 8). It took seven rotations of the plasma (corotating with the neutron star) to develop the structure in Fig.
Since the fully kinetic simulation has to resolve the gyro-motion, the magnetic field as well as the particle energies has to be scaled down. This also implies that the ratio between the light cylinder and the size of the neutron star is significantly smaller.
With the guiding center approximation we hope to be able to simulate the evolution of the plasma on the drift timescale and answer the question, rather or not previous results are stable.

COMPUTATIONAL METHODS

- **PIC Simulation** ➔ captures non-Maxwellian (due to loss cone, cyclotron cooling, relativistic velocities…) and kinetic effects (mirroring, phase-space holes…)
- **Full-f** (instead of $f \approx f^0 + \delta f$) ➔ can deal with large density gradients
- **Guiding center approximation** ➔

can deal with large magnetic fields/long timescales

- **Electrostatic** ➔ Is valid within the light cylinder

LEVITATED DIPOLE TRAP

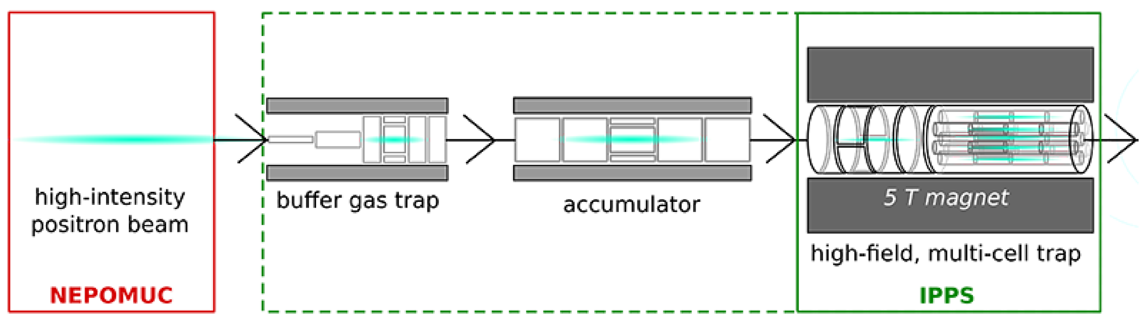

Fig. 3 General scheme for moderation and accumulation of positrons from the NEPOMUC source [4]

At the moment, an electron emitter is used for injection (Fig. 4). In the future electrons and positrons will enter from an external beamline as shown in Fig. 3. Depending on the charge on the coil and the charge of the particles, the plasma either closes around the coil (Fig. 6) or is restrained to distinct regions in the center of the coil and the outboard midplane (Fig. 5).

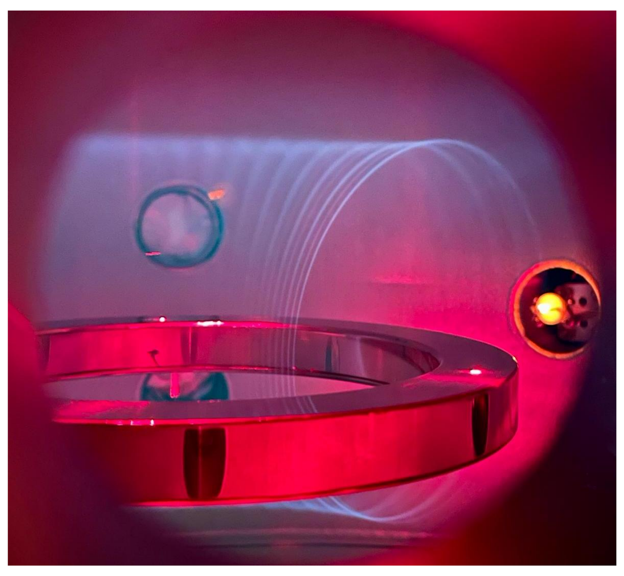

Fig. 4 Photograph of the levitated dipole trap. Electrons are accelerated away from the glowing emitter and excite helium that was introduced in the trap to visualize the trajectory.

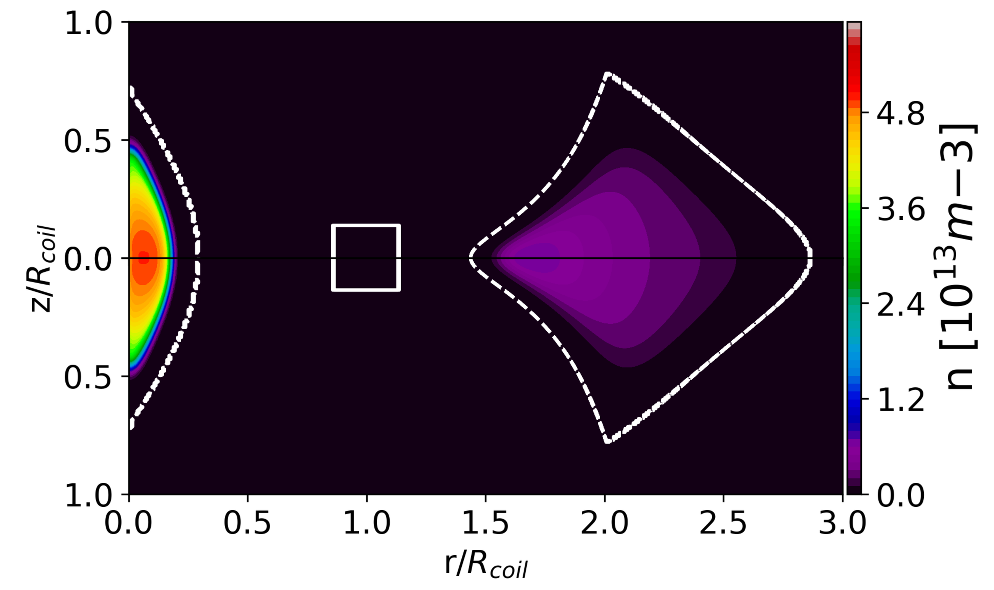

Fig. 5 Density distribution of electrons and positrons in a global thermal equilibrium state [5]. They are confined in separate domains defined by the potential well indicated by the white dashed lines. Complete charge separation is achieved by biasing the coil (white solid line).

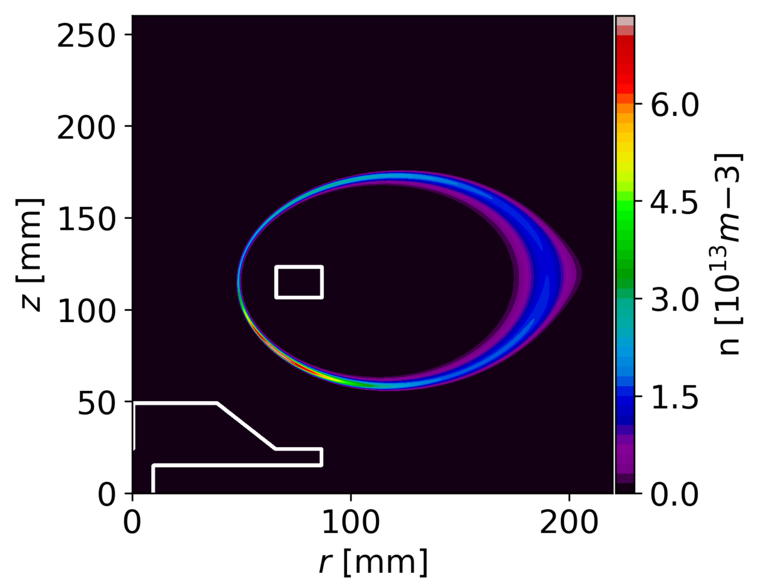

Fig. 6 Density distribution of an electron plasma in a local thermal equilibrium along magnetic field lines [5]. The coil is neutral and the lifter platform is grounded, both are indicated by white solid lines.

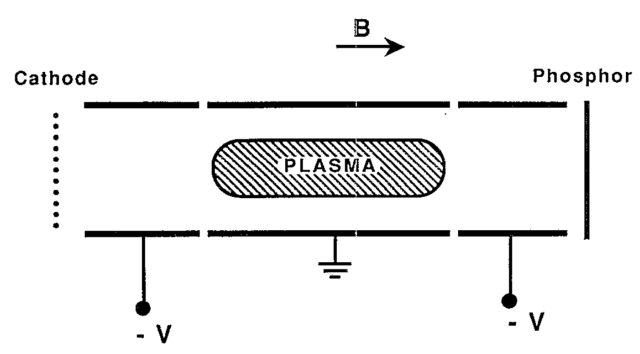

Fig. 8 Schematic of a Penning-Malmberg trap. [7]

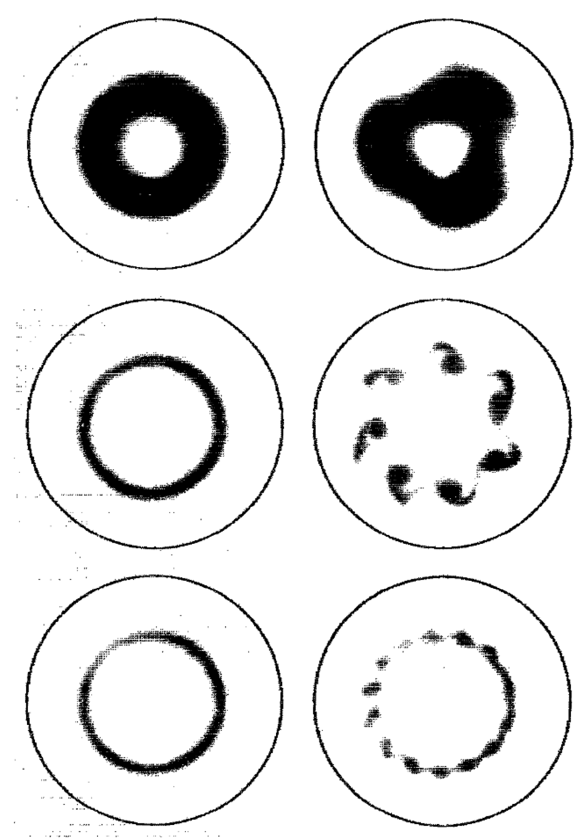

Fig. 9 Images of annular plasmas for three different thicknesses (0.67, 0.17, and 0.14 cm). The left column is at t=O. The right is after the onset of the diocotron instability. The outer circle indicates the conducting wall. [7]

The diocotron mode has been studied extensively in Penning-Malmberg traps shown in Fig. 8. These traps consist of cylindrical electrodes which provide electrostatic, axial confinement, A homogeneous magnetic field along the axis provides radial confinement. By lowering the potential on one side the plasma can be dumped onto a phosphor screen, revealing the mode structure

The fluctuations measured at with the wall probe (Fig. 10) has the scaling with the magnetic field expected for a drift wave $\omega \propto B^{-1}$ and is likely to be related to the diocotron instability.

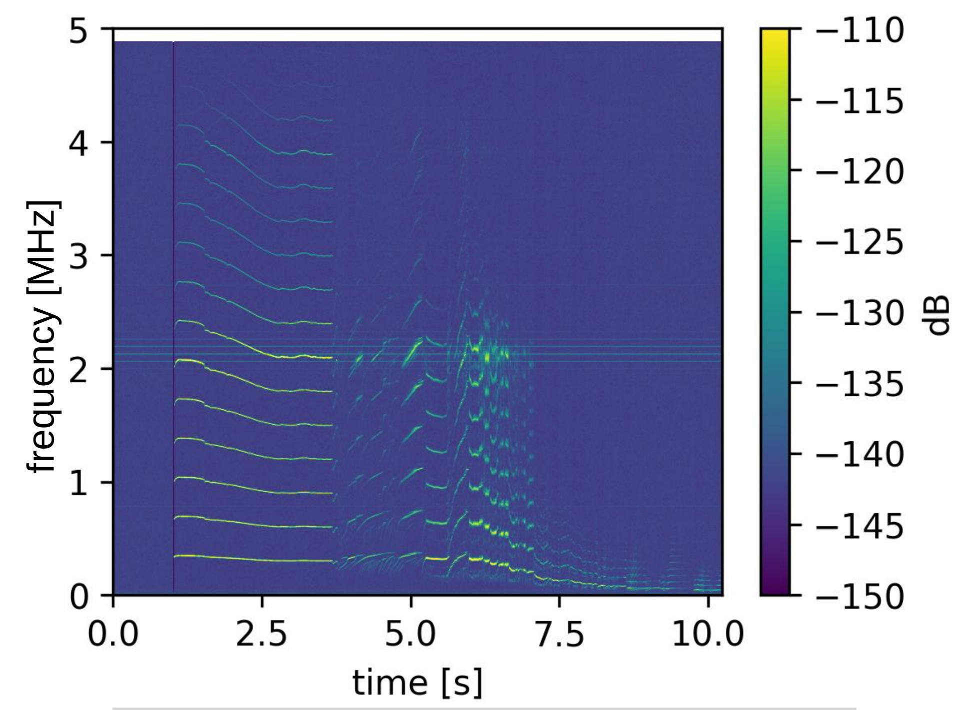

Fig. 10 Spectrogram of a potential perturbation measured with a wall probe in the levitated dipole trap after electrons were injected.

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