MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Applying positron-emission techniques to electron-positron pair plasma

Jens von der Linden

for the APEX collaboration

6.7.2024

5th Jagiellonian Symposium

Outline

Magnetically confined pair plasma

What is it and why make it?

APEX approach

Diagnosing positron bunch confinement experiments

21-detector array (BGO)

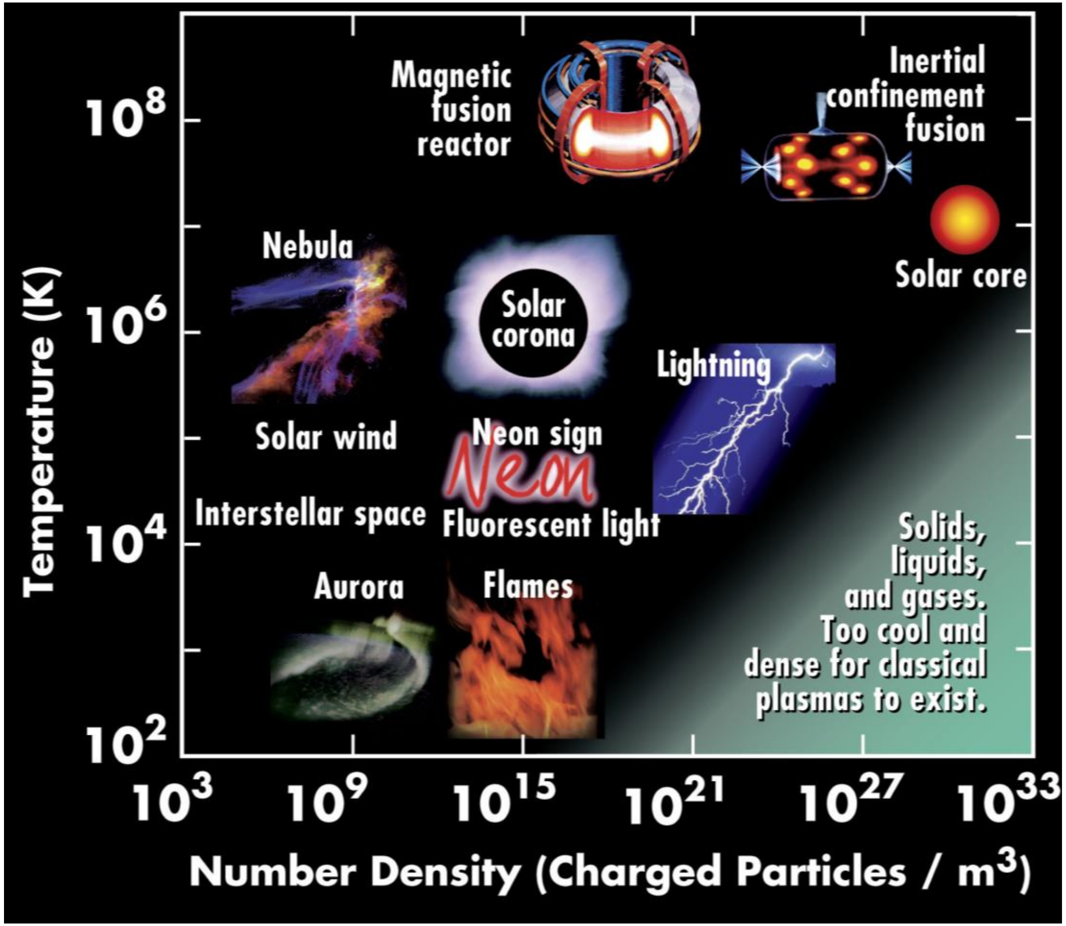
Positronium formation & transport to wall

Outlook: Annihilation of a magnetically confined pair plasma

Competing processes

Spatial separation enables distance-attenuated counting and tomography

Plasma on earth and in our universe

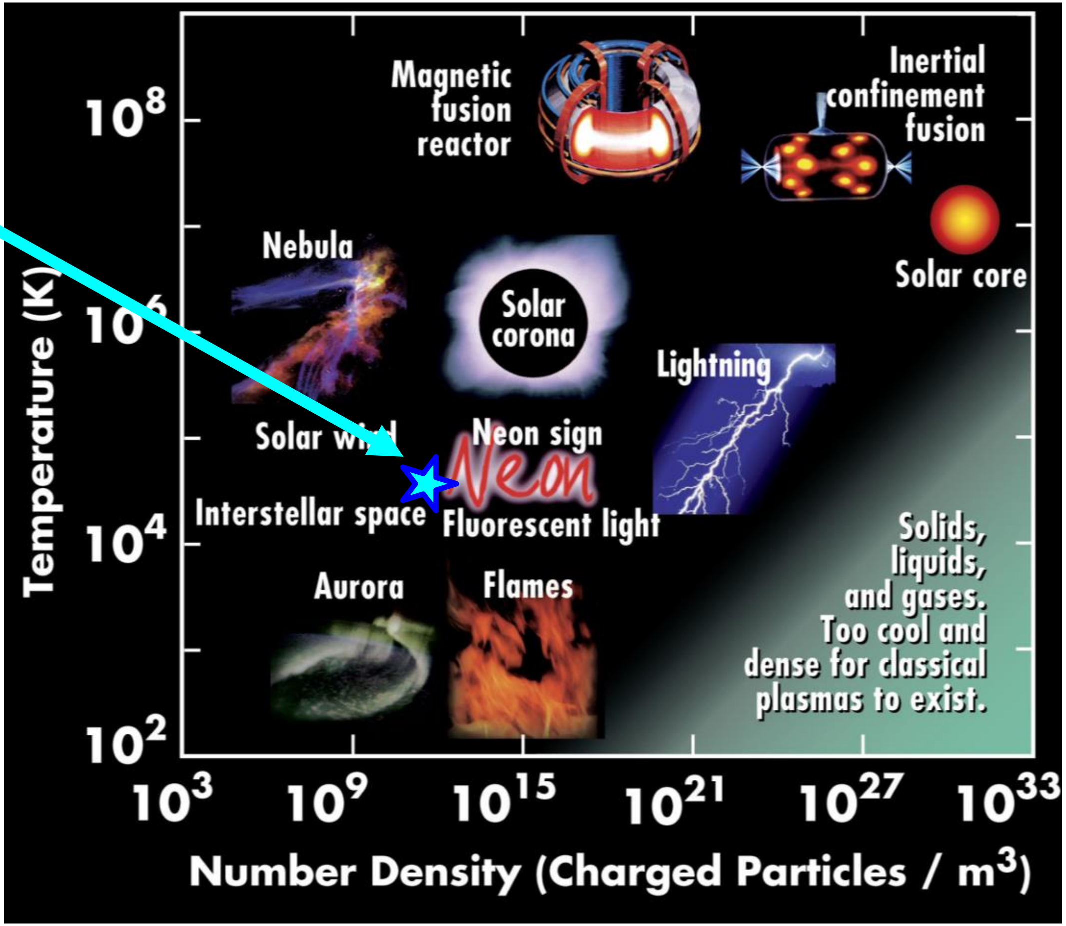


Magnetically confined electron-positron pair plasma

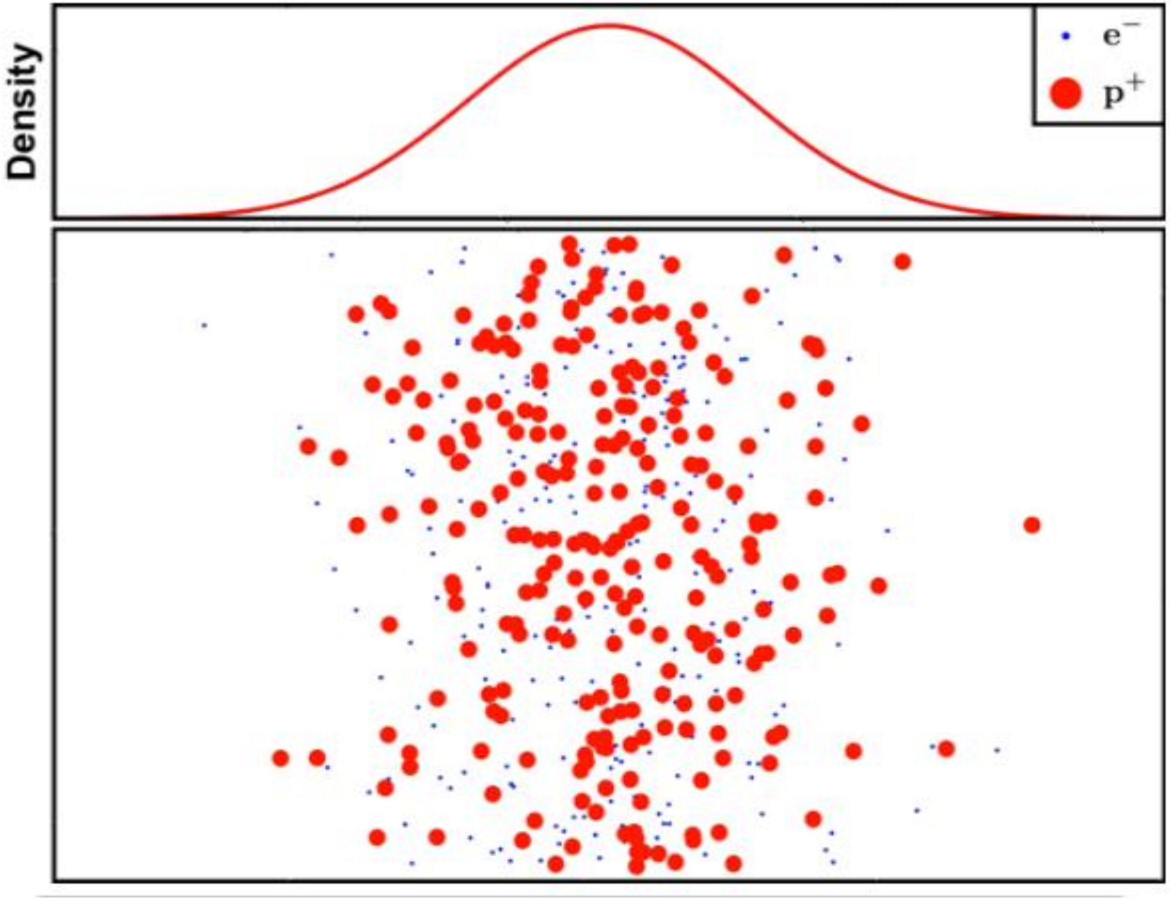
APEX goal
pair plasma

$$\frac{m_{e^+}}{m_{e^-}} = 1$$

$$\frac{m_i}{m_e} \geq 1836$$



Mass asymmetry responsible for many modes & waves



simulations courtesy of S. Nißl

Stoneking et al. (2020). J. Plasma Phys.

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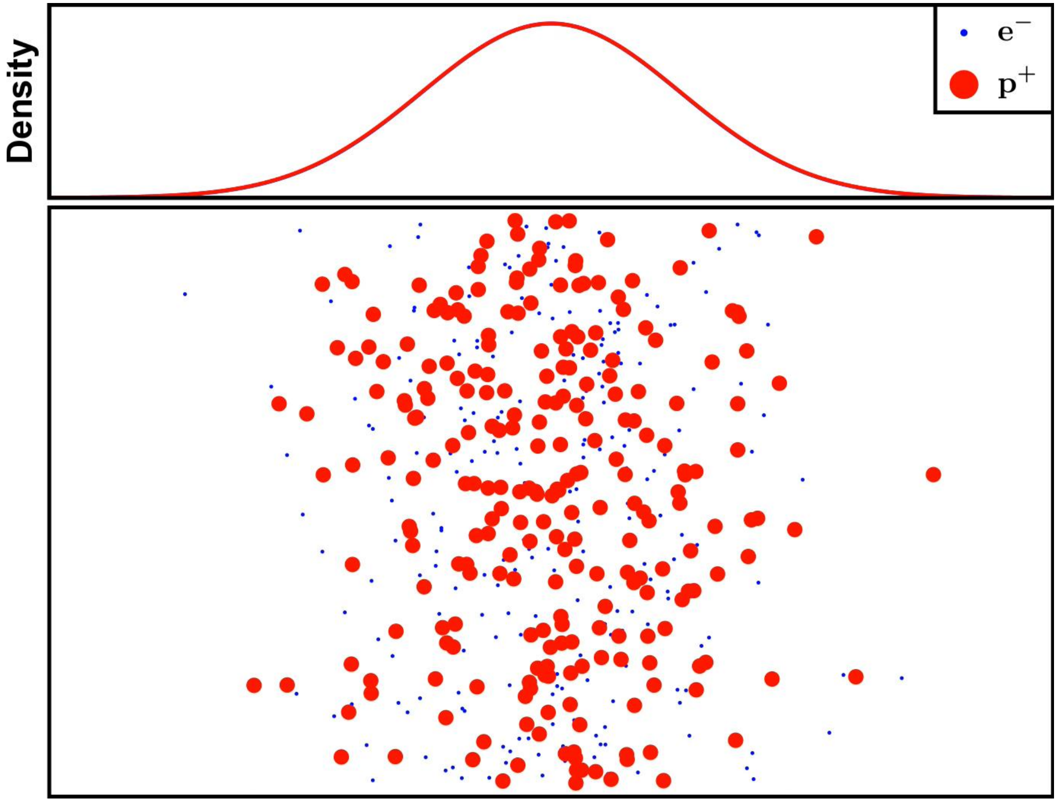

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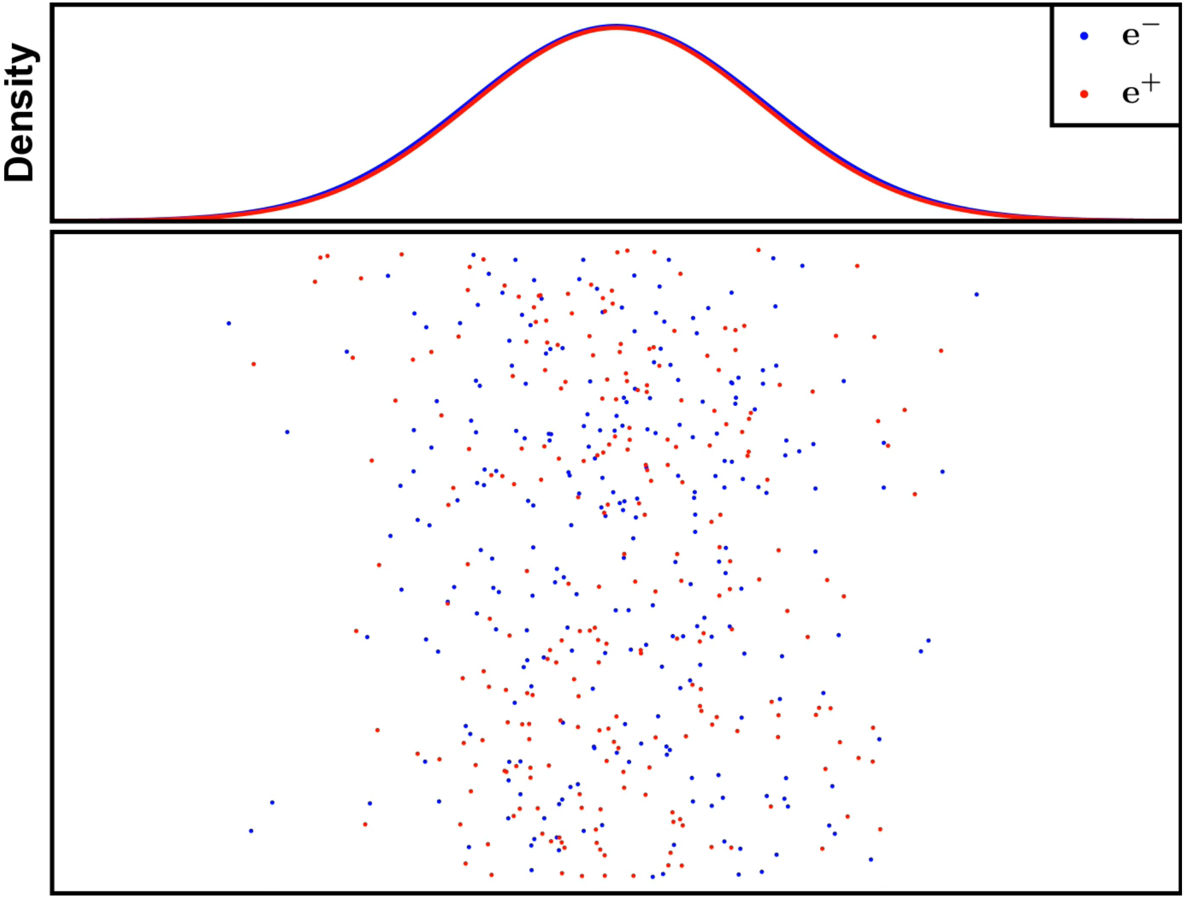


simulations courtesy of S. Nißl

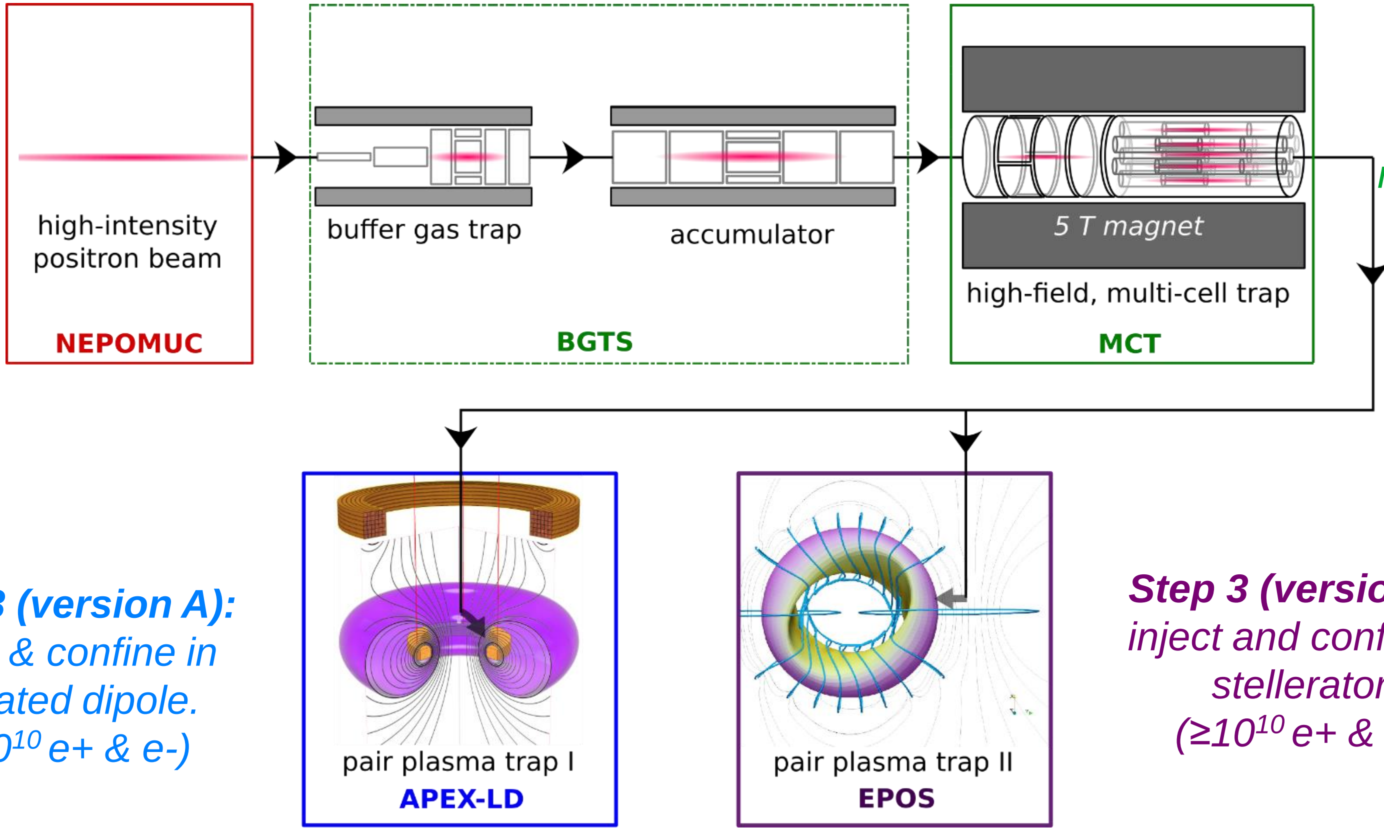
Stoneking et al. (2020). J. Plasma Phys.

The APEX grand scheme

Step 1:
Positron source
(up to $10^9/s$,
$5 \cdot 10^7/s$ remoderated)

Dickmann et al. (2020)
Acta Physica Polonica A

Huggenschmidt et al. (2012)
New J. Phys.



Step 2:
accumulate in non-neutral traps

Step 3 (version A):
inject & confine in levitated dipole.
($\geq 10^{10}$ e+ & e-)

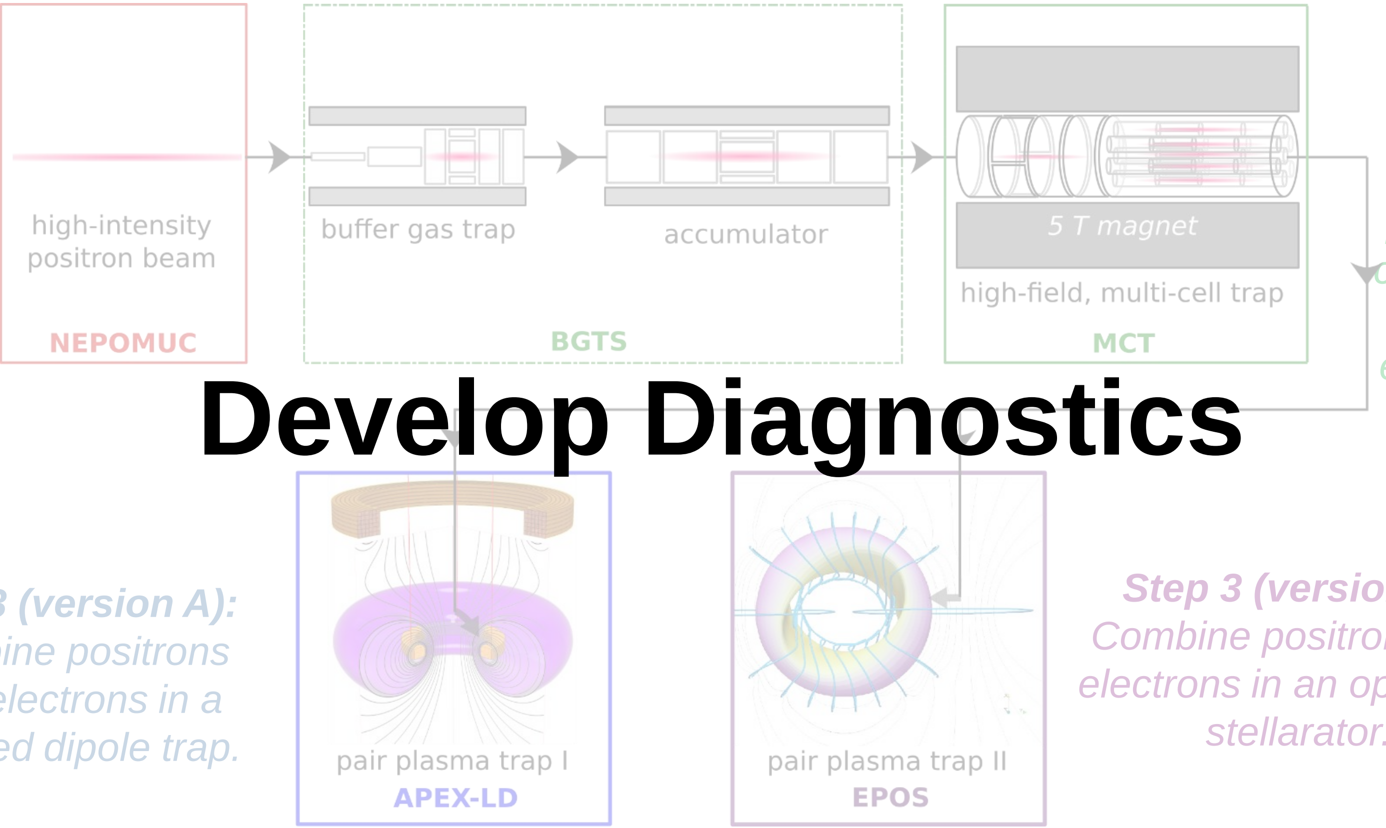
Step 3 (version B):
inject and confine in stellerator.
($\geq 10^{10}$ e+ & e-)

Step 4: *Study transition to the regime of collective, quasineutral behavior; stability (indeed turbulence-free?), transport (what limits confinement time?), robustness (e.g., to T asymmetry, ion contamination), . . .*

Stoneking et al. (2020) J. Plasma Phys.

The APEX grand scheme

Step 1:
Obtain positrons from world-class source (up to 10^9/s)



Step 2:
Use a series of non-neutral plasma traps to collect positrons, until we have enough to make a plasma.

Develop Diagnostics

Step 3 (version A):
Combine positrons with electrons in a levitated dipole trap.

Step 3 (version B):
Combine positrons with electrons in an optimized stellarator.

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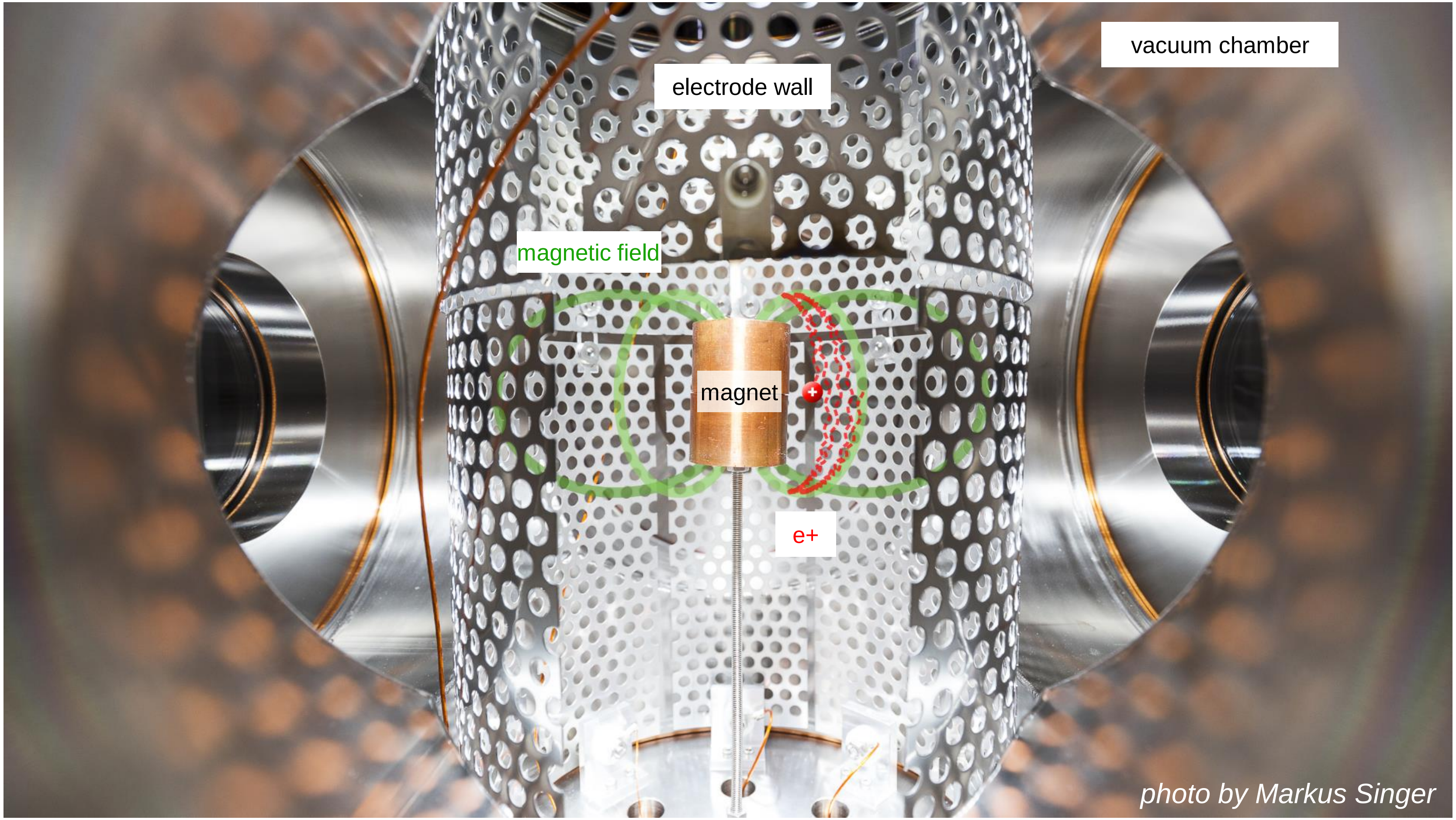
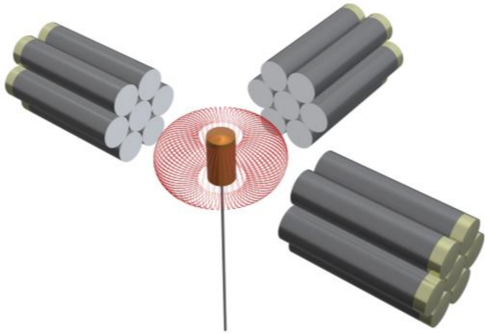
Distance-attenuated photon counting

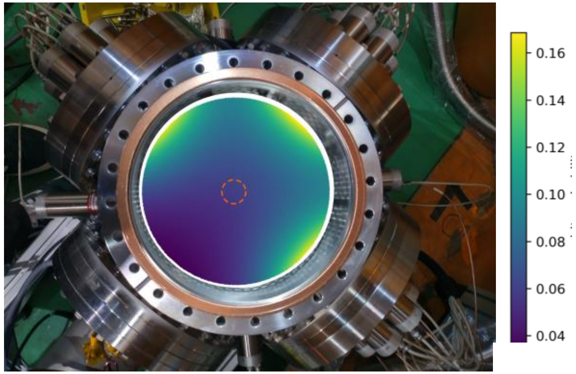
Tomography

Proto-APEX: sandbox for developing diagnostics

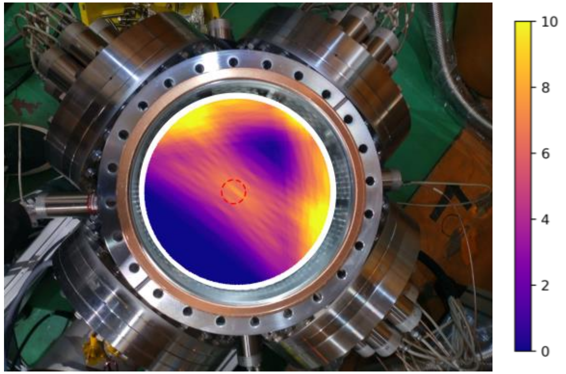


21 BGO detectors: counts, energy & timing

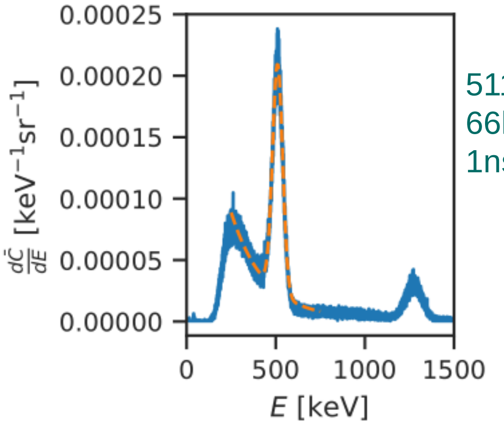




$\frac{\Omega}{4\pi}$

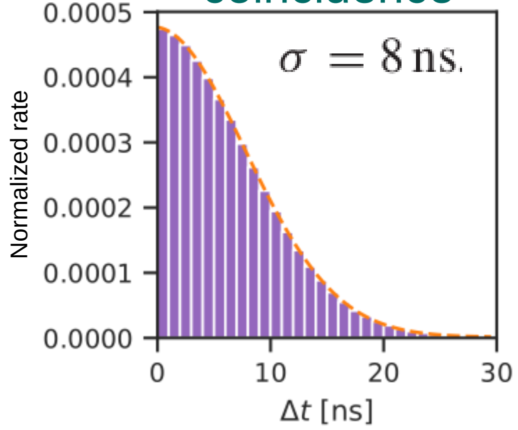


LOR



511keV FWHM 13%
66keV resolution
1ns time stamping

coincidence

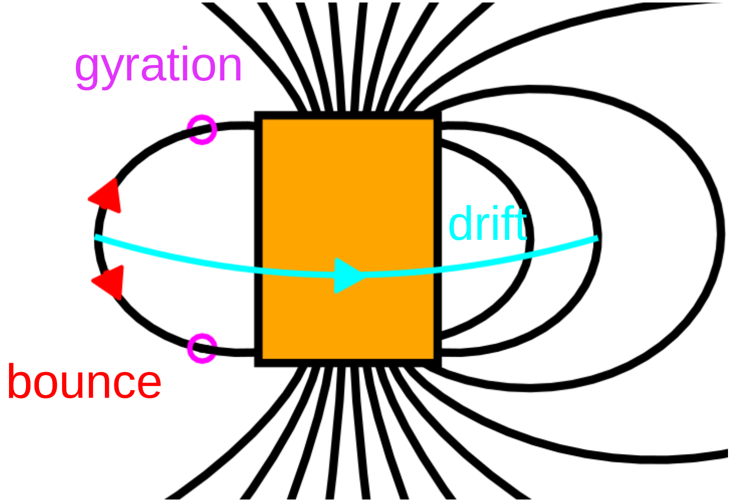


$\tau_C = 3\sigma = 24\text{ns}$

von der Linden et al. (2023) J. Plasma Phys.

Confinement through magnetic mirroring and electrostatic reflection in a permanent magnet trap

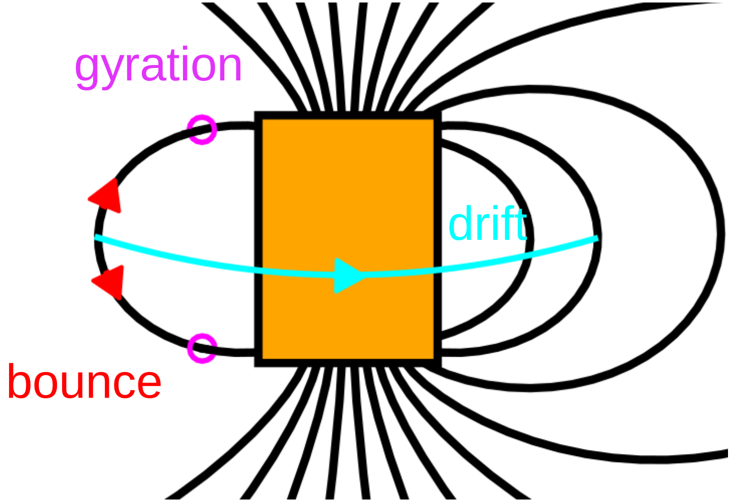
$$f_{\mathrm{gyration}} > f_{\mathrm{bounce}} > f_{\mathrm{drift}}$$



Confinement through magnetic mirroring and electrostatic reflection in a permanent magnet trap

$$f_{\text{gyration}} > f_{\text{bounce}} > f_{\text{drift}}$$

$$E = K_{\parallel} + \underbrace{e\phi + \mu B}_{U_{gc}} \qquad \mu = \frac{K_{\perp}}{B}$$



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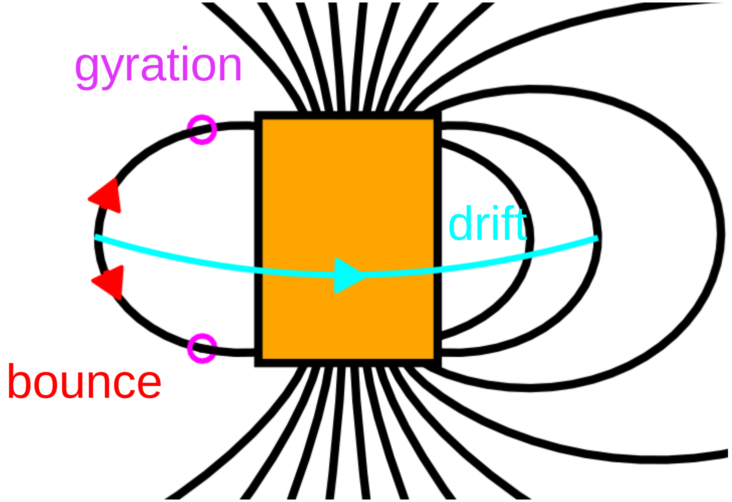

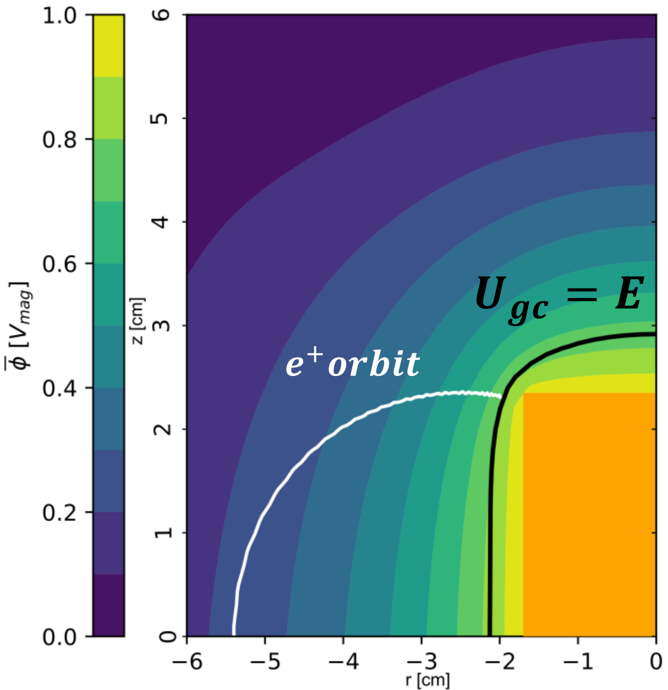

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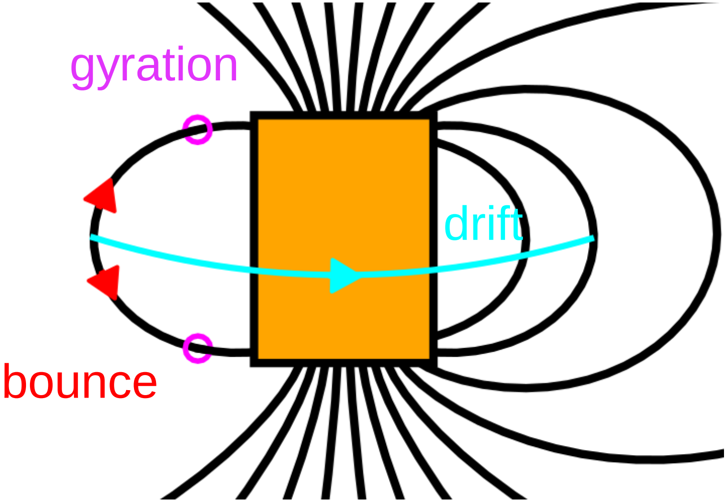
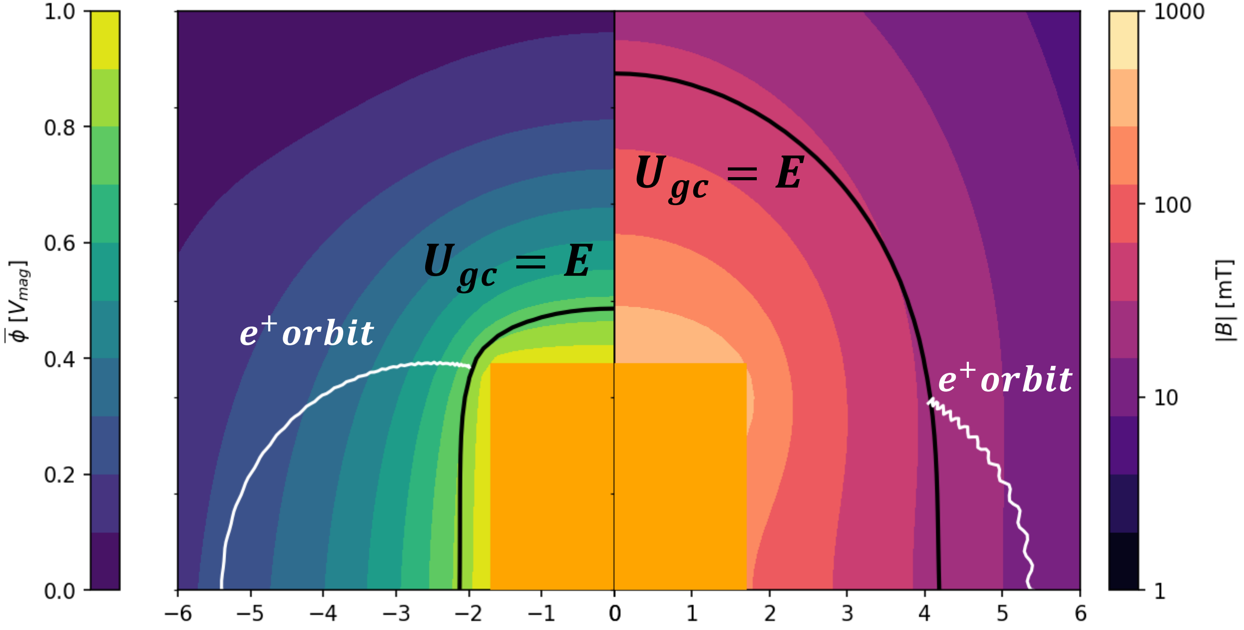
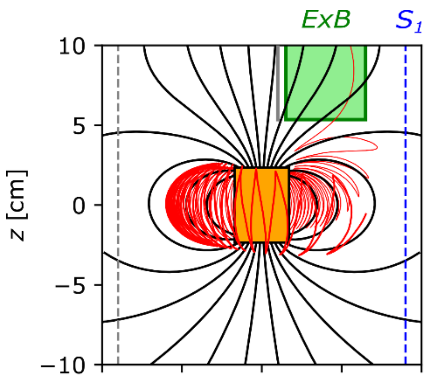




Diagnose efficient injection of 10^5 e^+ with lifetime spectroscopy



Beam steering

V_{ExB} = +/-217V

V_{mag} = 0 - 30V

V_{s1} = 20V

Stenson et al. (2018) Phys. Rev. Lett.
Nißl et al. (2020) Phys. Plasma

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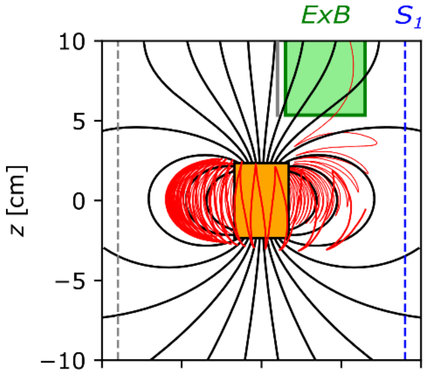

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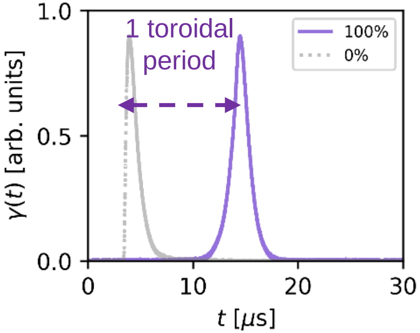

(Modified) SSPALS

Single-shot annihilation lifetime spectroscopy

Deller, von der Linden et al. (accepted) Phys. Rev. E

Cassidy et al. (2006) Appl. Phys. Lett.

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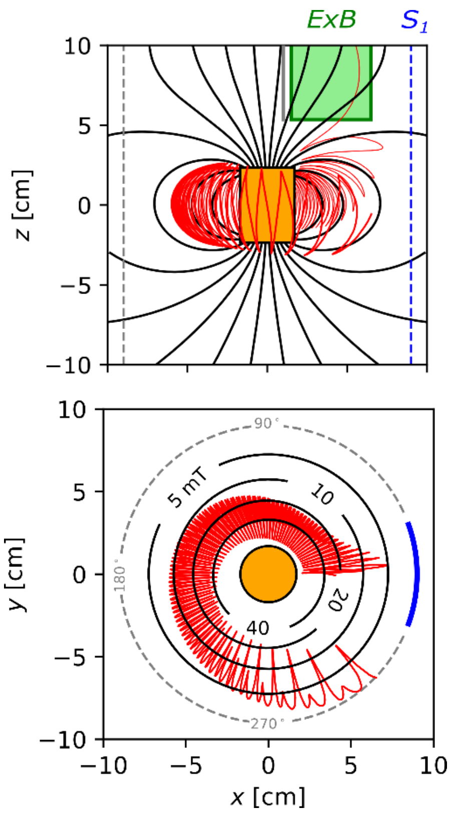


Beam steering

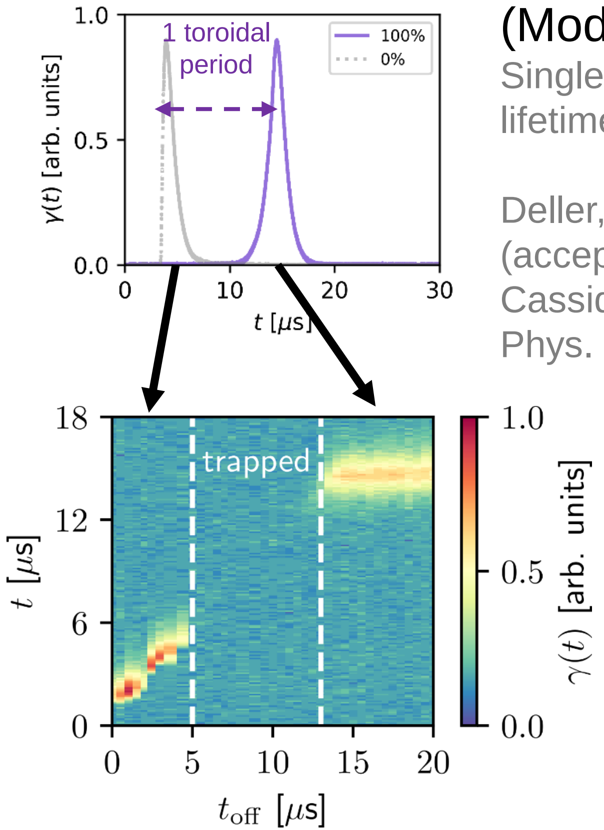
V_{ExB} = +/-217V

V_{mag} = 0 - 30V

V_{s1} = 20V

Switch
+20V to ground

Stenson et al. (2018) Phys. Rev. Lett.
Nißl et al. (2020) Phys. Plasma



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Three ways to eject

Electrostatic dump

$$U = e\phi + \mu B$$

+8V to 0V

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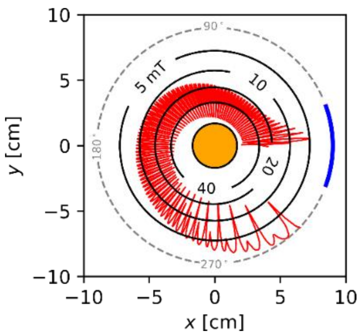
Electrostatic dump

$U = e\phi + \mu B$

+8V to 0V

Hard dump

0V to 20V



Three ways to eject

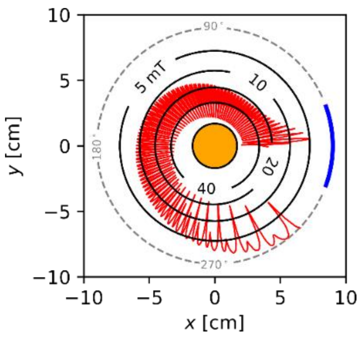
Electrostatic dump

$$U = e\phi + \mu B$$

+8V to 0V

Hard dump

0V to 20V



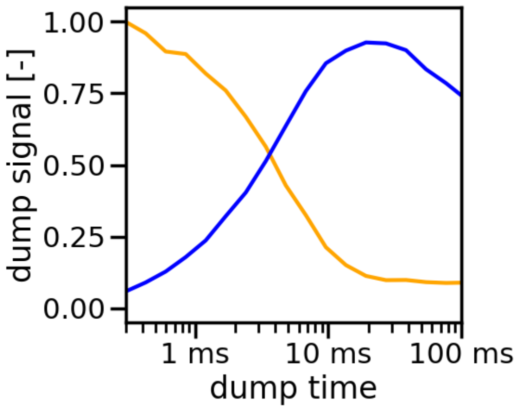
Wait ….

Transport to wall through elastic collisions with neutrals

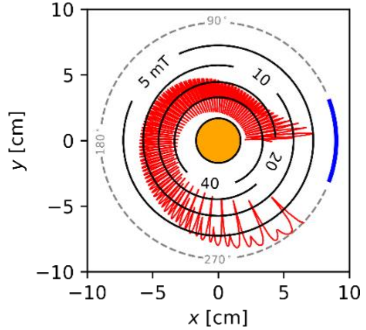
>100 collisions needed

Horn-Stanja et al. 2018 Phys. Rev. Lett.

Elastic collisions transition positrons from electrostatic to magnetic confinement



Electrostatic dump followed by **hard dump**



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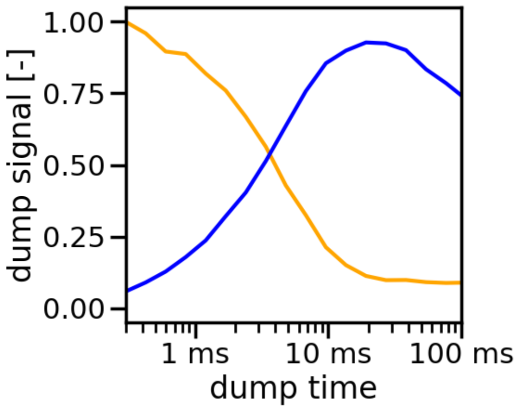
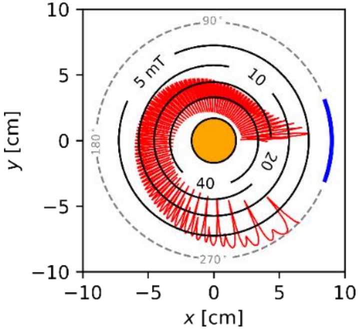
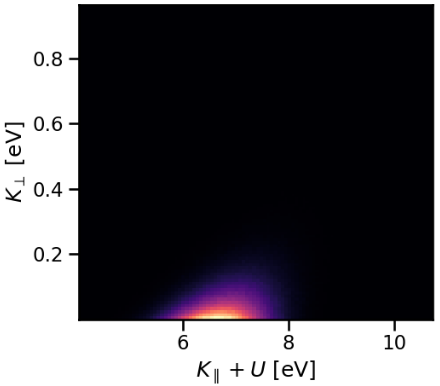
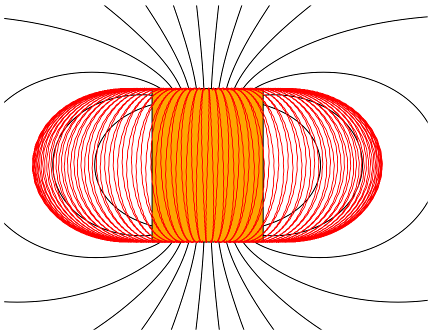


Electrostatic dump followed by hard dump



Intially all e+ are electrostaticlly confined





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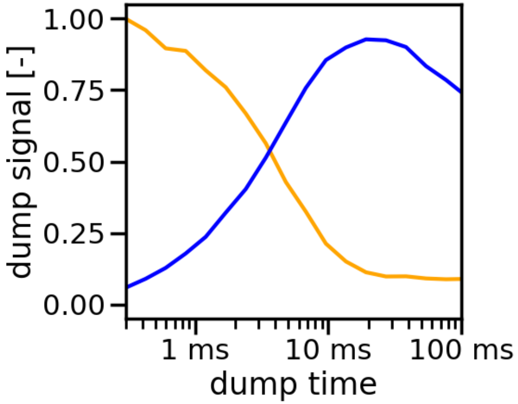
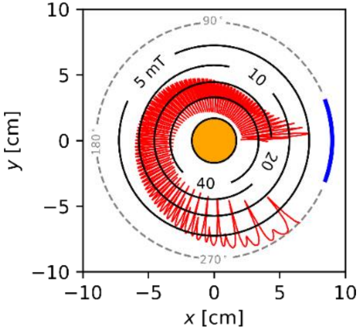
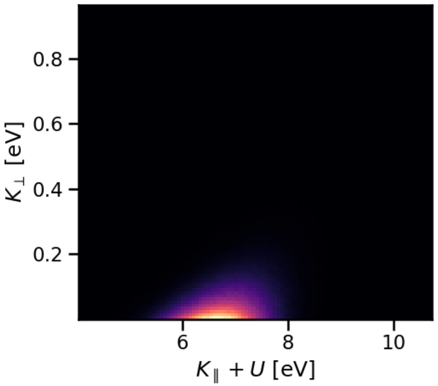
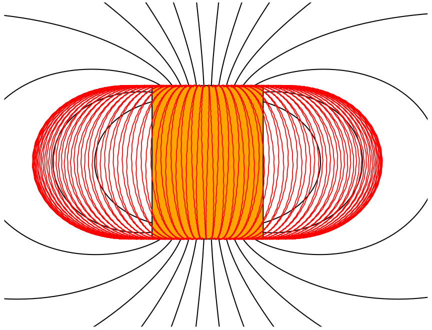


Electrostatic dump followed by **hard dump**

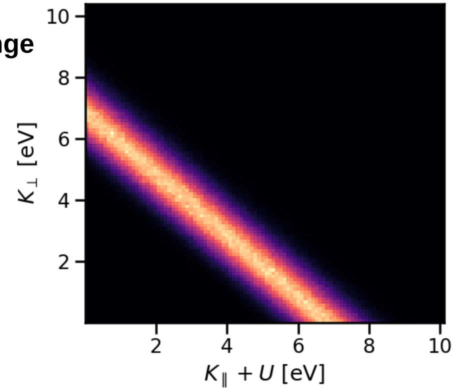


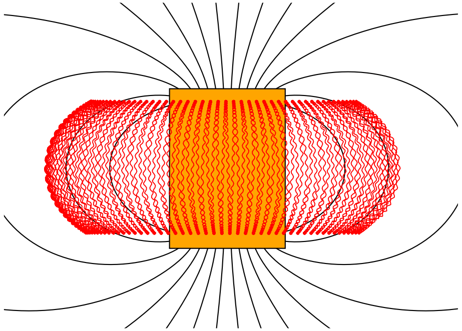
After one collision e+ are magnetically confined



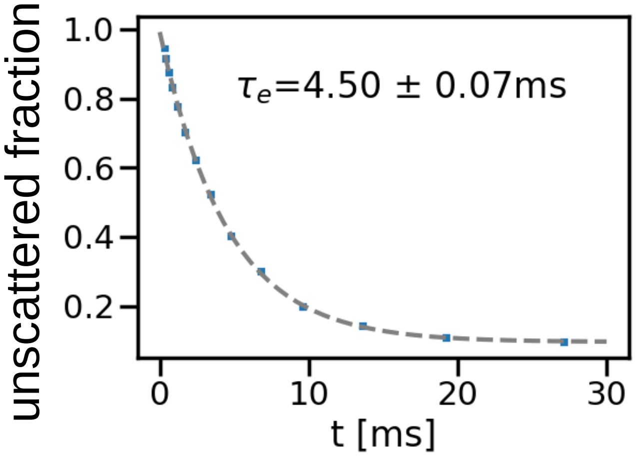


Note:
axis change

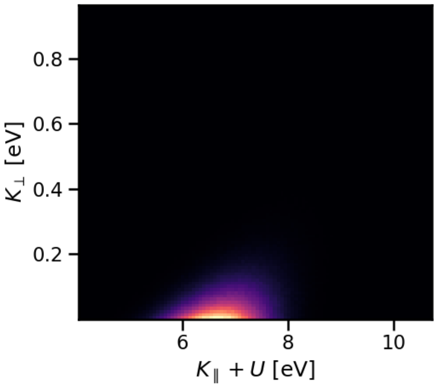


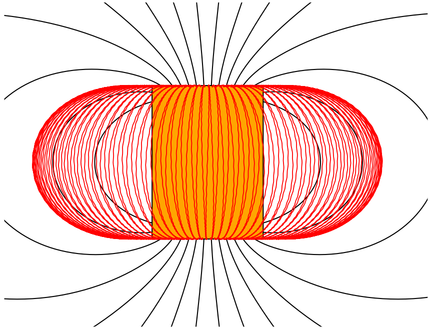


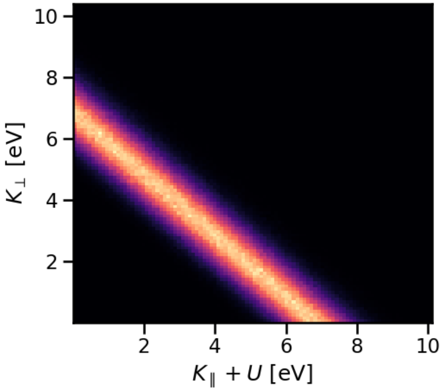
Transition time from electrostatic to magnetic confinement is 4ms

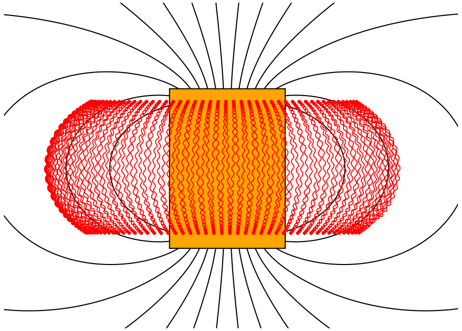


Ratio of dump curves gives elastic scattering time

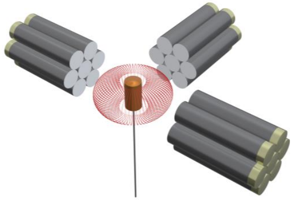


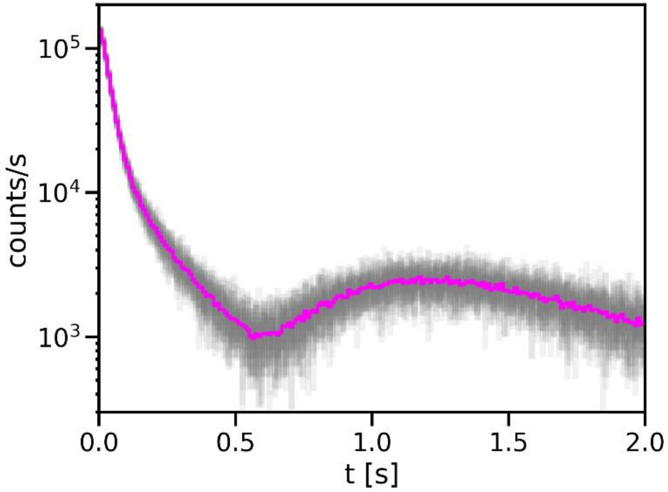






Single photon counting reveals complex lifetime spectra





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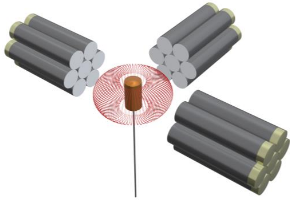
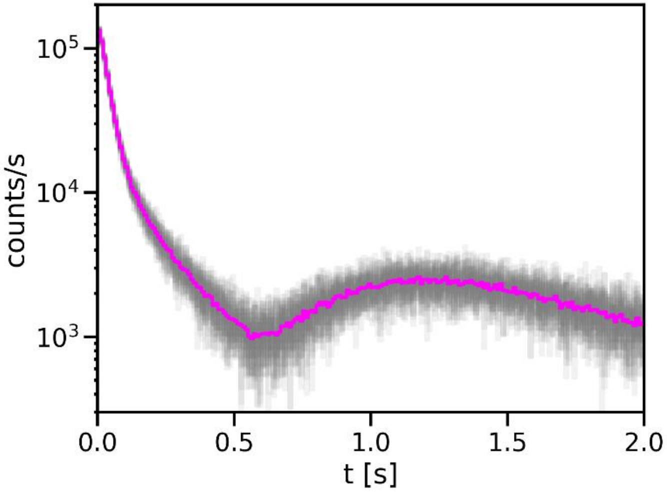
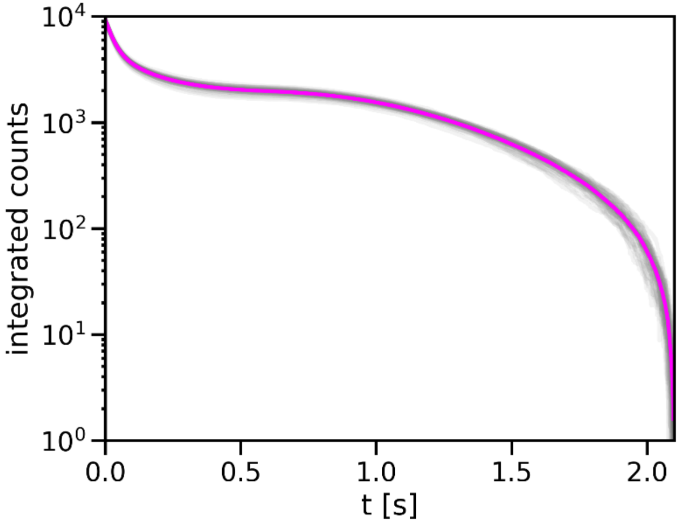




$\int dt$



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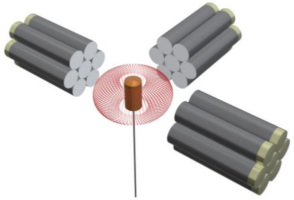
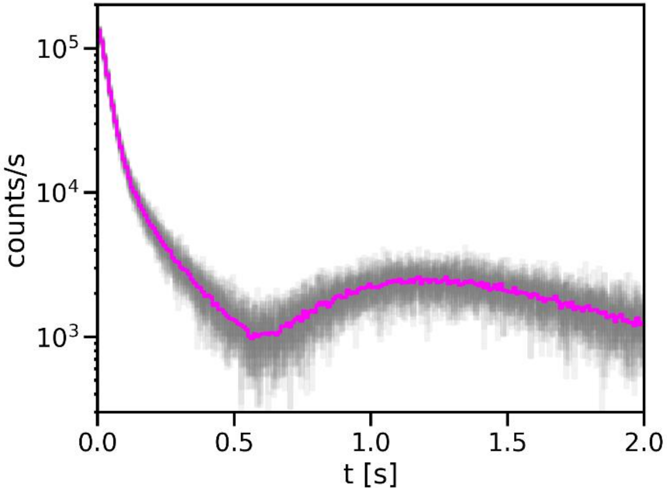
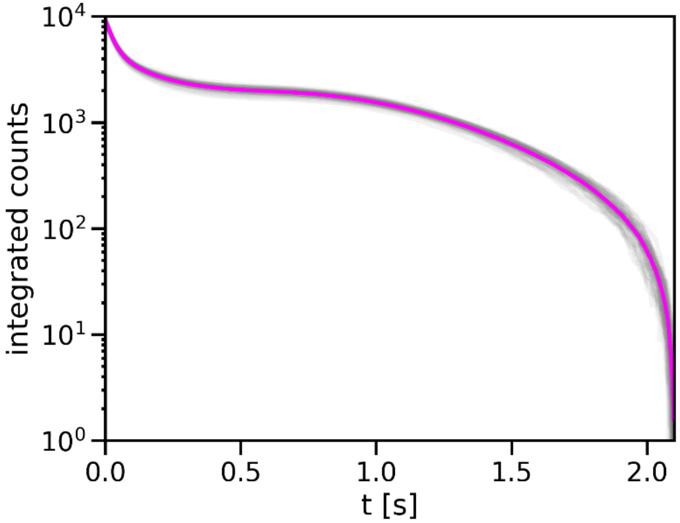
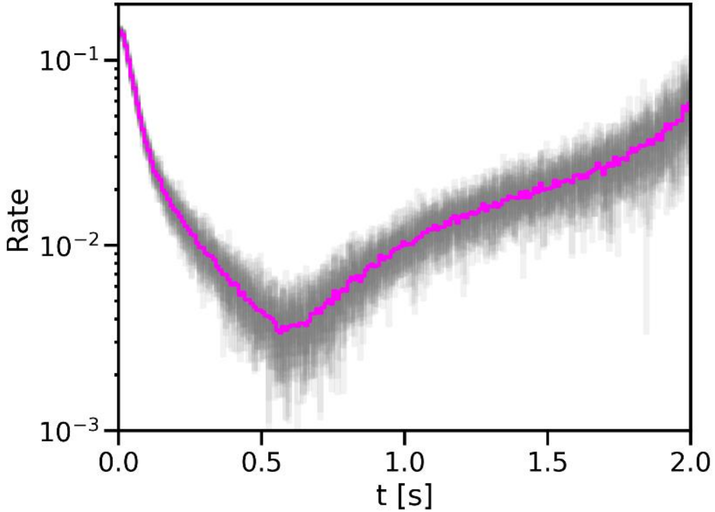




$$\int dt$$

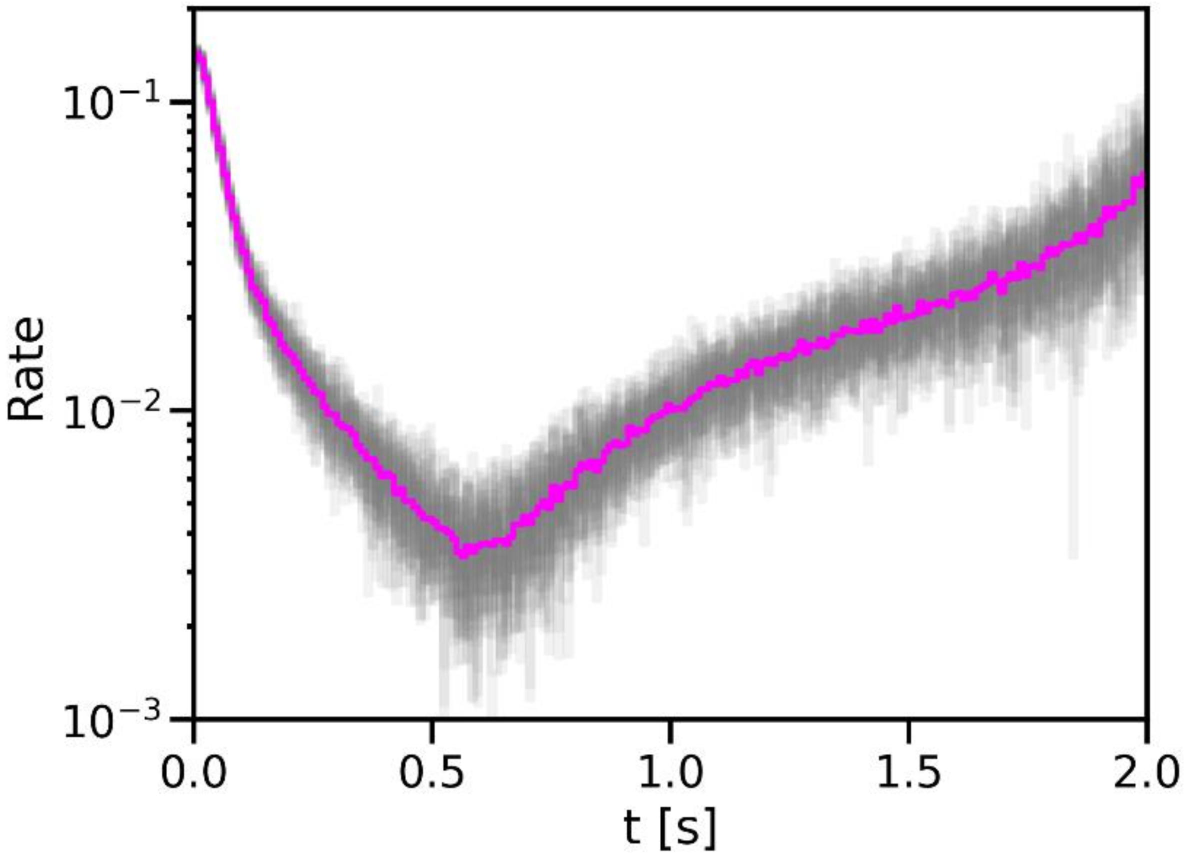


$$\frac{cps}{\int cps\, dt}$$

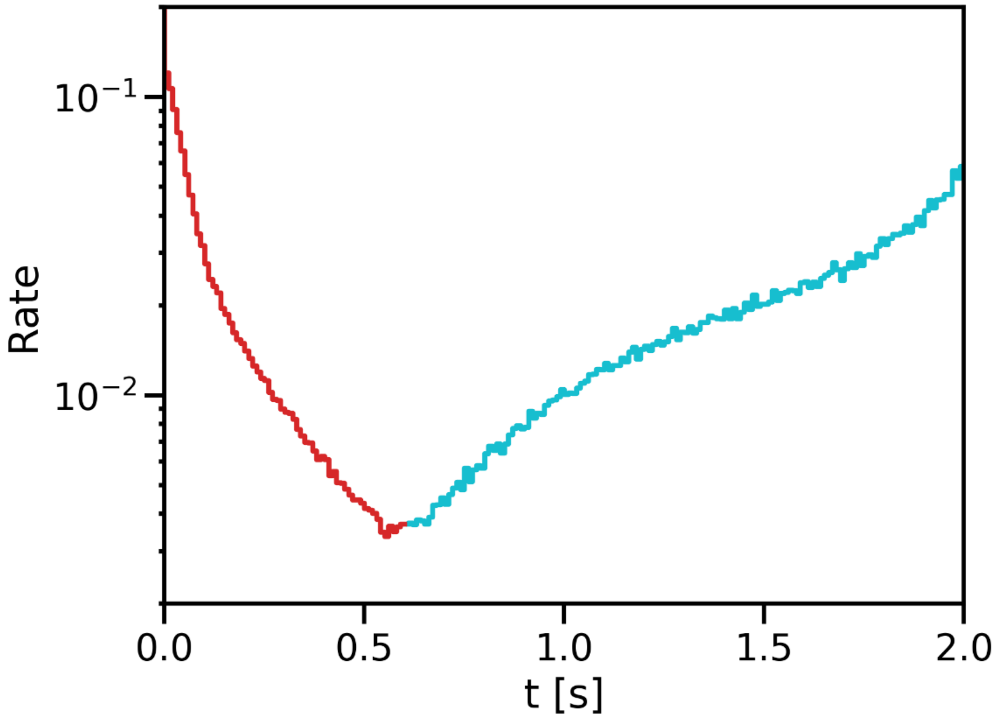


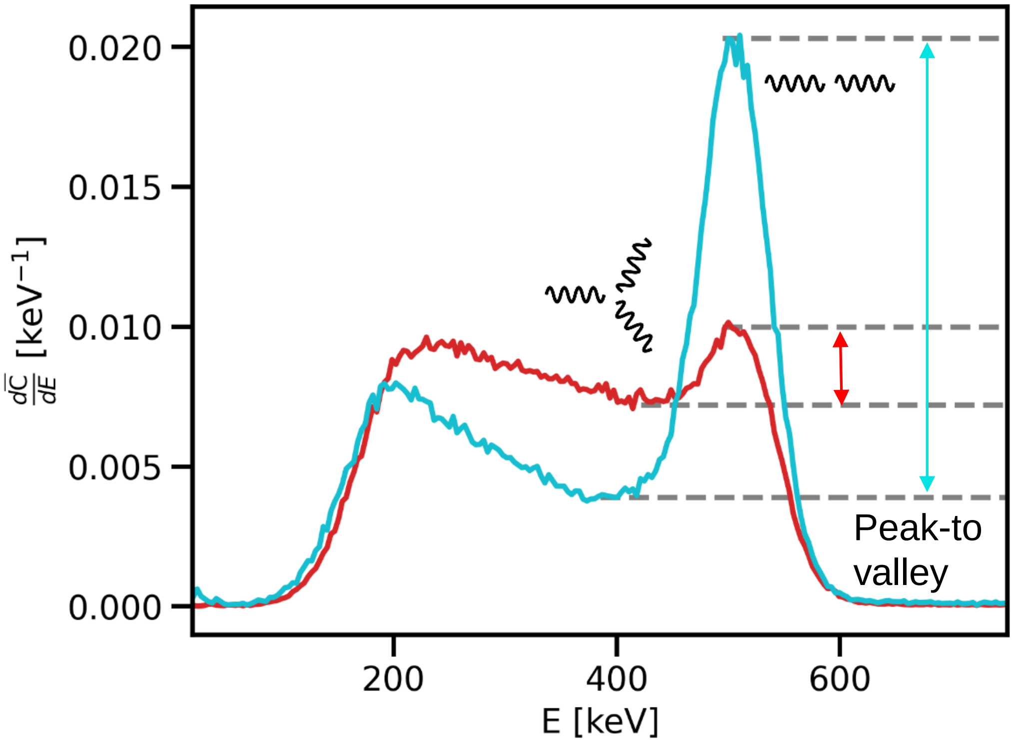
Possible loss channels

- transport to wall
  - elastic collisions with neutrals
  - plasma transport
- positronium formation
  - charge exchange
  - porous surfaces (oxides)
  - recombination
    - radiative
    - three-body
- direct annihilation
  - on neutrals
  - with free electrons



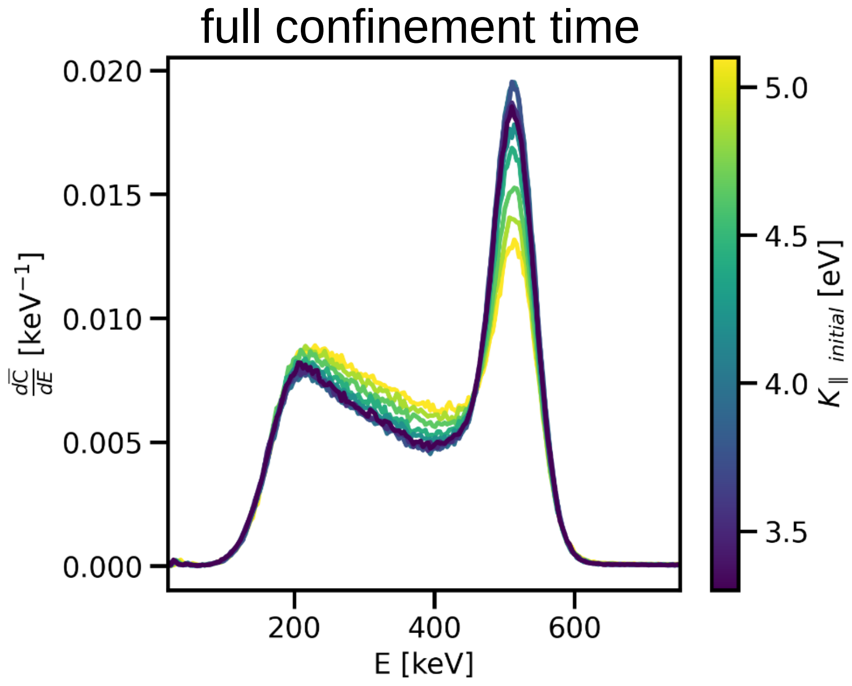
Energy spectra suggest positronium formation





Increase kinetic energy by decreasing magnet bias

$$E = K_{\parallel} + e\phi + \mu B$$



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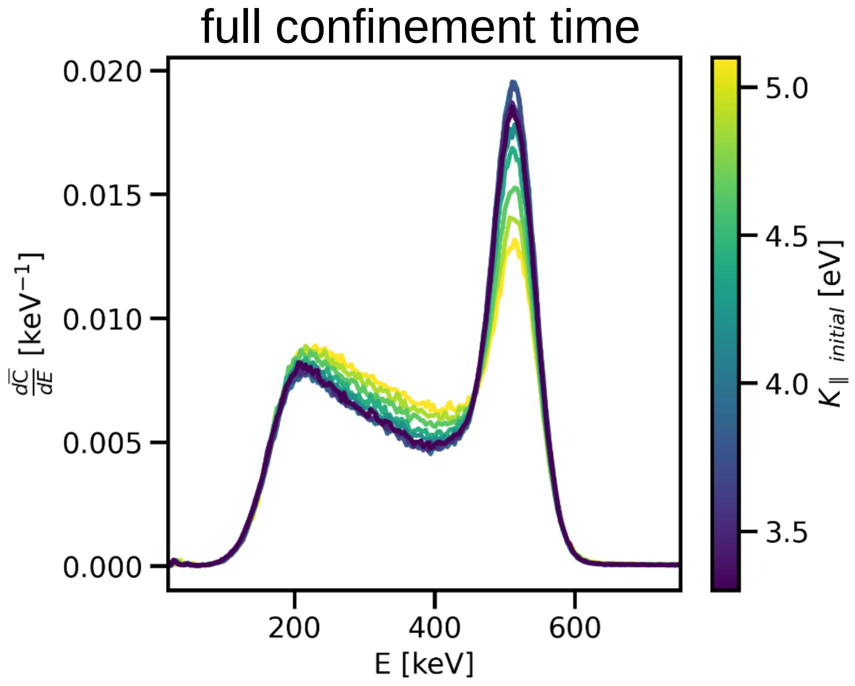
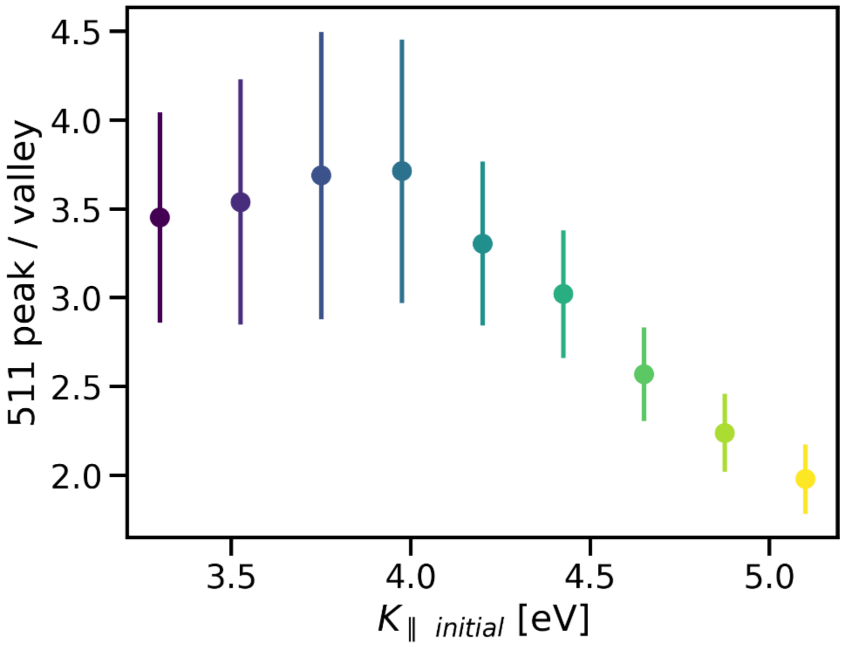
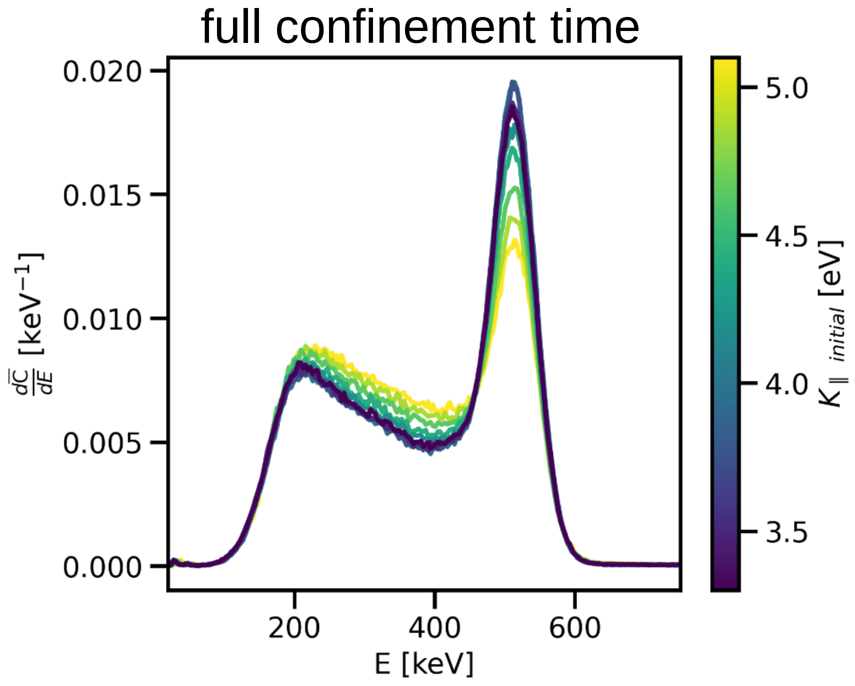
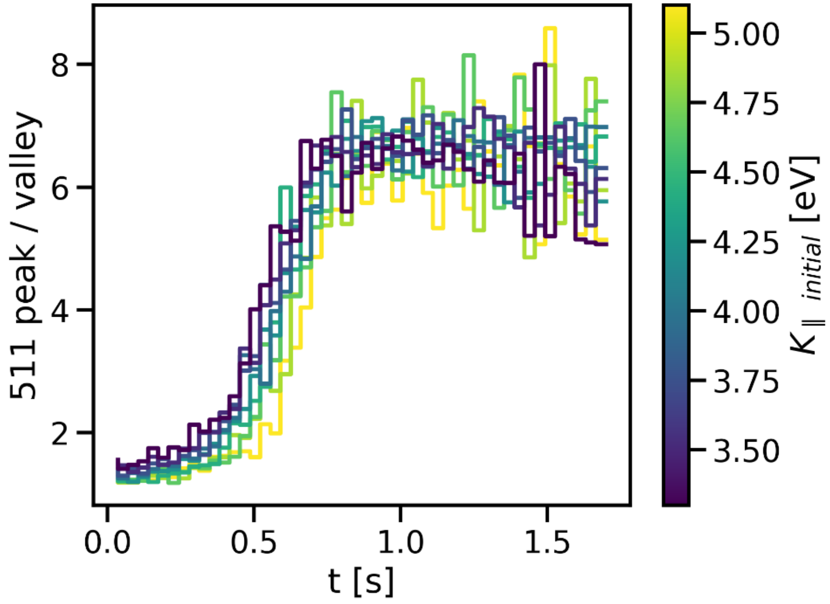




Increase kinetic energy by decreasing magnet bias

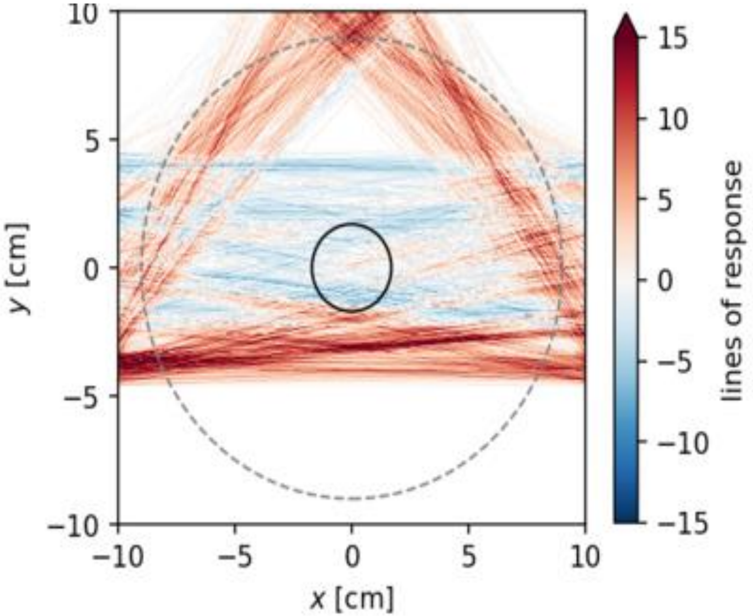
$$E = K_\parallel + e\phi + \mu B$$

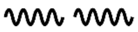




More evidence for Ps formation: vacuum LOR

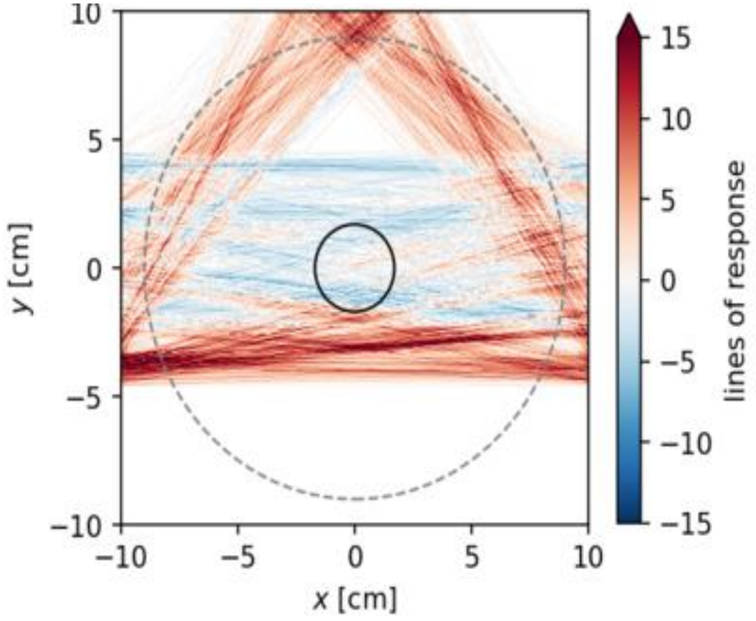
$$\mathrm{LOR}\left(K_{\parallel,initial} = 3.3eV\right) - \mathrm{LOR}\left(K_{\parallel,initial} = 5.2eV\right)$$

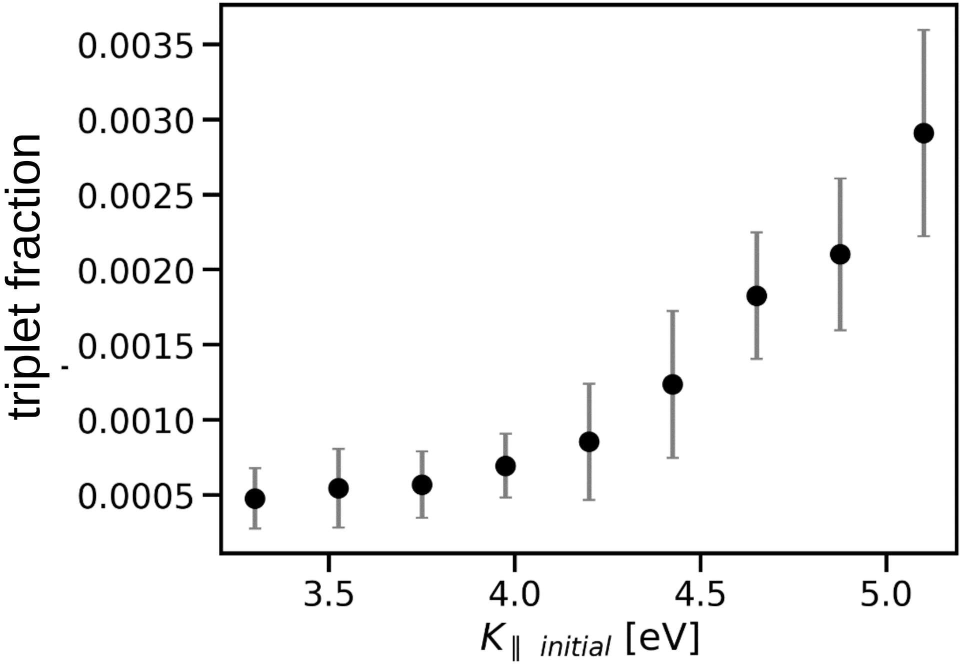


511keV & 

Strong evidence for Ps formation: triple coincidence

$$\mathrm{LOR}\left(K_{\parallel,initial} = 3.3eV\right) - \mathrm{LOR}\left(K_{\parallel,initial} = 5.2eV\right)$$

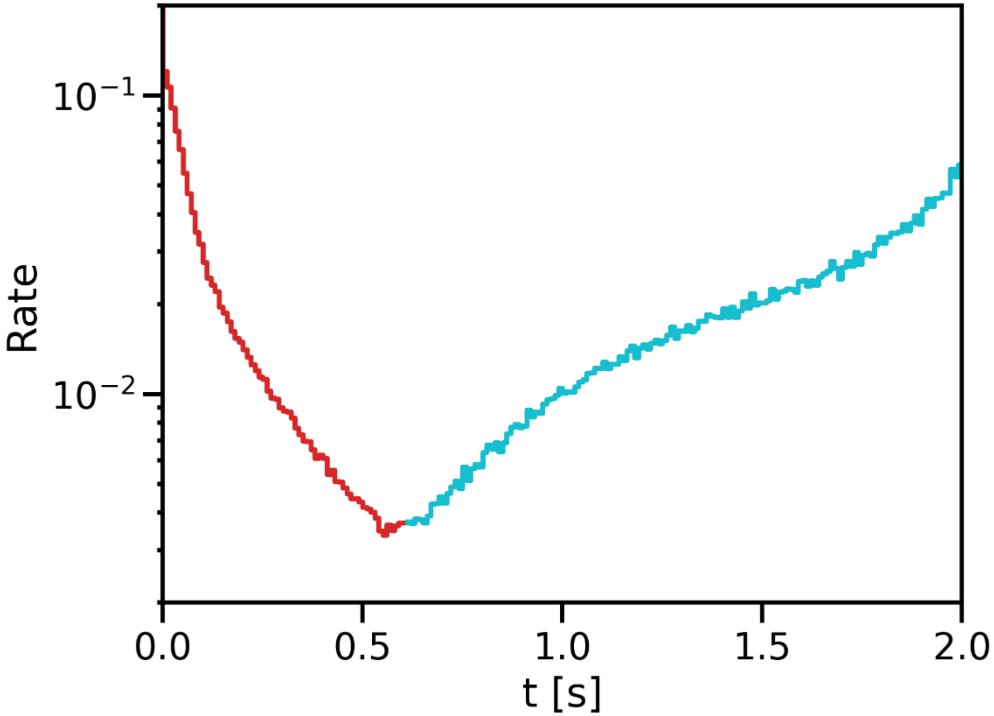




511keV &

Magnetically confined positrons forming Ps until e+ above threshold are depleted

Inital counts: dominated by Ps from charge-exchange



Later counts: dominated by transport through elastic collisions

Outline

Magnetically confined pair plasma

What is it and why make it?

APEX approach

Diagnosing positron bunch confinement experiments

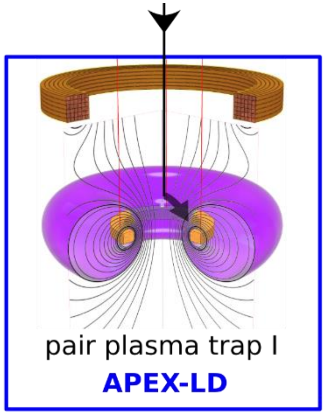
21-detector array (BGO)

Positronium formation & transport to wall

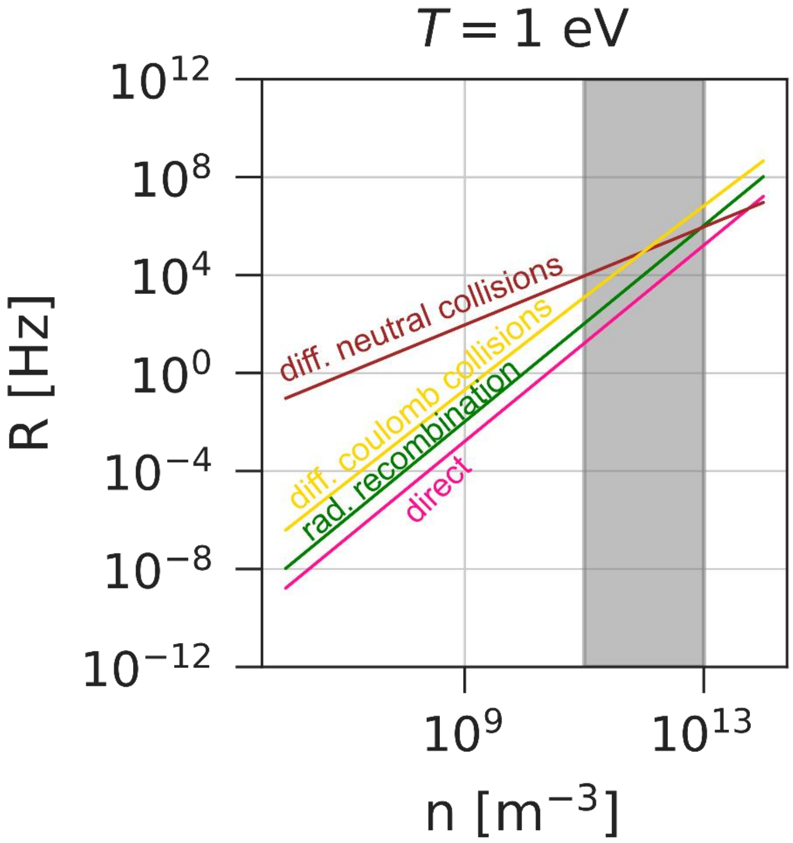
Outlook: Annihilation of a magnetically confined pair plasma

Competing processes

Spatial separation enables distance-attenuated counting and tomography



Outlook: pair plasma will have competing annihilation mechanisms



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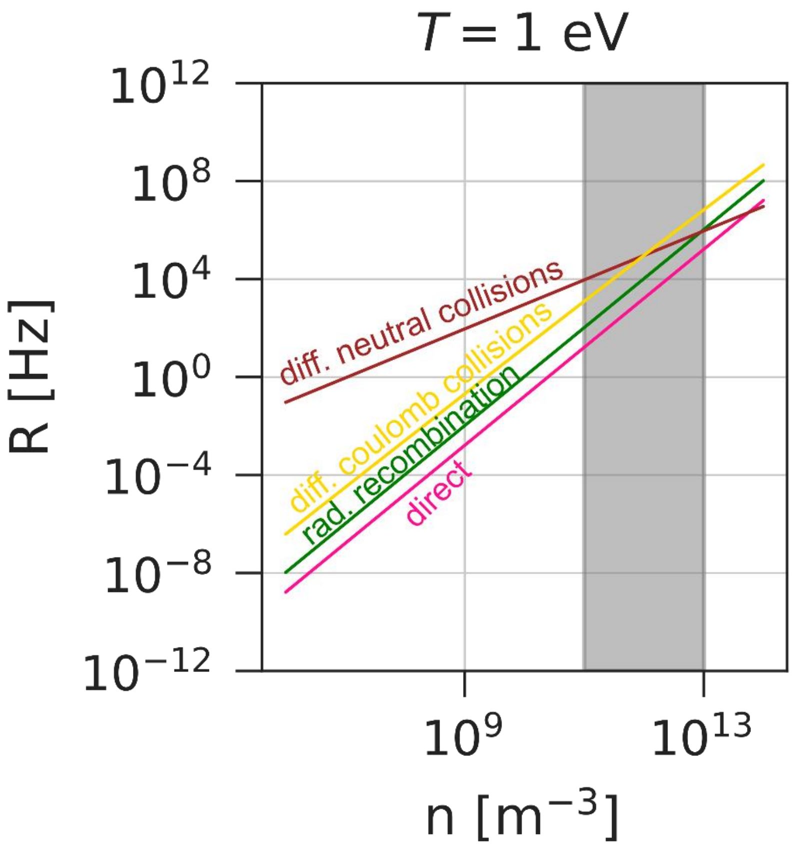
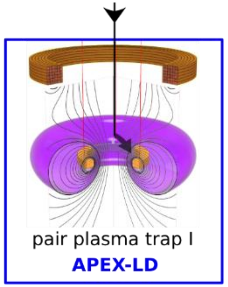
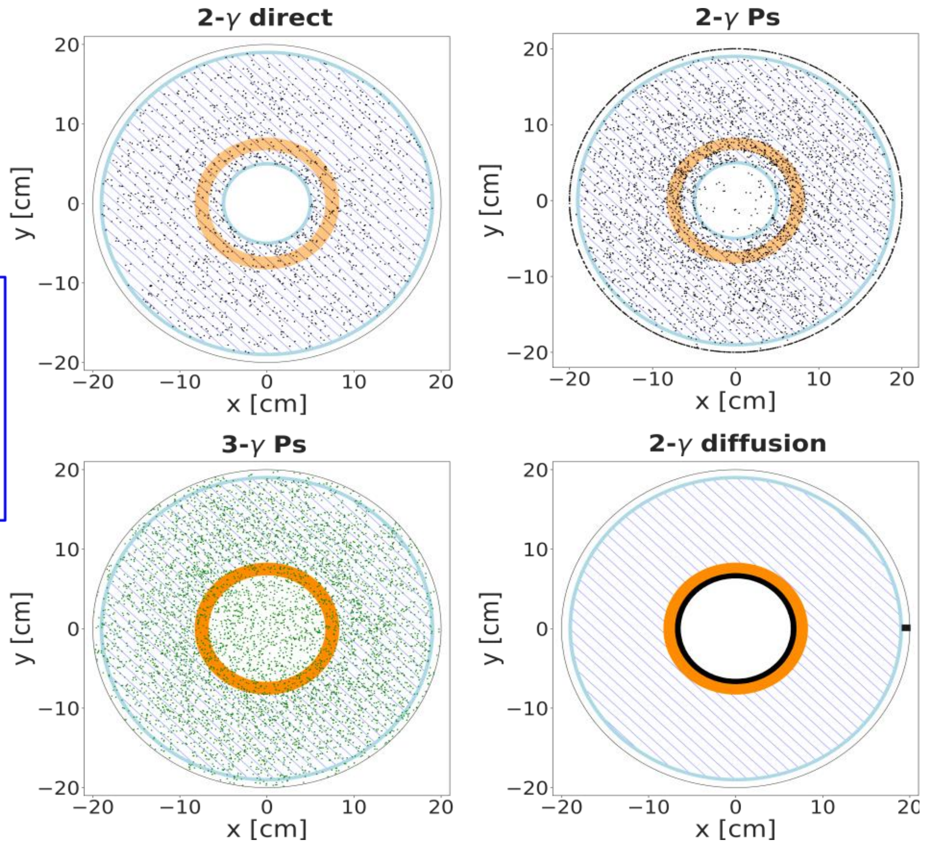
Outlook: pair plasma will have competing spatially separated annihilation mechanisms







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Simulate volumetric 2-γ emission with a turntable

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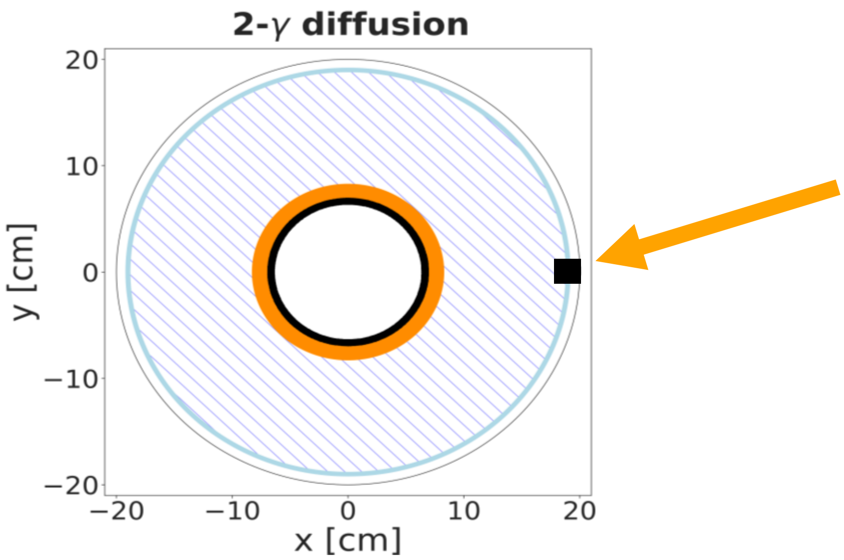
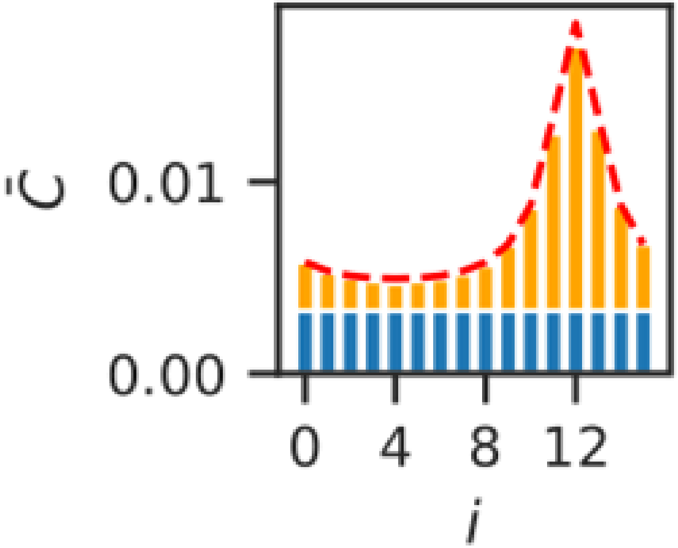
Outlook: Distance-attenuated counting to separate transport





detector

$$\overline{C} \propto \frac{1}{d^2}$$

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Outlook: Tomography of volumetric 2-γ annihilation

$$Counts = A \cdot Source$$

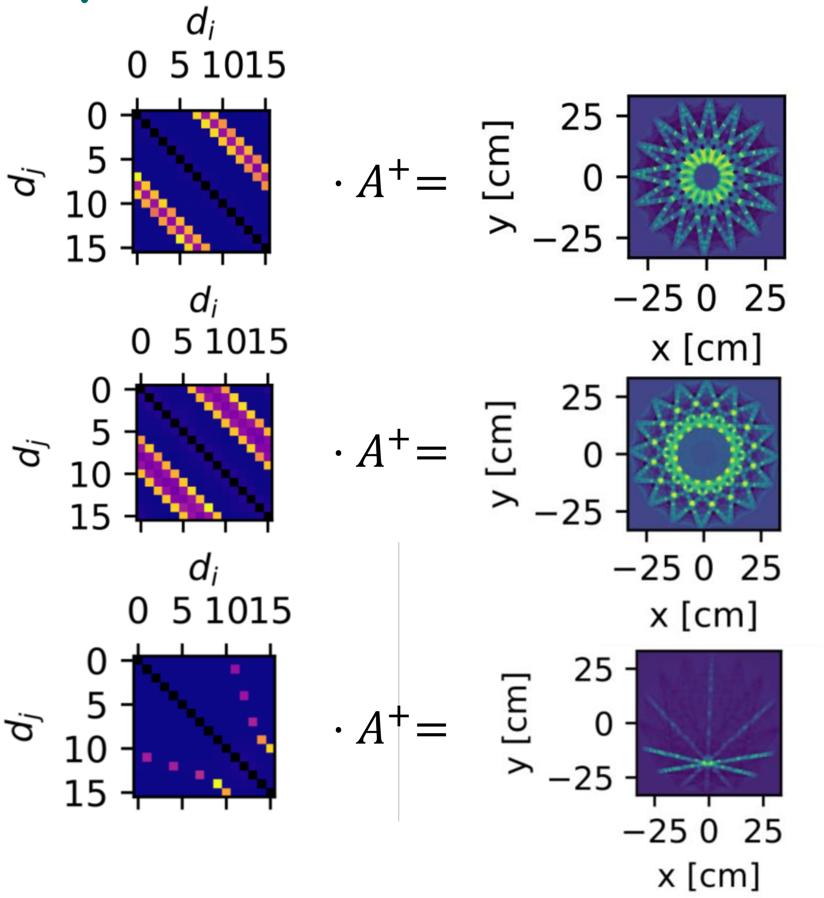
System response

1. Construct with Monte-Carlo
2. Invert SVD

ring source
at 7 cm

ring source
at 15 cm

point source



von der Linden et al. (2023) J. Plasma Phys.

Outlook: Tomography of volumetric 2-γ annihilation

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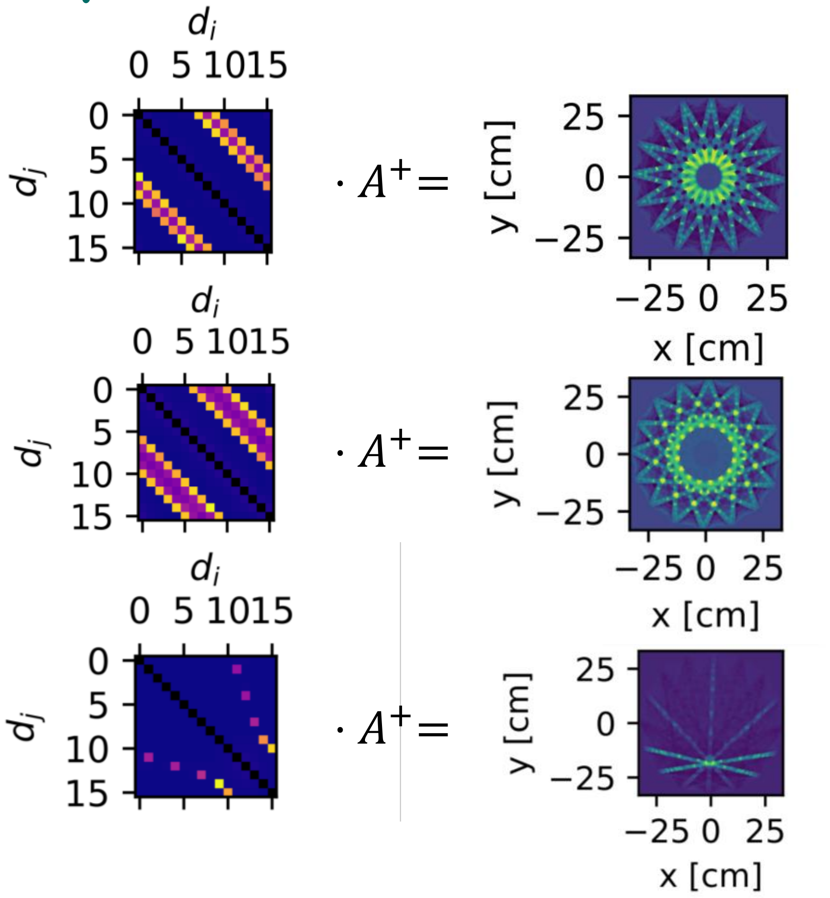


For pair plasma experiments we will use 48 BGO detectors.

von der Linden et al. (2023) J. Plasma Phys.

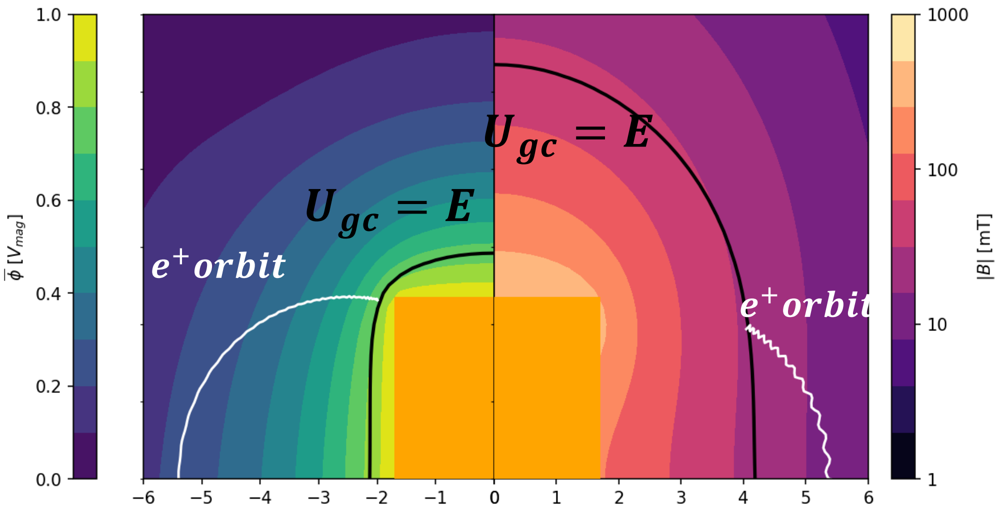
Conclusion

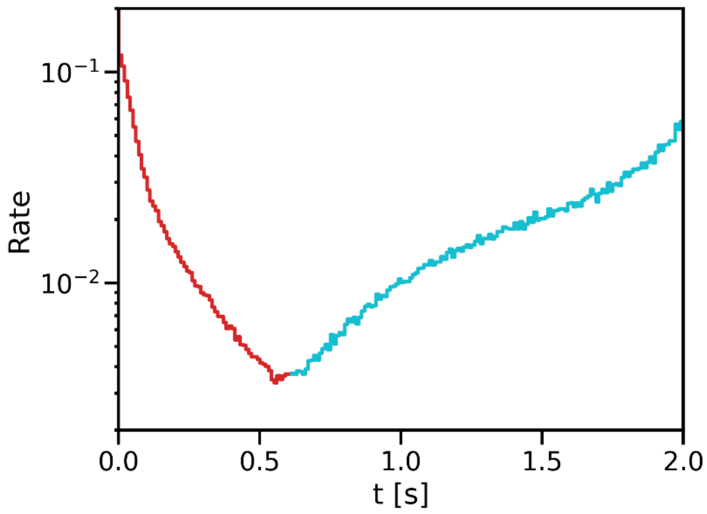
APEX: create and study magnetically confined pair plasma

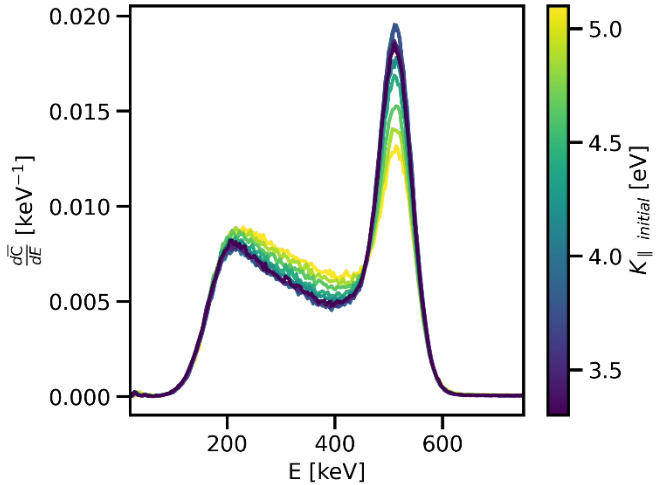
Annihilation-gamma-diagnosis of positron confinement
21-detector array: SSPALS, single counts, energy spectra, coincidence
Losses dominated by charge-exchange and diffusion to wall

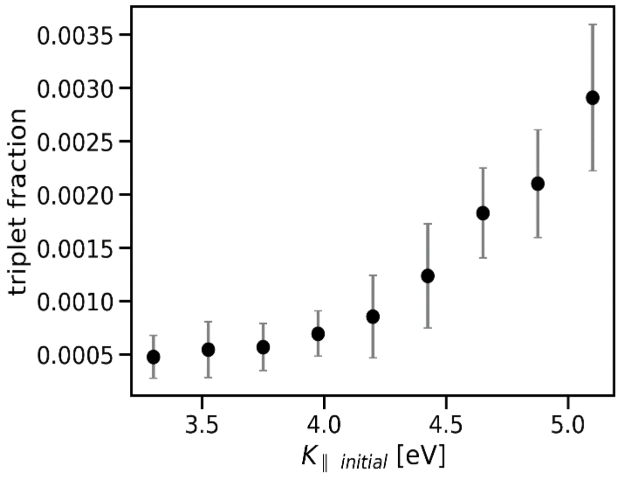
Outlook: Annihilation of a magnetically confined pair plasma
Competing processes
Spatial separation enables distance-attenuated counting and tomography

Thank you


$U_{gc} = E$
$U_{gc} = E$
$e^+ orbit$
$e^+ orbit$
$\bar{\phi}$ [V_{mag}]
|B| [mT]
1.0
0.8
0.6
0.4
0.2
0.0
1000
100
10
1
−6
−5
−4
−3
−2
−1
0
1
2
3
4
5
6


Rate
10^{-1}
10^{-2}
0.0
0.5
1.0
1.5
2.0
t [s]


$\frac{d\bar{C}}{dE}$ [keV^{-1}]
0.020
0.015
0.010
0.005
0.000
200
400
600
E [keV]
$K_{\parallel\ initial}$ [eV]
5.0
4.5
4.0
3.5


triplet fraction
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
3.5
4.0
4.5
5.0
$K_{\parallel\ initial}$ [eV]