EPOS: Electrons and Positrons in an Optimized Stellarator

Helmholtz Young Investigator Group to be based at the Max Planck Institute for Plasma Physics

with academic partner University of Greifswald
Outline

I. (Re)introductions
• The fourth state of matter
• Fundamental plasma physics experiments

II. Goals for EPOS
• Uniting two frontiers to advance both
  ◦ pair plasmas
  ◦ stellarators
• The six-year plan

III. Complementarity
• with the APEX collaboration
• with Simons Collaboration on Hidden Symmetries and Fusion Energy

IV. Summary
The “fourth state of matter”

- 99.9...% of observable matter in the universe
- the science of fusion energy
- spanning many orders of magnitude of temperature and density

**STP**
The “fourth state of matter”

- 99.9...% of observable matter in the universe
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- spanning many orders of magnitude of temperature and density
- scalability by identifying key dimensionless parameters
  → well-designed laboratory experiments can shed new light on fundamental physics

* STP
* typical lab astro

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The “fourth state of matter”

- 99.9...% of observable matter in the universe
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- spanning many orders of magnitude of temperature and density
- scalability by identifying key dimensionless parameters
  → well-designed laboratory experiments can shed new light on fundamental physics
- traditional plasmas: electrons and ions

STP
☆ typical lab astro
☆ EPOS target
Why “do the experiment”?  

- Sometimes terms expected to be important turn out not to be (and vice versa).
- Sometimes the experiment works better (or worse) than anticipated.
- Sometimes, a system may start in one regime and evolve to cross a boundary into another.

"Experiment can simulate computation: Resolves all scales, includes all correlations, includes all MHD and kinetic effects, ‘CPU time’ < 1 second"

~Stewart Prager

e.g., a transition from ideal MHD to magnetic reconnection

Frontier I. The physics of pair plasmas

Mass asymmetry is a cornerstone of the physics of quasi-neutral plasmas ...
A juncture of two frontiers

Frontier I. The physics of pair plasmas

Mass asymmetry is a cornerstone of the physics of quasi-neutral plasmas . . .

. . . but what if the mass ratio were unity?

~1000 papers on “pair plasmas”
An illustrative example: basic waves

- “look-up” table (wave frequency, magnetic field, density)
- plasma is homogeneous, infinite, magnetized (z)
- two frictionless fluids with T=0
- linear modes
- up to 2 solutions to dispersion relation
- boundaries: cut-offs, resonances
- wave normal surface: locus of the normalized phase velocity vector

\[ \frac{\omega_{ce}^2}{\omega^2} \] 

\[ \frac{m_i^2}{m_e} \] 

\[ \frac{\omega_{pe}^2 + \omega_{pi}^2}{\omega^2} \]

\[ \frac{u_z}{u_x} = \omega/(k_x c) \]
An illustrative example: basic waves

standard CMA diagram (Bellan)

larger magnetic field

higher density

Stenson et al. J. Plasma Phys. 83 (1), 2017
An illustrative example: basic waves

standard CMA diagram (Bellan)

Next, add finite T, curvature, gradients, . . .

pair plasma CMA diagram

Stenson et al. J. Plasma Phys. 83 (1), 2017
Why explore this frontier?

Understanding plasma physics at the limit of a mass ratio of unity will advance:

Our understanding of fundamental aspects of plasmas.

Our understanding of our universe.

- Lepton Epoch = 1-10 s after the Big Bang
- More recent phenomena involving e+/e- plasmas: gamma ray bursts, pulsar winds, jets from active galactic nuclei
- Likely low-energy (as well as relativistic) e+

→ experiments needed on the “H atom of plasma physics”
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Goal: many Debye lengths, both species magnetically confined

Low-temperature e-/e+ plasmas in a toroidal trap
Frontier II: Stellarator optimization

Strong reduction of neoclassical (NC) transport = a primary goal of stellarator optimization.

- in present-day stellarators (esp. high n, low T), transport dominated by turbulence
- at the reactor scale (Ti > 10 keV), however, neoclassical optimization will be key
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Even without optimization, NC transport suppressed by electric fields → poloidal ExB drifts → “orbit healing”:

- especially when Te >> Ti
- even when Te = Ti, the large mass difference → strong ambipolar electric field
- But at large scales, orbit healing insufficient, particularly for α particle confinement

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For a confined e+/e- plasma:

- no plasma current to speak of
- predicted to be essentially absent of turbulence
  
  \( (T. \text{ Sunn Pedersen 2004. P. Helander 2016+}) \)
- zero ambipolar field (when T+ = T-)

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- But at large scales, orbit healing insufficient, particularly for \( \alpha \) particle confinement

Close collaboration with ST, Simons

Despite the primary operational scenarios being very different than those of fusion reactors . . .

. . . EPOS should be able to provide a valuable test case for robust, next-generation stellarator optimization (M. Drevlak, J.-F. Lobsien, Simons “Hidden Symmetries” collaboration, et al.).

(Strict test of how good NC optimization can be.)

- strong magnetic fields, small size
- low temperatures, very low densities
- no magnetohydrodynamics (MHD)
- no ions (though they can/will be deliberately introduced, when desired)
- no pressure, heat loads, or neutrons
- significant flexibility with respect to coil design (modular vs. extended; multiple layers; low ripple; close to plasma)
- e+ as a very sensitive diagnostic

QH:

QA:

QI:

EPOS: the six-year plan

Stage 1: Designing the stellarator (2020)

- choose the magnetic field for the desired physics investigations (including strategic de-optimization)
- determine which superconductor to use (first HTSC stellarator?)
- coil design using state-of-the-art optimization techniques

large.stanford.edu/courses/2011/ph240/kumar1/
In the 60s, Marvin Minsky assigned a couple of undergrads to spend the summer programming a computer to use a camera to identify objects in a scene. He figured they’d have the problem solved by the end of the summer. Half a century later, we’re still working on it.
Magnetohydrodynamics combines the intuitive nature of Maxwell's equations with the easy solvability of the Navier-Stokes equations. It's so straightforward physicists add "relativistic" or "quantum" just to keep it from getting boring.
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Stage 2: Construction, testing, installation (2021-2022)

- 3D printing of advanced materials
- build on established methods (e.g., for magnetic surface validation, injection of e+ across magnetic surfaces)
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Stage 3: Studying e-/e+ plasmas (2023-2025)
- density & temperature measurements, compare to stability predictions
- effects of contaminant ions, fractional non-neutrality, heating
the APEX collaboration

A Positron Electron eXperiment (APEX), as planned for 2020+:

- e+ world-class source
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A Positron Electron eXperiment (APEX), as planned for 2020+:

- e+ world-class source, accumulated into ever denser bunches, injected into dipole trap
- multi-institutional and international effort, based at the MPI for Plasma Physics

→ important cross-comparison of pair plasmas in systems with highly distinct topologies (and thus physics) but comparable parameters

*not EPOS

Importance of the magnetic topology

Disparate magnetic topologies → vastly different physics

part of a single stellarator field line:

16 individual dipole field lines:

bonus movie (field lines to full surface):
DrawLinesCombined.avi
**Goal of EPOS:** to create and study electron-positron plasmas in a tabletop-sized, optimized stellarator

I. Pair plasmas:
- studied theoretically and computationally for decades, predicted to display a host of unique properties
- test our fundamental understanding of plasma systems, validate simulations, enhance our understanding of our universe

II. Stellarators
- being researched for use in next-generation fusion reactors
- EPOS as an ideal test bed for state-of-the-art stellarator design

By bringing together these two forefronts of plasma physics research, we can substantially advance knowledge in both.
bonus slides
Why can a e+/e- plasma exist?

**direct annihilation?**

→ greater than 1 day for $10^{12}$ positrons and electrons in a 1-liter volume

**positronium formation?**

→ not a limiting factor unless the temperature is very low

**annihilation on neutral gas?**

→ solved by UHV ($10^{-10}$ torr) and elimination of organics ($N_2$: 17 days; He: 121 days)

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**FIGURE 2.** Electron-positron plasma lifetime due to direct annihilation (dashed line) and positronium formation (solid lines) as a function of plasma density.

Greaves and Surko at NNP IV --&gt; AIP Conf. Proc. 606, 10 (2002)
Reduced mass ratios are an established tool in plasma simulations. (Sometimes this works better than others.)

Magnetic reconnection:

Turbulent transport:

In physics, it’s important to understand the limits. ("H atom of plasma physics")
Two complementary confinement schemes

Both steady state, purely magnetic, no internal currents.

Both can confine either non-neutral or quasi-neutral plasmas.

Vastly different (but complementary) physics.

There are also some instabilities (e.g., GDC) that can be stabilized with magnetic shear.

Complementary technical strengths/weaknesses, as well.

<table>
<thead>
<tr>
<th>levitated dipole</th>
<th>stellarator</th>
</tr>
</thead>
<tbody>
<tr>
<td>steady state on typical plasma timescales</td>
<td>steady state</td>
</tr>
<tr>
<td>astrophysical relevance</td>
<td>fusion relevance</td>
</tr>
<tr>
<td>strong flux expansion</td>
<td>negligible flux expansion</td>
</tr>
<tr>
<td>each B-field line closes after one pass</td>
<td>magnetic flux surfaces</td>
</tr>
<tr>
<td>short B-field connection lengths</td>
<td>long B-field connection lengths</td>
</tr>
<tr>
<td>parallel force balance does not counteract instabilities</td>
<td>parallel force balance counteracts instabilities</td>
</tr>
<tr>
<td>drift orbits always confined (axisymmetry)</td>
<td>drift orbit confinement requires optimization</td>
</tr>
<tr>
<td>levitation requires cooling/warming cycles</td>
<td>indefinite operation</td>
</tr>
<tr>
<td>2-3 planar coils (floating, lifting, charging)</td>
<td>many 3D coils</td>
</tr>
<tr>
<td>detachable current leads OR inductive charging</td>
<td>permanently attached current leads</td>
</tr>
<tr>
<td>possibility for steady state fueling</td>
<td>requires positron pulses for fueling</td>
</tr>
</tbody>
</table>

Columbia Non-neutral Torus

The NEPOMUC e+ source

The NEPOMUC e+ source

- operated at the FRM-II neutral source (Garching)

- neutron-capture in $^{113}\text{Cd} \rightarrow$ high-energy $\gamma$-rays
  $\rightarrow$ pair production and moderation in Pt foils

- e+ are accelerated, magnetically guided down the beam line
  $\rightarrow$ primary beam ($\sim$1 keV, $10^9$ e+/s)

- optional second moderator step
  $\rightarrow$ remoderated beam ($\sim$10 eV, $10^7$ e+/s)

- five-way switch $\rightarrow$ different experiment stations

APEX beam time:
- 20 days in 2015
- 13 days in 2016
- 34 days in 2017
- 21 days in 2018