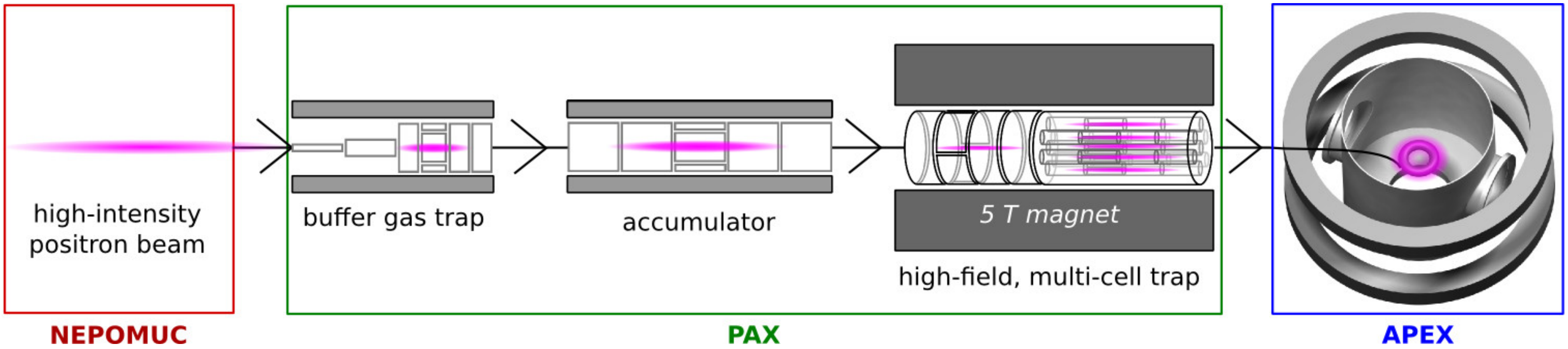
Plans for creation and studies of positron-electron plasmas in a laboratory magnetosphere



Thomas Sunn Pedersen, for the APEX/PAX collaboration (next slide)

Max Planck Institute for Plasma Physics,

Greifswald and Garching, Germany

The PairPlasma Team:
A Positron-Electron plasma eXperiment (APEX)
Positron Accumulation eXperiment (PAX)

APEX – PAX team
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Overview

- Electron-positron (pair) plasmas and their importance around astrophysical objects
- Some unique basic properties of pair plasmas
- First pair plasma in the laboratory – Sarri group
  - Short-lived, unconfined, dense, hot pair plasma beam
- Debye length and skin depth – two important scale lengths in a plasma
- Our attempt to create small-Debye length, confined pair plasmas
  - The “grand” plan
  - How far we are
- Summary

Astrophysical relevance

- Pair plasmas are created around compact, high-energy density astrophysical objects
- Continuous sources include:
  - Accreting black holes
  - Magnetars
- Pulsed or explosive sources include:
  - Magnetar flares
  - Cosmological gamma-ray bursts (GRB)
- Copious pair creation can be thought of as a “breakdown of the vacuum”
  - Gamma-gamma (photon-photon) collisions
  - Gammas+ seed electrons+ strong magnetic fields: “pair cascade”
- Conversion of matter- and charge-free space to highly conducting, matter-filled space – a pair plasma

Inspired by and partly taken from talk by A. Beloborodov, Columbia University, JPP workshop, Spineto, Italy (2017) (with permission)

Take-home points

- Energy release in compact sources is accompanied by copious pair creation
- Pair plasma regulates the dissipation mechanism and dynamics
- Pairs dominate the plasma and shape its observed emission (synchrotron, inverse Compton)
- A few more details on the next slide

Inspired by and partly taken from talk by A. Beloborodov, Columbia University, JPP workshop, Spineto, Italy (2017) (with permission)

Pair plasma relevance for gamma-ray bursts

- Shock formation of an exploding ball evolves differently when pair plasma is included self-consistently in simulations – shock front becomes optically thick, confining the photons
- Shock front steepens and narrows
- Synchrotron radiation is generated by the electrons and positrons
- Also outside the exploding ball, the release of gammas from the GRB is affected by pair creation, and may explain features in the observed spectra [a]:

- The peak of the flash is emitted by **copious pairs created and heated in the blast wave**; our first-principle calculation determines the pair-loading factor and temperature of the shocked plasma. Using detailed radiative transfer simulations we reconstruct the observed double flash. **The optical flash is dominated by synchrotron emission from the thermal plasma** behind the forward shock, **and the GeV flash is produced via inverse Compton (IC) scattering by the same plasma.**

[a] Vurm, Hascoet, Beloborodov (2014) arXiv:1402.2595v2 [astro-ph.HE]

Inspired by and partly taken from talk by A. Beloborodov, Columbia University, JPP workshop, Spineto, Italy (2017) (with permission)

A new frontier in basic plasma physics

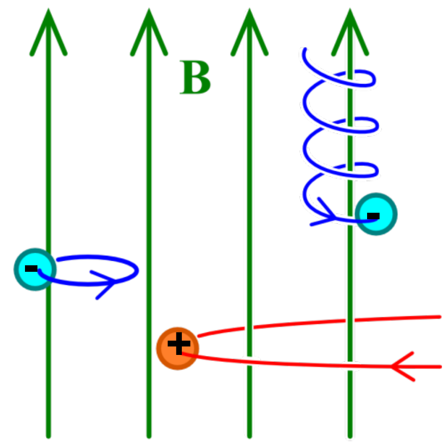
We aim to produce the first magnetically confined electron-positron plasmas on Earth

In comparison to "normal" plasmas, dramatic changes to plasma properties are predicted:

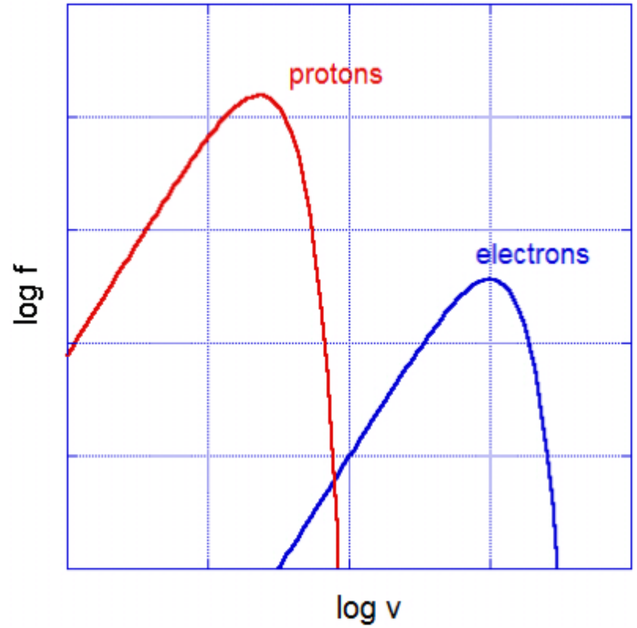
- floating potential=plasma potential (electron-ion plasma: material objects charge up negative)
- Much simplified wave dispersions, e.g. no Faraday rotation
- ion acoustic and drift waves eliminated
- "remarkable stability properties"

Laboratory astrophysics as mentioned, plus:

Experimental proxy for the very early Universe.

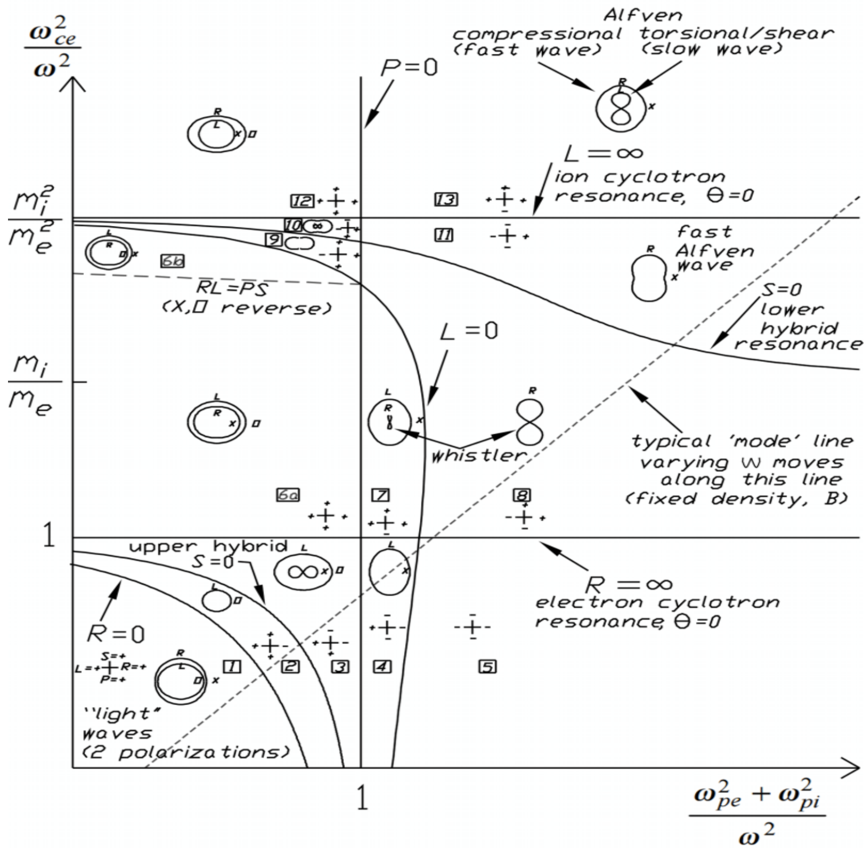


"Normal plasmas": mass ratio ~2000 or more

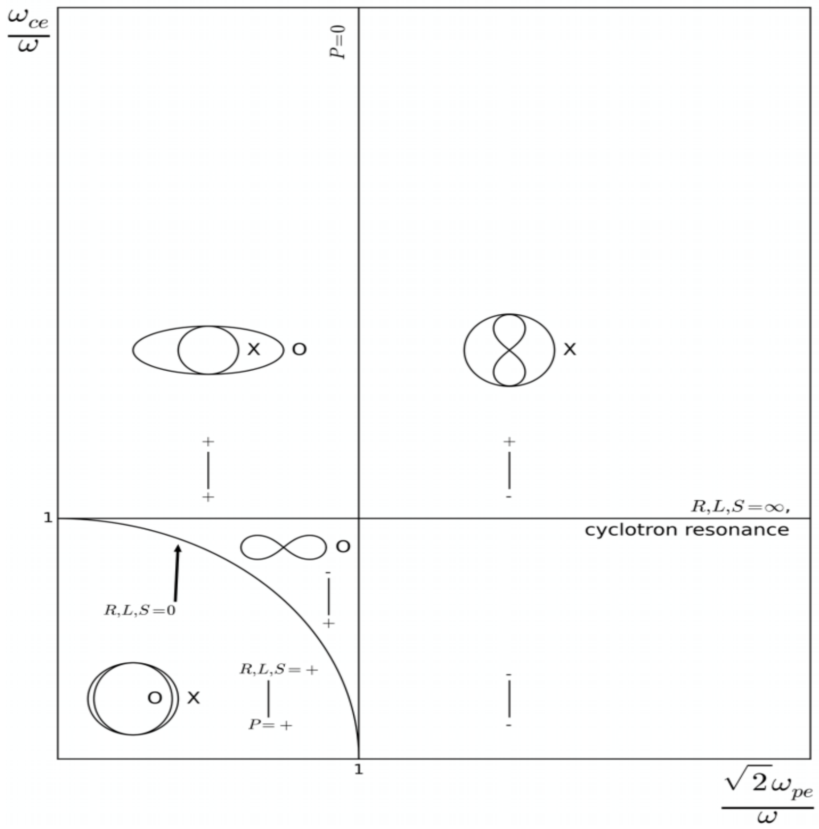


A relatively simple, tractable plasma: Cold plasma

Wave dispersion relations - cold plasma (T=0) approximation



From Paul Bellan
"Fundamentals of Plasma Physics",
Cambridge U. Press (2008)



From E. V. Stenson et al,
Journal of Plasma Physics, 2017

A relatively simple, tractable plasma: Example

Detailed example: L, R, and X waves coalesce in pair plasma

- L-wave propagates along B and is circularly polarized in the ion gyration sense
- R-wave propagates along B and is circularly polarized in the electron gyration sense
  - Because of the mass difference, they have different cutoffs and resonances and generally do not propagate at the same phase velocity
  - This leads to Faraday rotation
- X-wave propagates perpendicular to B and is elliptically polarized
- All three get the exact same dispersion relation in an electron-positron plasma!

$$n^2 = L \qquad n^2 = L$$

$$n^2 = R \qquad n^2 = R = L$$

$$n^2 = \frac{2RL}{R+L} = \frac{2LL}{L+L} = L$$

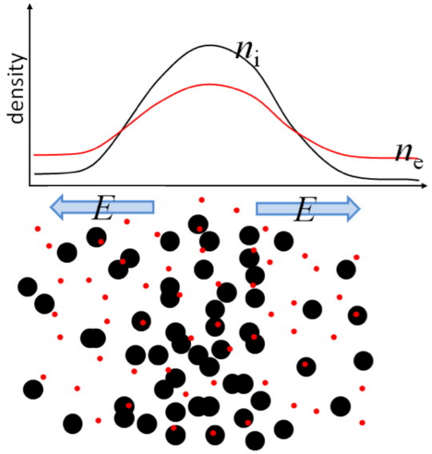
$$R = 1 - \frac{\omega_p^2}{\omega(\omega-\omega_c)} - \frac{\Omega_p^2}{\omega(\omega+\Omega_c)} = 1 - \frac{\omega_p^2}{\omega(\omega-\omega_c)} - \frac{\omega_p^2}{\omega(\omega+\omega_c)}$$

$$L = 1 - \frac{\omega_p^2}{\omega(\omega+\omega_c)} - \frac{\Omega_p^2}{\omega(\omega-\Omega_c)} = 1 - \frac{\omega_p^2}{\omega(\omega+\omega_c)} - \frac{\omega_p^2}{\omega(\omega-\omega_c)}$$

A relatively simple, tractable plasma: Warm waves

Drift waves in magnetized plasmas (T>0)

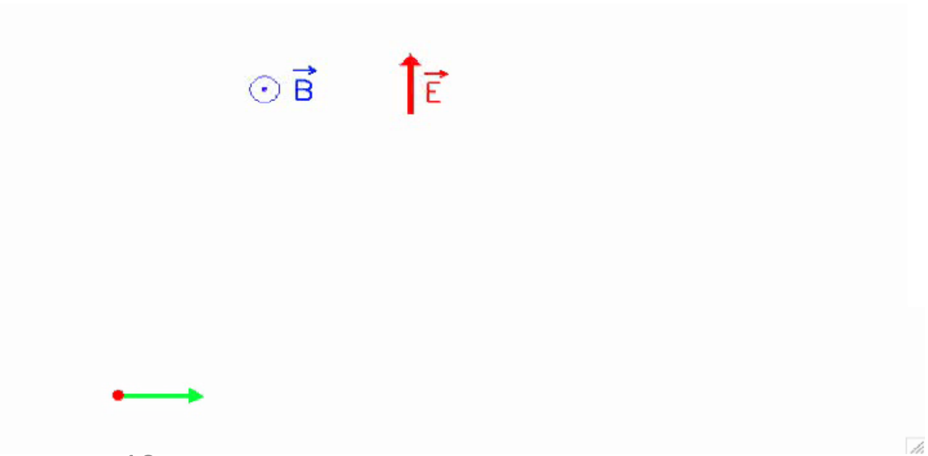
In an electron-ion plasma, a density perturbation leads to an electrostatic potential due to a mild charge separation.
This electrostatic potential leads to ExB drift of both species
This can lead to an amplification of the density perturbation if the density gradient across B is large enough – a drift wave is born
The ϕ-n coupling is absent in a $T_{e-}=T_{e+}$ electron-positron plasma….both species expand at the same rate, collisions are generally negligible – just free streaming



electron-ion plasma

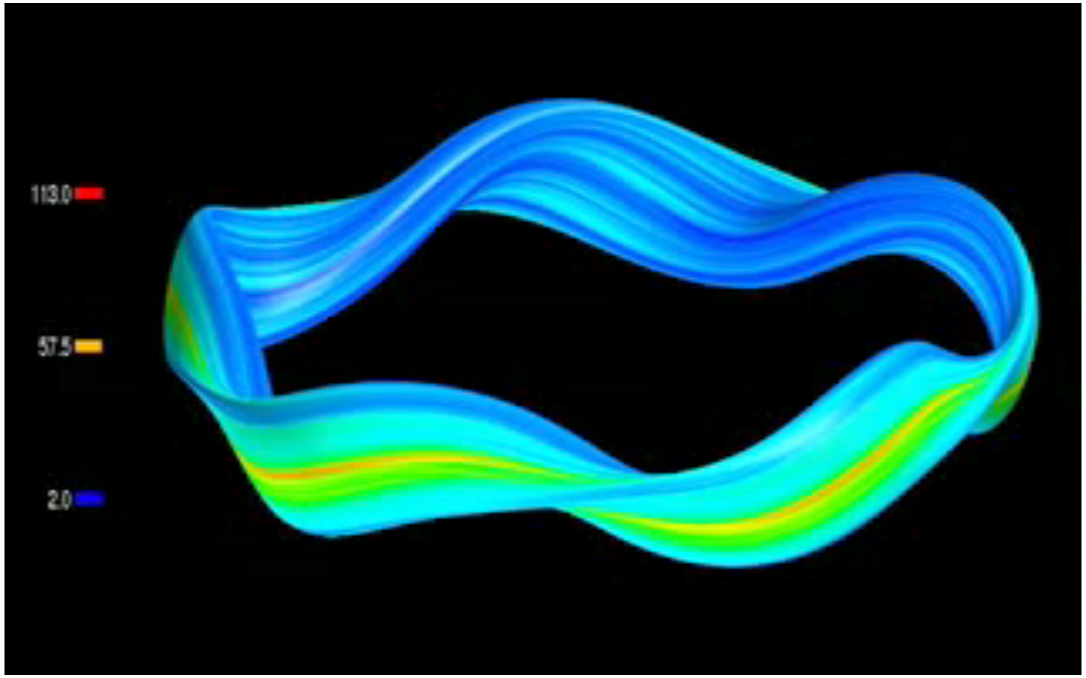
$$\vec{v}_E = \frac{\vec{E}\times\vec{B}}{B^2} = -\frac{\nabla\phi\times\vec{B}}{B^2}$$

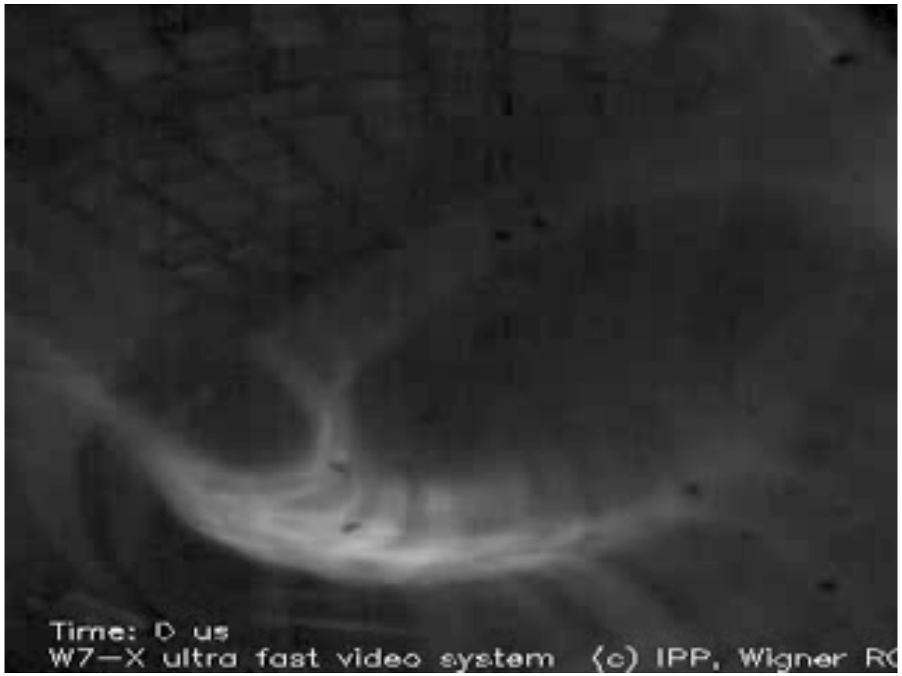
Electron



Drift wave instabilities are "everywhere"

- Drift waves are generally unstable in inhomogeneous plasmas
  - Typically many wavelengths are unstable and together build a nonlinear turbulent state
  - Elongated (along B) density and potential perturbations drift across B
- The turbulence causes faster rates of perpendicular transport of:
  - Particles
  - Momentum
  - Heat





Gyrokinetic analysis (Helander, PRL 2015)

- Pair plasmas are very different from electron-ion plasmas!
  - Absence of drift waves confirmed also by this analysis
- Linear gyrokinetic stability analysis predicts:
  - no instabilities without magnetic curvature (!)
  - interchanges possible, but only if the wavelength is very large
  - Can have complete microstability in the expected regime for the experiments my group is preparing
- In a dipole magnetic field, quasilinear theory predicts:
  - inward particle flux (!) due to temperature gradient and magnetic-field curvature

Laboratory pair plasma: also a “benchmark”

- A magnetically confined pair plasma should also be considered a strong test of gyrokinetic codes we use in fusion and space plasma physics
  - With today’s supercomputers, codes exist that treat both electrons and ions (gyro)kinetically
  - These can be used (trivially, in most cases) to simulate electron-positron plasmas
  - For electron-positron plasmas, the problem of resolution/fidelity is three orders of magnitude less severe
- Appr 1000 papers with predictions (Web of Science search)
- This begs for laboratory pair plasma experiments to verify or falsify the many theoretical and numerical predictions, and help us understand high energy density astrophysical phenomena
- The first paper[a] talking about the virtues of a pair plasma experiment was written in 1978!
- In 2002, I proposed a stellarator as an appropriate confinement device[b]
- In 2014, unconfined, relativistic electron-positron plasmas were reported by Sarri et al. (next slides)

[a] V. Tsytovic and C. B. Wharton, Comments Plasma Phys. Cont. Fusion, pp. 91-100 (1978)

[b] T. Sunn Pedersen and A. H. Boozer, PRL 88, 205002 (2002)

Relativistic, short-lived electron-positron beam

nature COMMUNICATIONS

ARTICLE

Received 4 Apr 2014 | Accepted 24 Feb 2015 | Published 23 Apr 2015 DOI: 10.1038/ncomms7747 OPEN

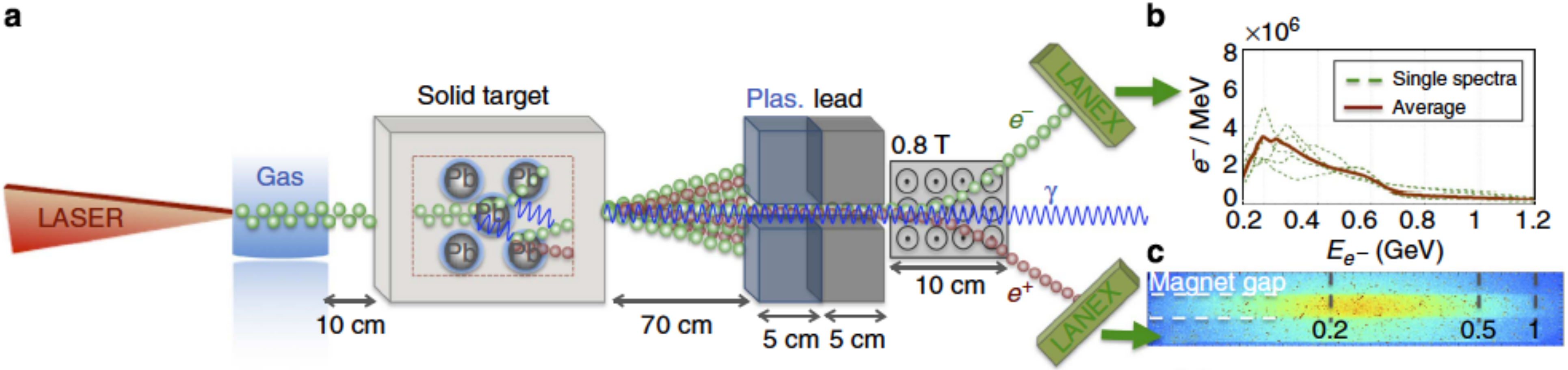
Generation of neutral and high-density electron–positron pair plasmas in the laboratory

G. Sarri[1], K. Poder[2], J.M. Cole[2], W. Schumaker[3,†], A. Di Piazza[4], B. Reville[1], T. Dzelzainis[1], D. Doria[1], L.A. Gizzi[5,6], G. Grittani[5,6], S. Kar[1], C.H. Keitel[4], K. Krushelnick[3], S. Kuschel[7], S.P.D. Mangles[2], Z. Najmudin[2], N. Shukla[8], L.O. Silva[8], D. Symes[9], A.G.R. Thomas[3], M. Vargas[3], J. Vieira[8] & M. Zepf[1,7]

Queen's University Belfast

EPSRC Engineering and Physical Sciences Research Council

Electron-positron beam with some plasma characteristics, created and probed by lasers. Figures courtesy of Gianluca Sarri (errors due to me)



Relativistic, short-lived electron-positron beam

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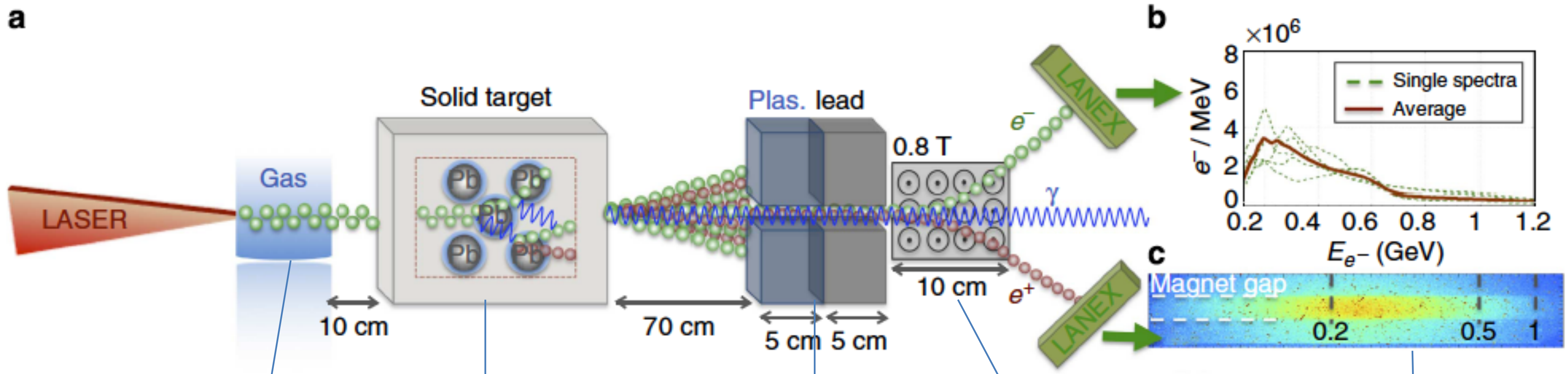


Laser wake-field creation and acceleration of electrons to >100 MeV

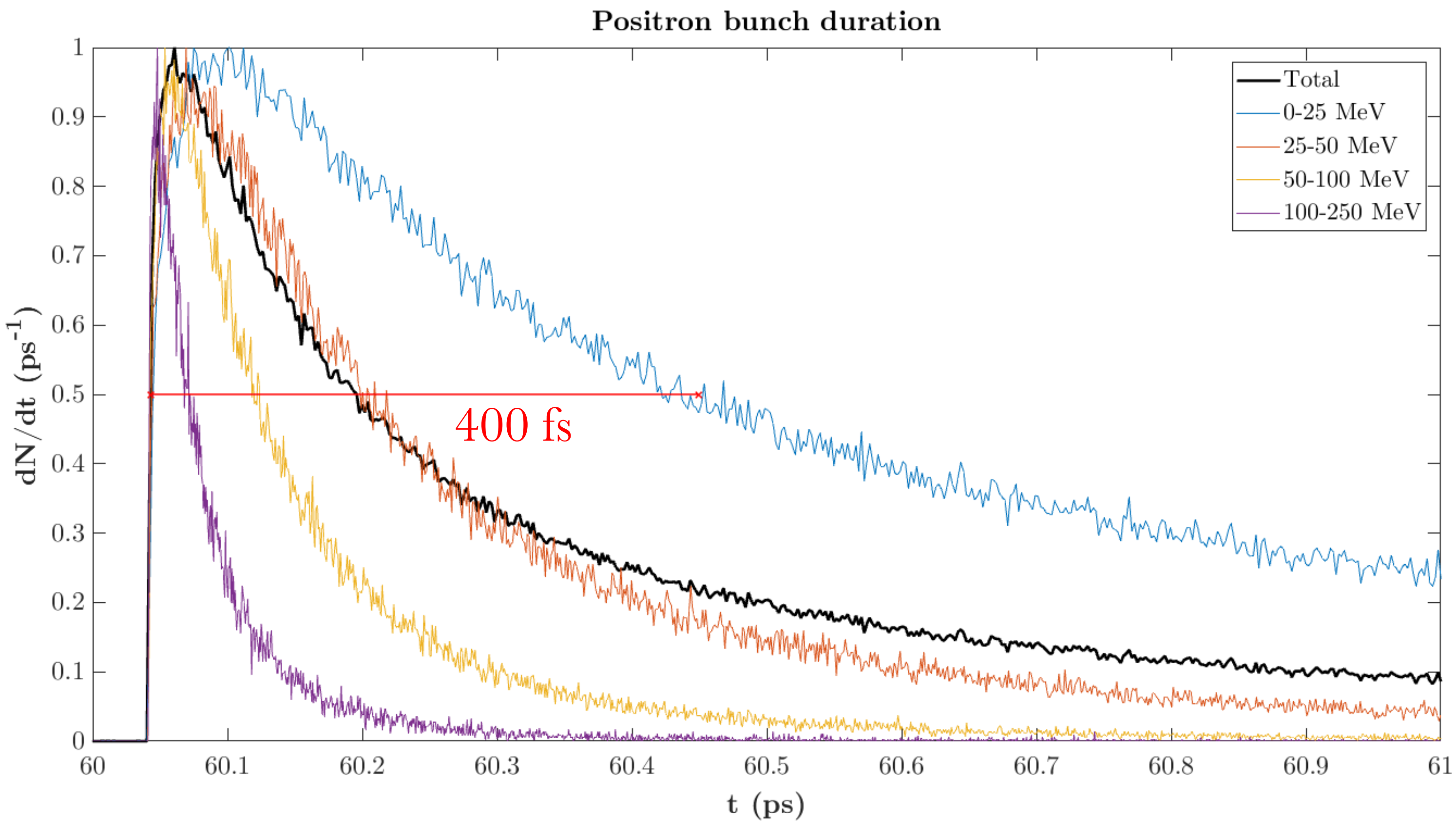
Hits solid target: Sea of gammas and pair production

Beam is skimmed

Electrons, gammas, and positrons separate in B=0.8 T

Separately diagnosed

Bunch duration



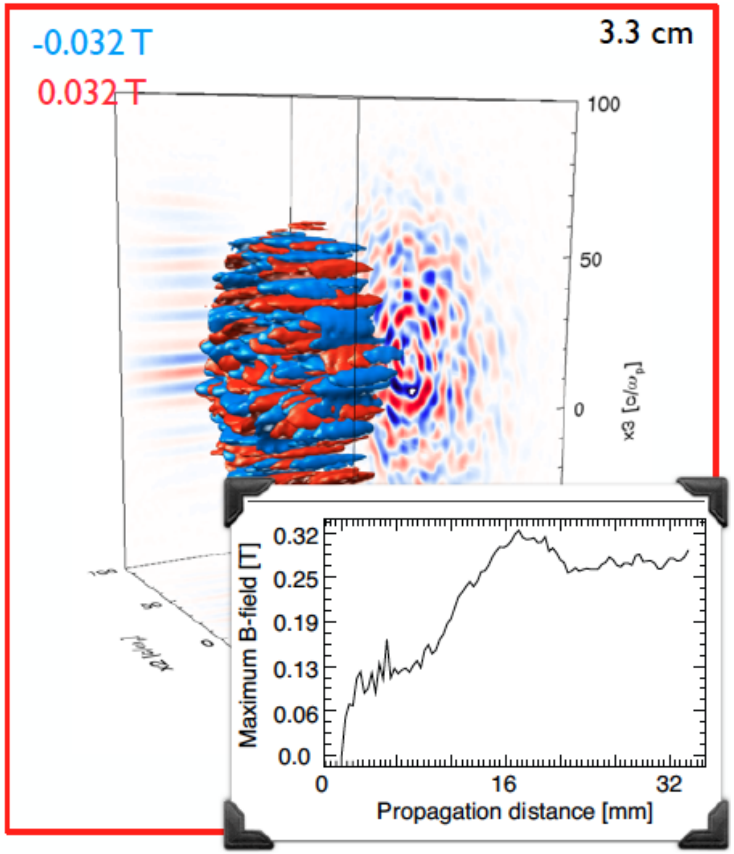
High-energy component (>100 MeV): number of positrons: ~10^8

A. Alejo et al., in preparation (2017)

Gianluca Sarri

A neutral pair beam

- Nearly neutral mix of electrons and positrons
- Beam duration: ~ tens to hundreds of fs
- Beam diameter: ~ 1.2 c/w_p
  - See next slide



- Code predicts filamentation of the beam when it travels through a cold stationary plasma (as it does in the experiment)
- This is the well-known Weibel beam-plasma instability
- Work is progressing to confirm this results experimentally

Adapted from Gianluca Sarri

When is a collection of charges a plasma?

Plasma text books generally agree that a collection of charges is a plasma when

$$\lambda_D = \sqrt{\frac{\varepsilon_0 T}{ne^2}} << a$$

Why is a small Debye length important? One answer is:

So that self-generated (plasma space charge) electrostatic potentials can compete with, or even dominate over, the kinetics of the particles

The largest imaginable electrostatic potential is when the two species have separated completely. Can this compete with their kinetic energy?

$$\frac{1}{2}mv_{th}^2 = \frac{3}{2}kT << e\phi_{pl} \Leftrightarrow \frac{T}{e} << \phi_{pl} \qquad \left|\varepsilon_0 \nabla^2 \phi\right| \le en_e \Leftrightarrow \varepsilon_0 \frac{|\Delta\phi|}{a^2} \le en_e \Leftrightarrow |\Delta\phi| \le en_e a^2 / \varepsilon_0$$

$$\Rightarrow \frac{T}{e} << en_e a^2 / \varepsilon_0 \Leftrightarrow \frac{\varepsilon_0 T}{n_e e^2} << a^2 \qquad \Leftrightarrow \lambda_D^2 << a^2$$

In the work by Sarri and collaborators, this is not fulfilled, if one takes the positron energy as a measure of T

Indirectly, the easy separation of the e- and e+ in the B=0.8T field confirms this

Can we have plasma effects without a small Debye length?

For (purely) electromagnetic phenomena, the collisionless skin depth $\lambda_s = c/\omega_{pe}$ matters, and the Debye length is not necessarily important.

Example: electromagnetic waves propagation in a collisionless homogeneous plasma with no or negligible background magnetic field:

$$\omega^2 = \omega_p^2 + c^2k^2 \qquad \omega_p^2 = \frac{ne^2}{\epsilon_0 m_e}$$

This wave will be reflected if the wave frequency is below the plasma frequency - the “plasma cutoff”

But! What if the plasma is very thin or small? A low frequency wave, well below the plasma frequency, can tunnel through a $\lambda_s > a$ plasma without problem:

The skin depth is the decay length of the evanescent wave

$$0 \approx \omega_p^2 + c^2k^2 \Leftrightarrow k^2 \approx -\frac{\omega_p^2}{c^2} \Rightarrow k = \pm i\frac{\omega_p}{c} \qquad e^{ikx-\omega t} \rightarrow e^{-x/\lambda_s}e^{i\omega t}$$

The laser-produced plasmas do (marginally) satisfy $\lambda_s < a$ - they are electro-magnetically “thick” but electrostatically “thin”

We aim to create an electrostatically ”thick” plasma – which unfortunately will be electromagnetically “thin”.

For more on this topic, ”plasma existentialism”, see E. V. Stenson et al., Journal of Plasma Physics (Feb. 2017) https://doi.org/10.1017/S0022377817000022

How many positrons are needed for small Debye length?

The Debye length needs to be small compared to the device size:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 T}{ne^2}} << a$$

How large is the trap? Given a finite number of positrons at a given temperature, should we make the trap small (maximize *n*) or large (maximize *a*)?

$$n = \frac{N}{V} \approx Na^{-3}$$

$$\frac{\lambda_D}{a} \propto \frac{\sqrt{T}}{a\sqrt{n}} \propto \frac{\sqrt{T}}{a\sqrt{Na^{-3}}} \propto \frac{\sqrt{T}\sqrt{a}}{\sqrt{N}}$$

An extremely small plasma (Sarri et al.) would make coil design for toroidal confinement difficult.

→ ***Aim for tabletop size.***

Assume: $T_{e-} = T_{e+} = 1$ eV

a = 7 cm, V = 10 liter, $\lambda_D = 0.7$ cm

→ **N > 10^{10} positrons**

(and equal electrons)

T Sunn Pedersen, et al. ***New Journal of Physics*** *(2012)*

Won't a e+/e- plasma just annihilate?

Annihilation on neutral gas?

→ solved by UHV (10^{-10} torr) and elimination of organics
(N_2: 17 days; He: 121 days)
Greaves and Surko, AIP Conf. Proc. 606, 10 (2002)

Annihilation of free (plasma) electrons and positrons:
Dominated by radiative capture below 100 eV~1 MK
At $n=10^7$ cm^{-3}, T~5 eV, lifetime is $5*10^5$ sec ~ several days

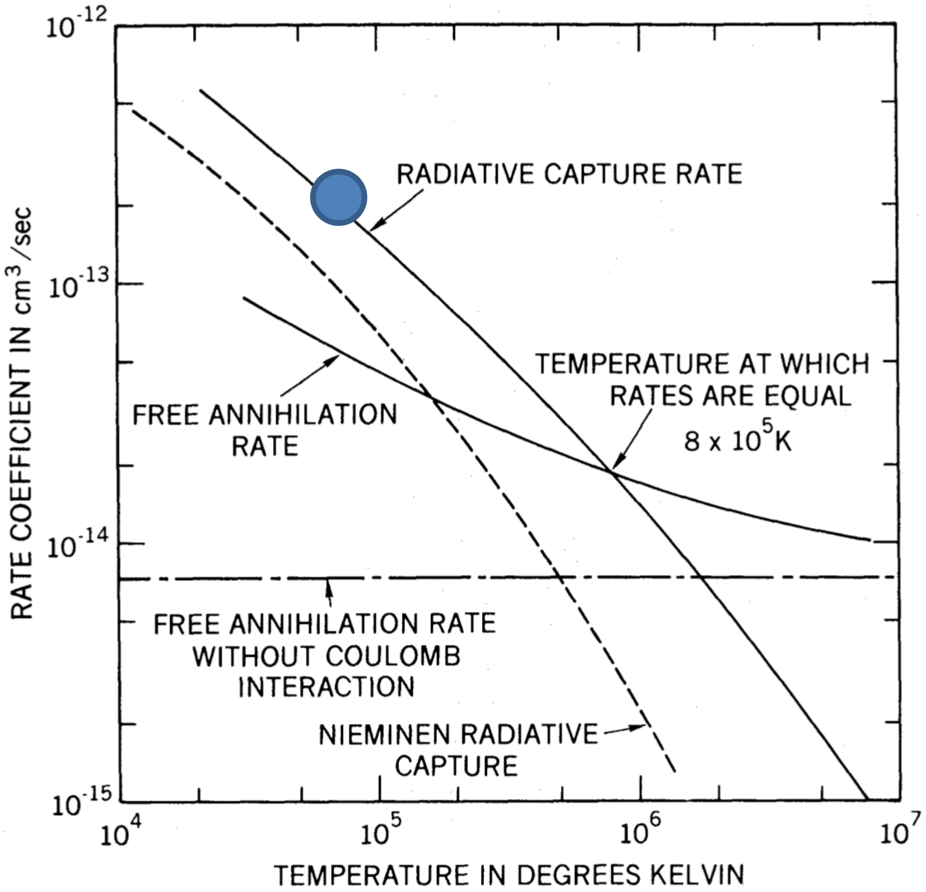
Lifetime will likely be dominated by plasma transport to the walls

Still, could be a useful diagnostic signal:
At 10 l volume, $N=10^{11}$
we get $2*10^5$ annihilations/sec

FORMATION OF THE 0.511 MeV LINE IN SOLAR FLARES*

CAROL JO CRANNELL, GLENN JOYCE, AND REUVEN RAMATY
NASA/Goddard Space Flight Center
AND
CARL WERNTZ
Department of Physics, The Catholic University of America
Received 1976 January 19; revised 1976 May 18

THE ASTROPHYSICAL JOURNAL, **210**: 582–592, 1976



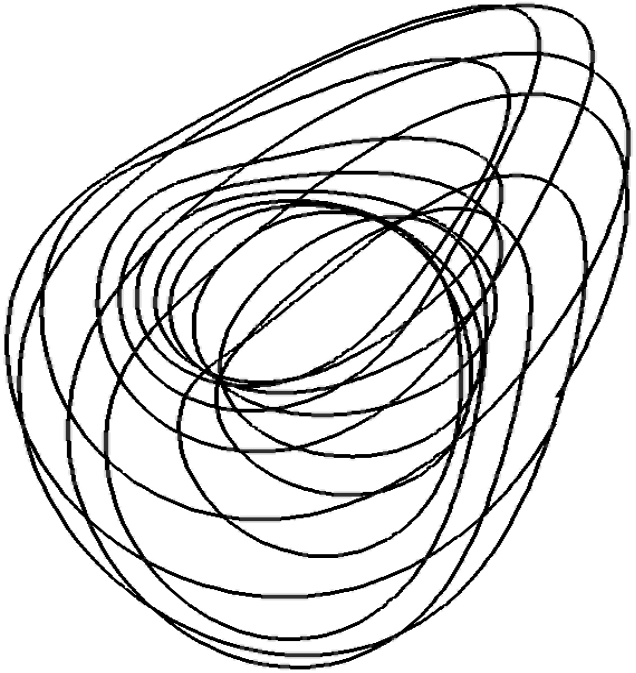
What kind of trap to use?

- Must confine both species (both signs of charge)
    - Rules out electrostatic confinement, eg. a Penning trap

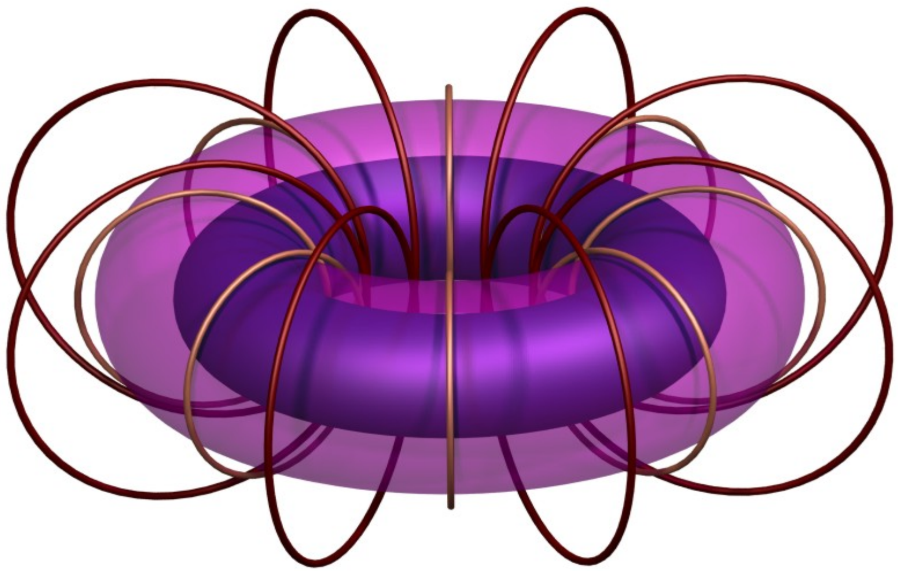
- Must be compatible with the low mass (Paul trap: challenging)
- Would be nice if relatively high energies can be confined
- Should have confinement for more than a few collision/relaxation times
    - Rules out magnetic mirrors, unoptimized stellarators
- A realistically achievable electron-positron plasma cannot sustain a large current – density is too low.
    - Rules out tokamak or reversed field pinch, both of which rely on strong plasma currents to have closed particle orbits
- Topology should ideally be astrophysically relevant, given the astrophysical relevance of pair plasmas
- Injection into the confining field should be possible, somehow

Two confinement schemes: different physics

stellarator



dipole



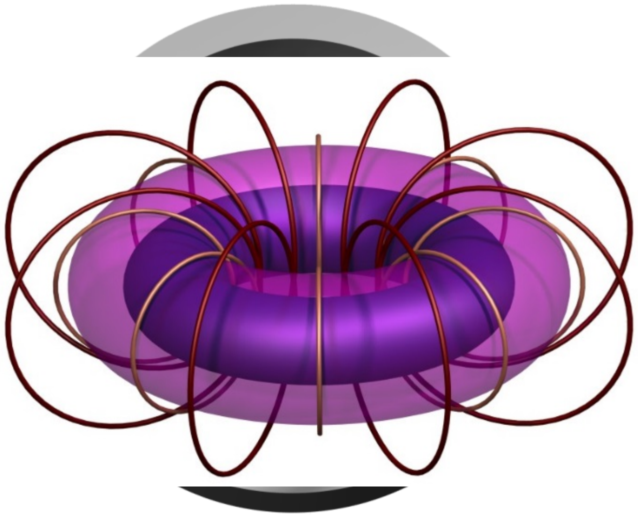
Two confinement schemes: different physics

APEX-D: levitated dipole
• astrophysically relevant
•all drift orbits confined
• parallel force balance does not counteract instabilities
• strong flux expansion
• requires levitation and re-cooling
• e- confinement in RT-1: 5 minutes

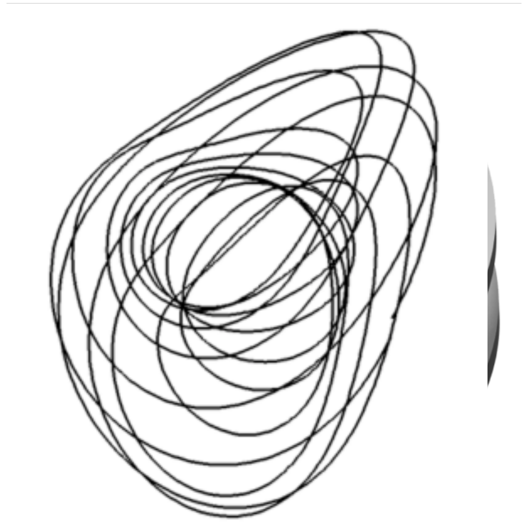
APEX-S: stellarator
• fusion relevant
•drift orbits not all confined
• parallel force balance counteracts instabilities
•negligible flux expansion
• e- confinement in CNT: 90 ms

Both steady state, purely magnetic, no internal currents.

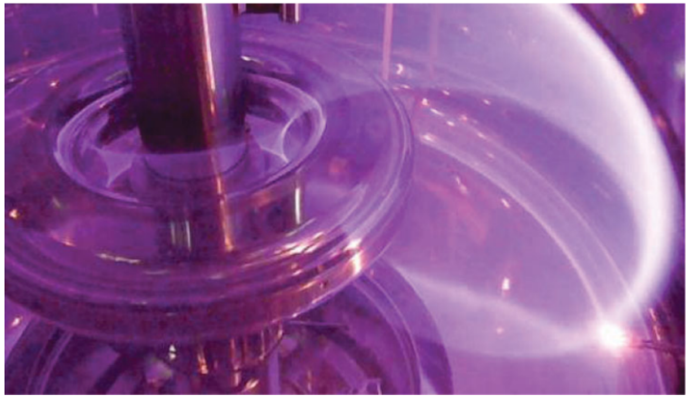
Both can confine either non-neutral or quasi-neutral plasmas.



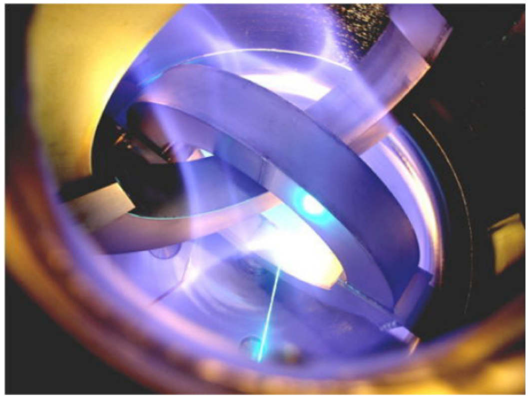
dipole



stellarator



Ring Trap 1



Columbia Non-neutral Torus

1.) Z. Yoshida, H. Saitoh, J. Morikawa, Y. Yano, S. Watanabe, and Y. Ogawa.. **Phys. Rev. Lett.** (Jun 2010)
2.) T. Sunn Pedersen et al. **New Journal of Physics** (2012)

Is a small λ_D realistic (and how?)

1.) Positron availability

For > 10 Debye lengths of 5-eV plasma in 10 L:

→ about 10^{11} positrons needed

→ world-class positron source needed

→ **NEPOMUC (NEutron-induced POsitron source MUniCh)[2]**

Will NEPOMUC's rate of 10^9 positrons/second be enough?

- confinement time >100 s
- 100% injection
- heating during transfer

→ **Positron Accumulation Experiment (PAX)**

2.) Simultaneous confinement

Whether dipole or stellarator:

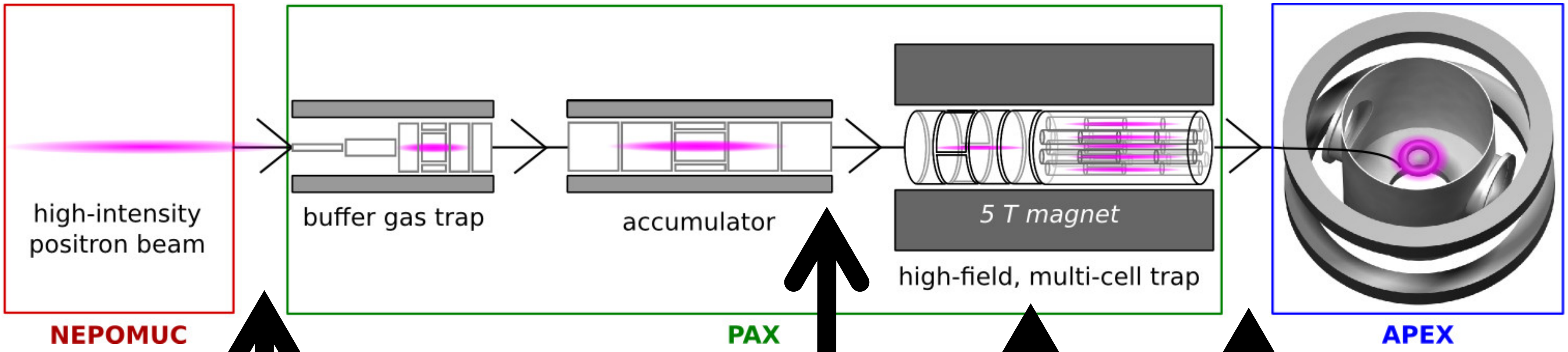
Injection techniques needed.

→ **A Positron-Electron Experiment (APEX)**

1) *T Sunn Pedersen, et al.* ***New Journal of Physics*** *(2012)*

2) *C. Hugenschmidt, C. Piochacz, M. Reiner, and K. Schreckenbach.* ***New Journal of Physics*** *(2012)*

The APEX scheme, and pieces thereof



reactor beam

energy spread reduction: proof-of-principle simulations

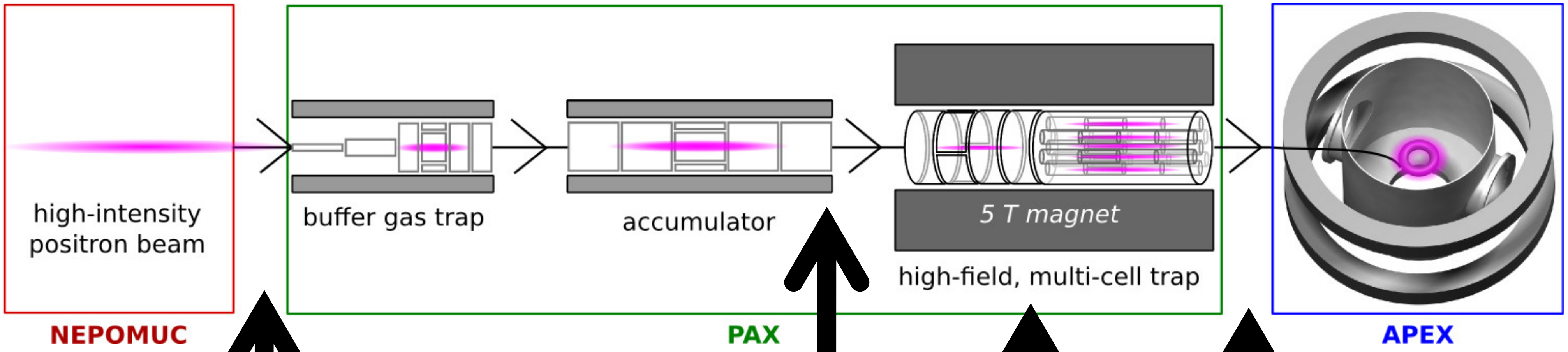
anodo- versus cathodoluminescence

high-field trapping and long term storage

high-efficiency positron injection into a dipole magnetic field and subsequent confinement

levitated dipole development

The APEX scheme, and pieces thereof



energy spread reduction: proof-of-principle simulations

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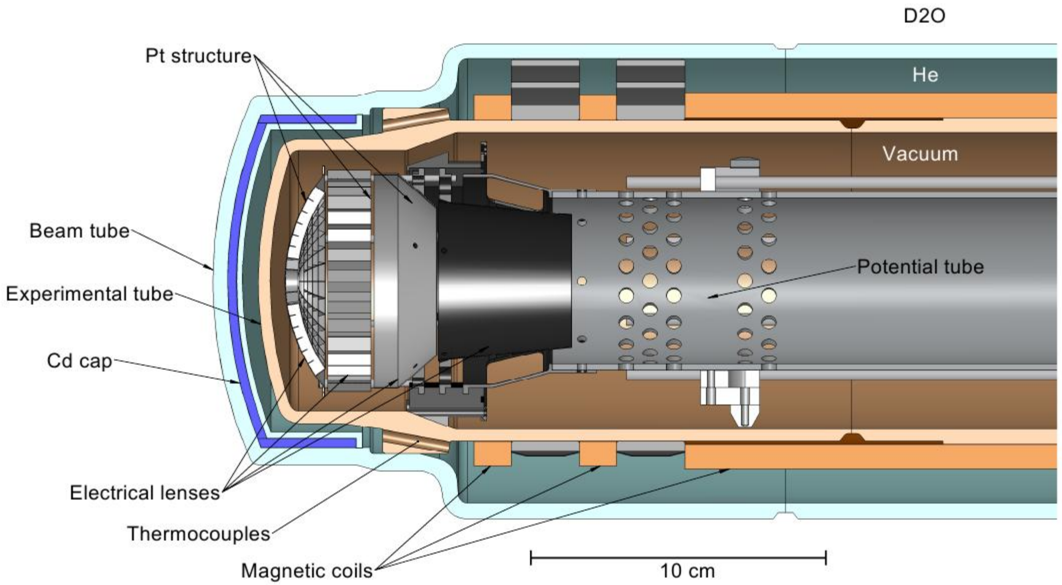
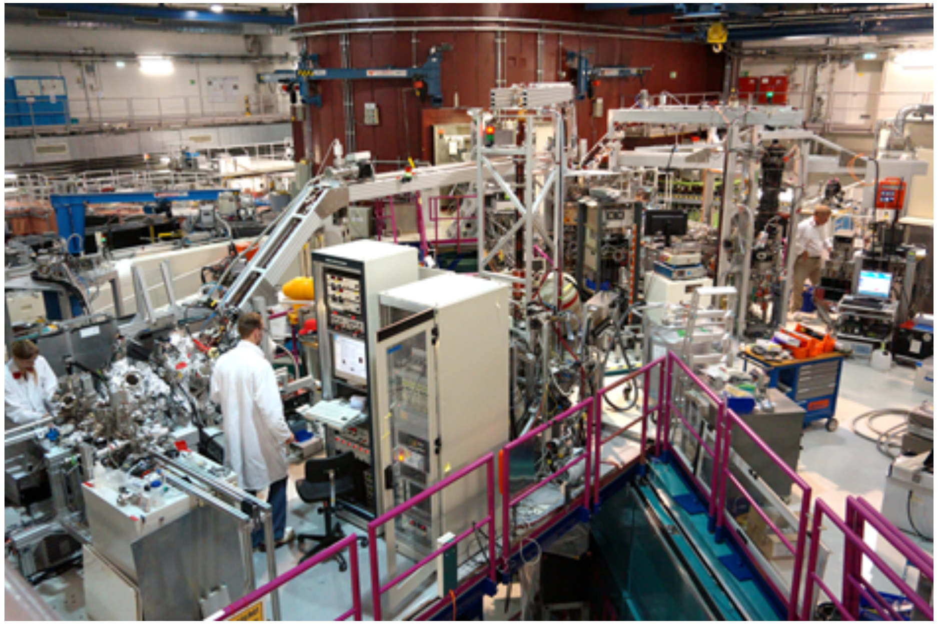
The NEPOMUC e+ source





- operated at the FRM-II research reactor in Garching
- high-energetic γ-rays produced from neutron-capture in ^{113}Cd give rise to positrons via pair production in Pt
- e+ are moderated in the Pt, accelerated and magnetically guided to the experiments (primary beam, 1 keV, 10^9 e+/s, 400 eV and below: 10^8 e+, s)
- optionally a second moderator setup is available (remoderated beam, ~10 eV, 10^7 e+/s)

C. Hugenschmidt et al., **J. Phys.: Conf. Ser.** 443, 012079 (2013)

Why do we care to characterize the beams?

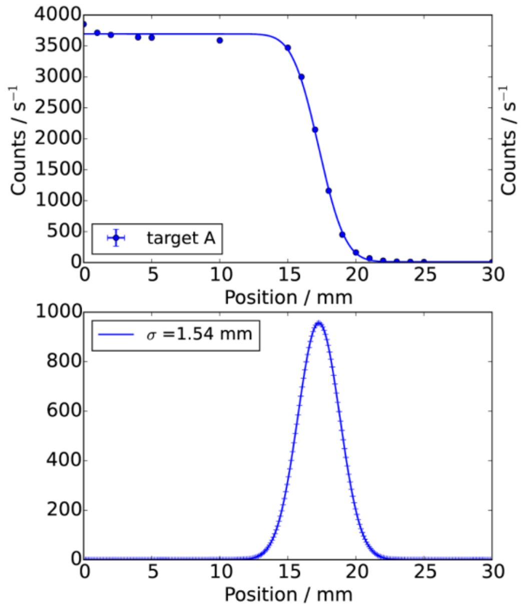
$$\tfrac{1}{2}mv_\perp^2 + \tfrac{1}{2}mv_{||}^2 = \mu B + \tfrac{1}{2}mv_{||}^2 = const.$$

$$\mu = const.$$

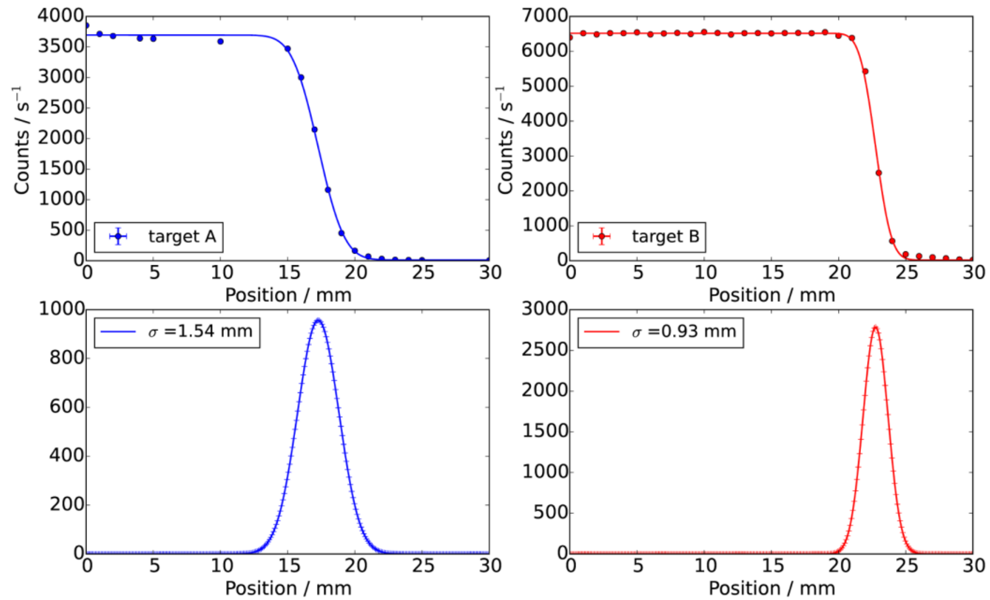
- We want to inject the positron beam into higher magnetic fields
  - Positron guide field is only 5 mT
- If μ is too large, the positrons may reflect
- Or we will need to accelerate them further to overcome the reflection – increased energy
- μ also has importance for the magnetic drifts in bent magnetic fields
- We need to know the diameter of the beam to guide it efficiently into our traps

Flux and spatial profile of NEPOMUC e+ beams

remoderated



primary

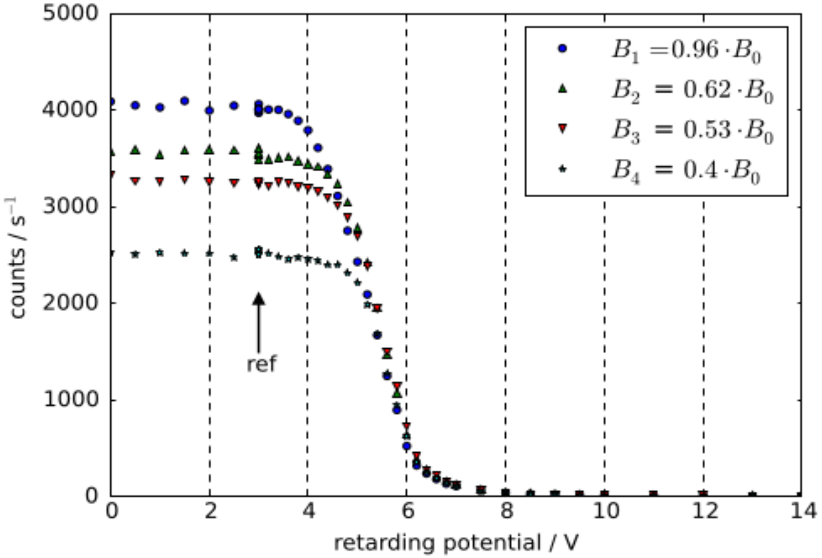


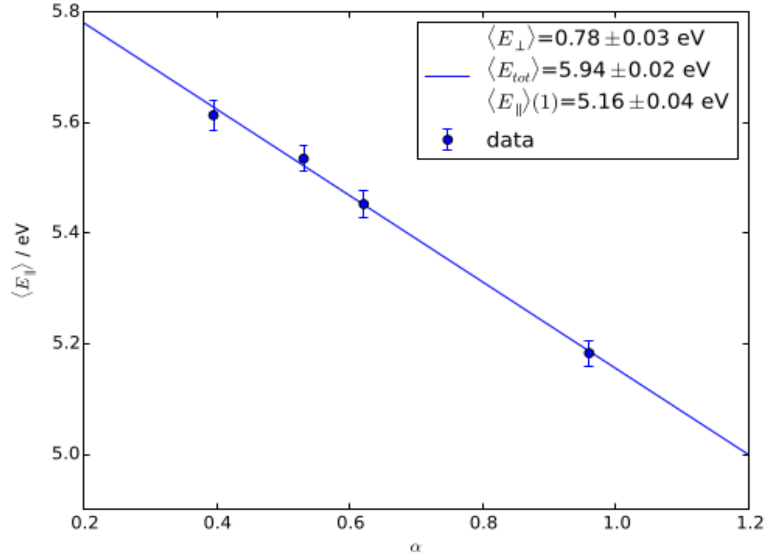
	remoderated	primary
energy / eV	5, 12, 22	400, 1000
intensity / e^+/s	2-6·10^7	1-5·10^8
mean spread / mm	< 4	~ 15

J. Stanja, et al. ***Nuclear Instruments and Methods in Physics Research A*** *(2016)*

Energy distribution of the NEPOMUC e+ beams

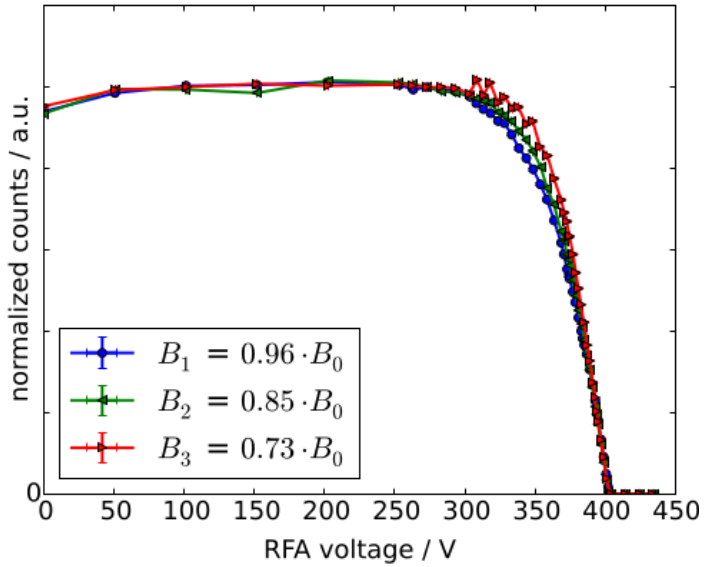
remoderated

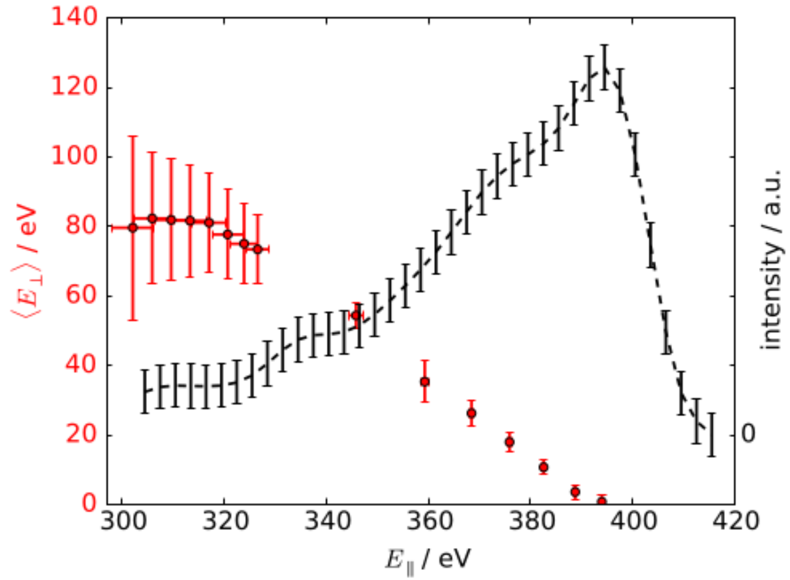




→ energy spread of 2-4 eV exceeds expectations

primary





→ evidence of non-adiabatic (but energy conserving) guiding

Future plan: Producing the optimal beam

Beam optimization at the source:

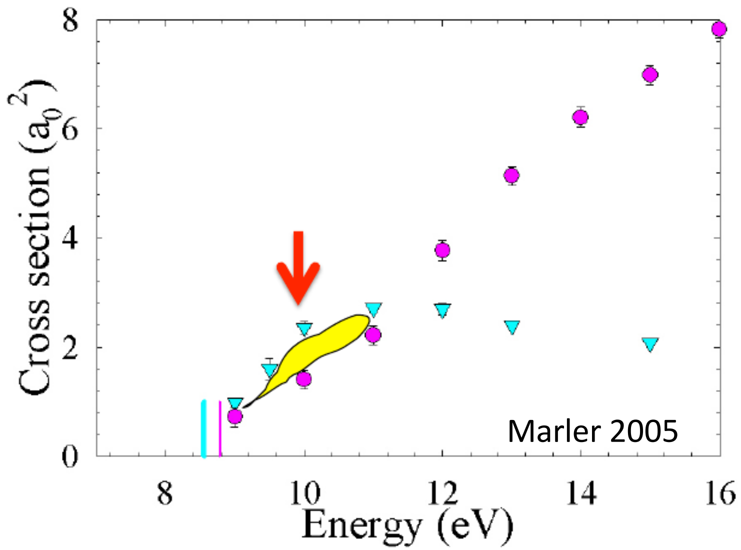
• lower primary beam energy to guarantee adiabatic guiding

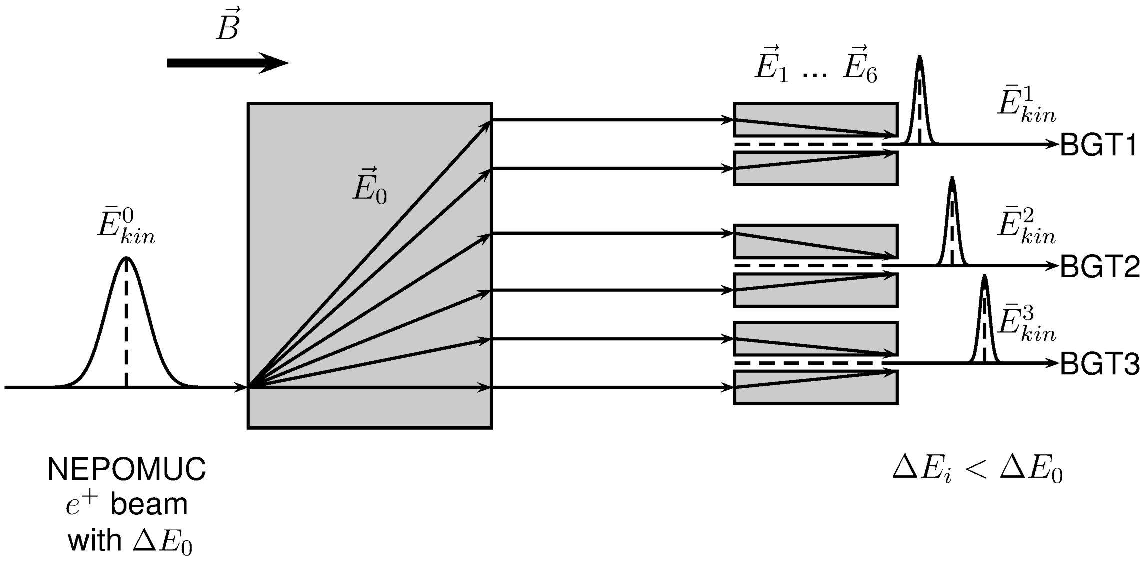
• optimize remoderation conditions to increase beam intensity of the remoderated beam

Beam manipulation at the experiment:

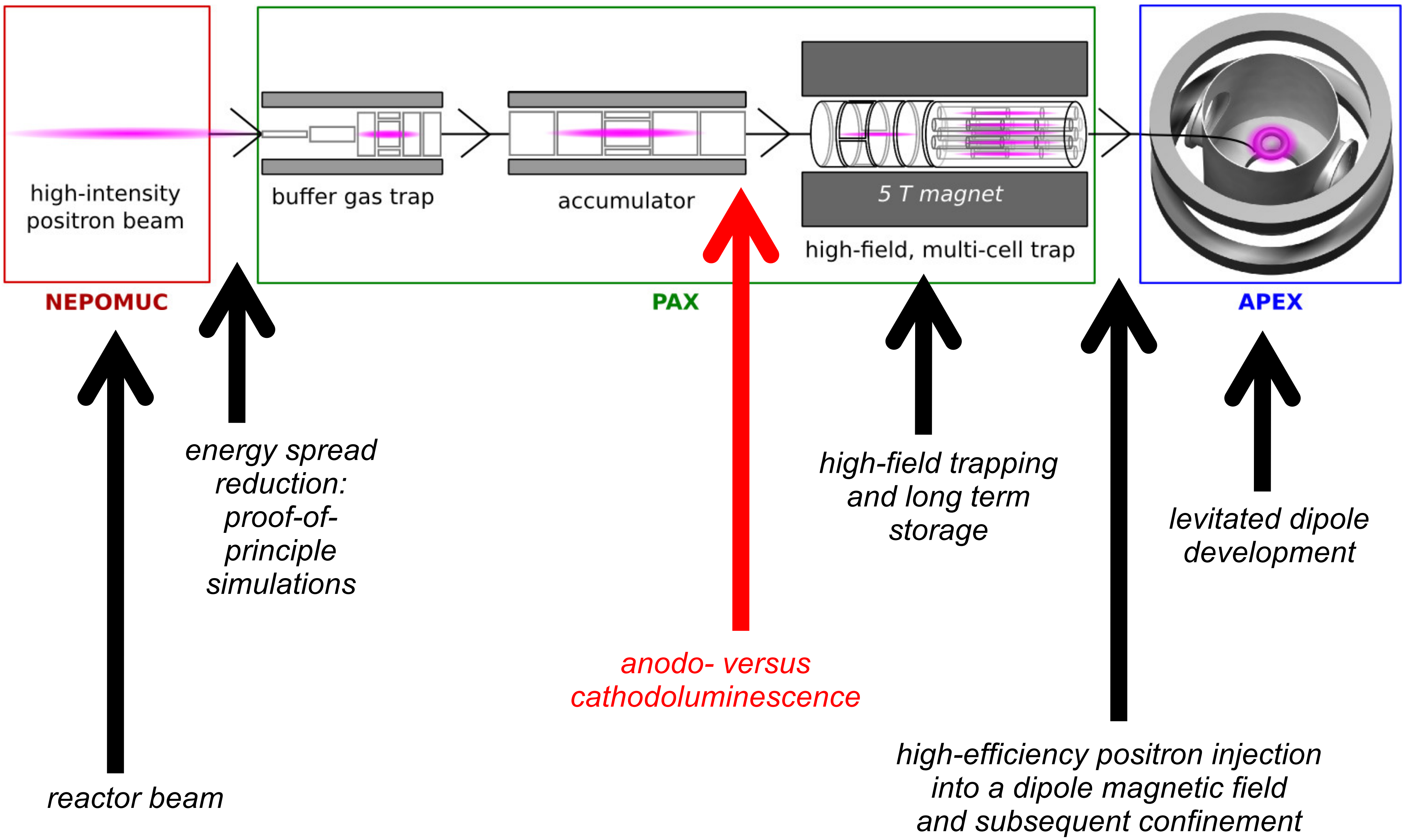
• sort the initial beam (broad energy distribution) into sub-beams with smaller energy distributions to target efficient cooling regime in a buffer gas trap

Comparison of Electronic Excitation and Ps Formation in N_2



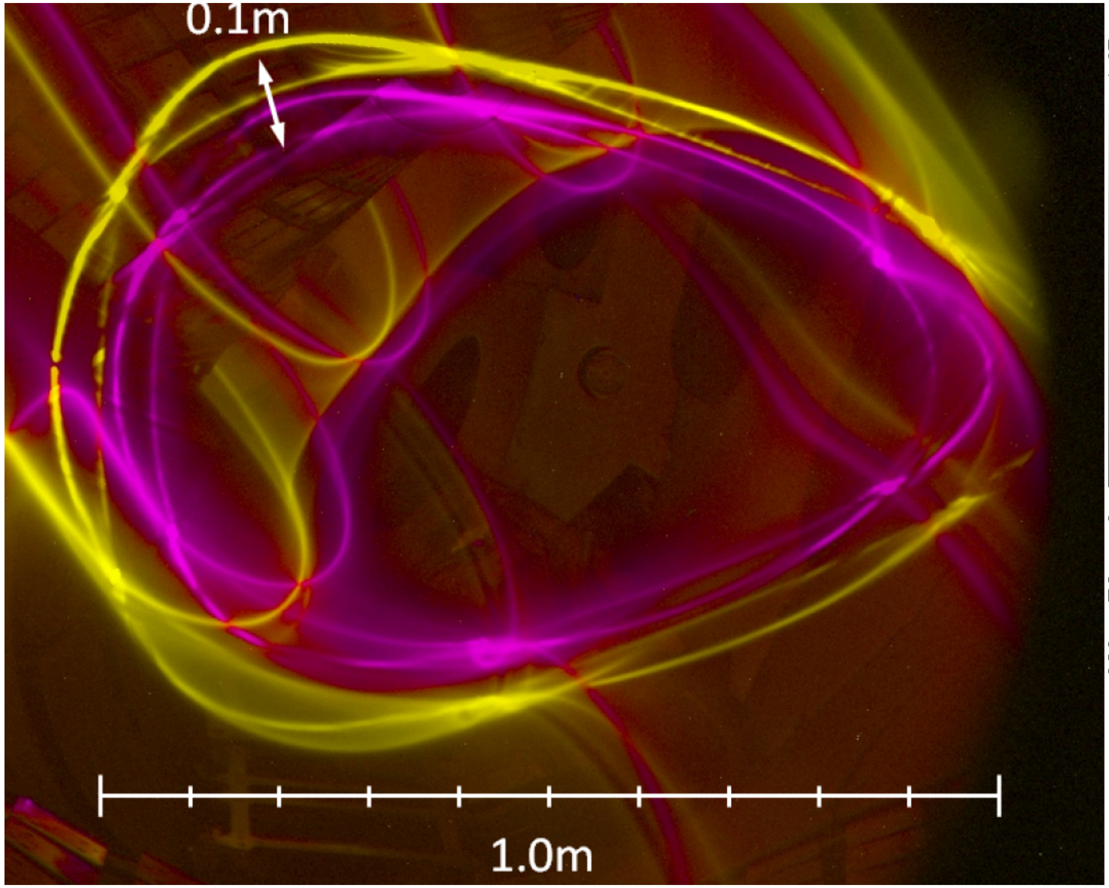


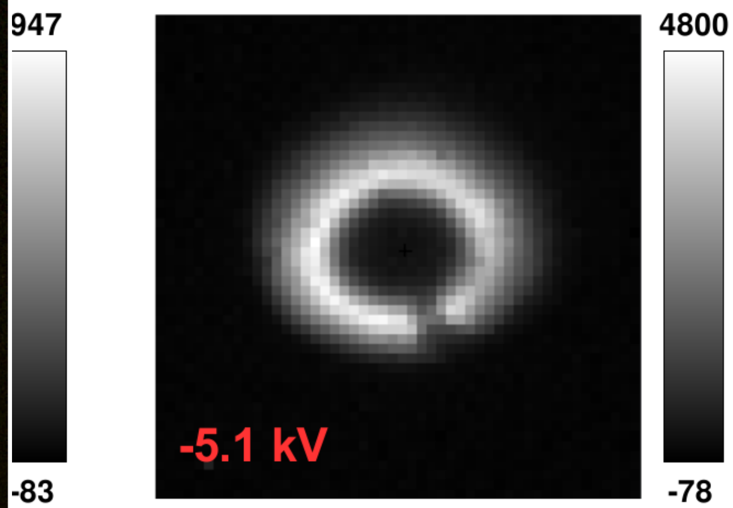
The grand scheme, and pieces thereof



Phosphor screens: electrons and positrons equal?

- Valuable non-neutral plasma diagnostic, in particular for Penning traps
- Are used for both e+ and e- …but are the phosphor responses the same?
- (Incidentally, phosphorescent powder is also used to measure and adjust the magnetic topology of stellarators, a favorite topic of mine)



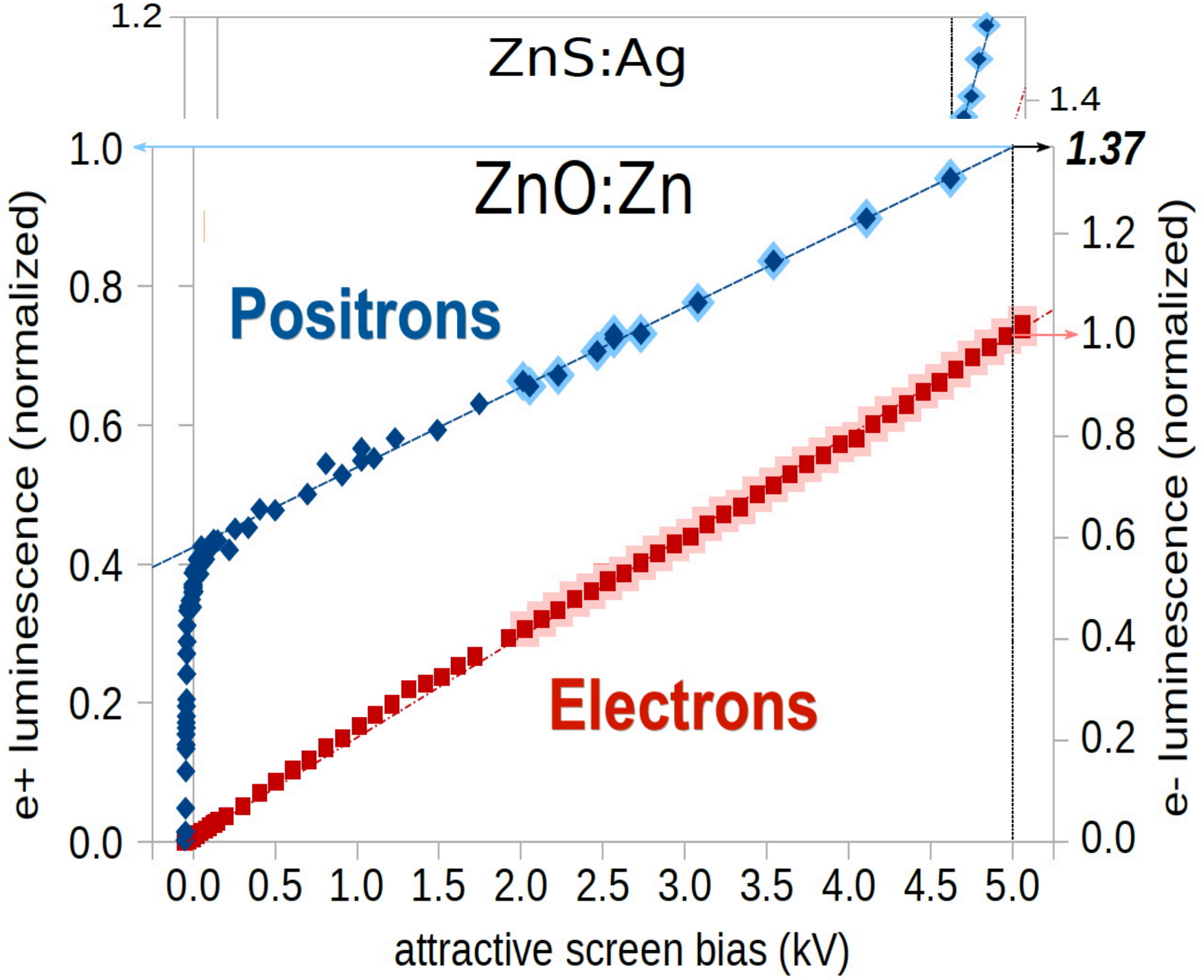


ponse for many
scale! Positrons in PAX

From TSP et al., Nature Comm. (2016)

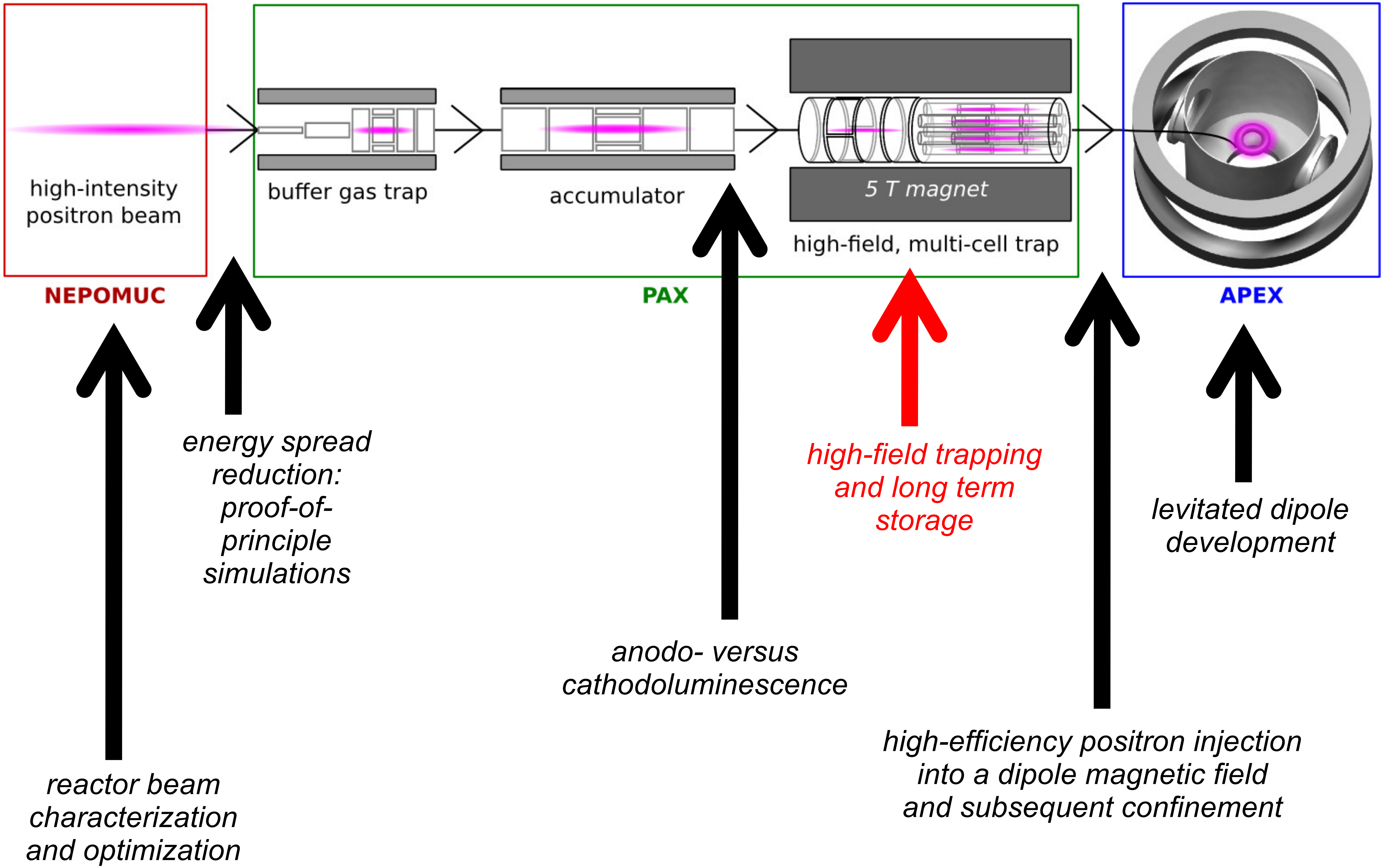
Result: Large differences!

- ZnS:Ag has a large "dead voltage" for electrons but none for positrons
- What about trying a different phosphor?
- ZnO:Zn (used for the stellarator flux surface measurements) has no dead voltage
- Also large differences
- Phosphorescence possibly caused by Auger electrons:
    - Positron annihilates with an inner-shell electron, an outer shell electron is expelled



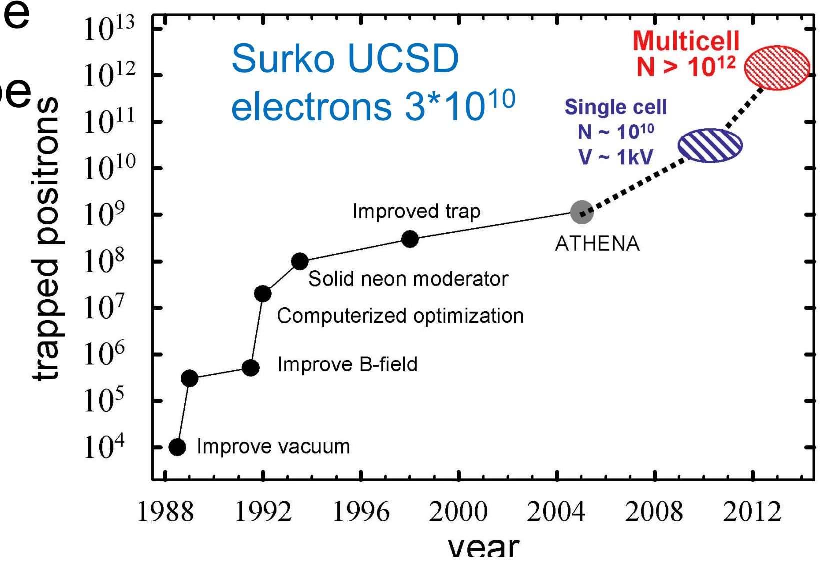
E. V. Stenson, et al., submitted to PRL

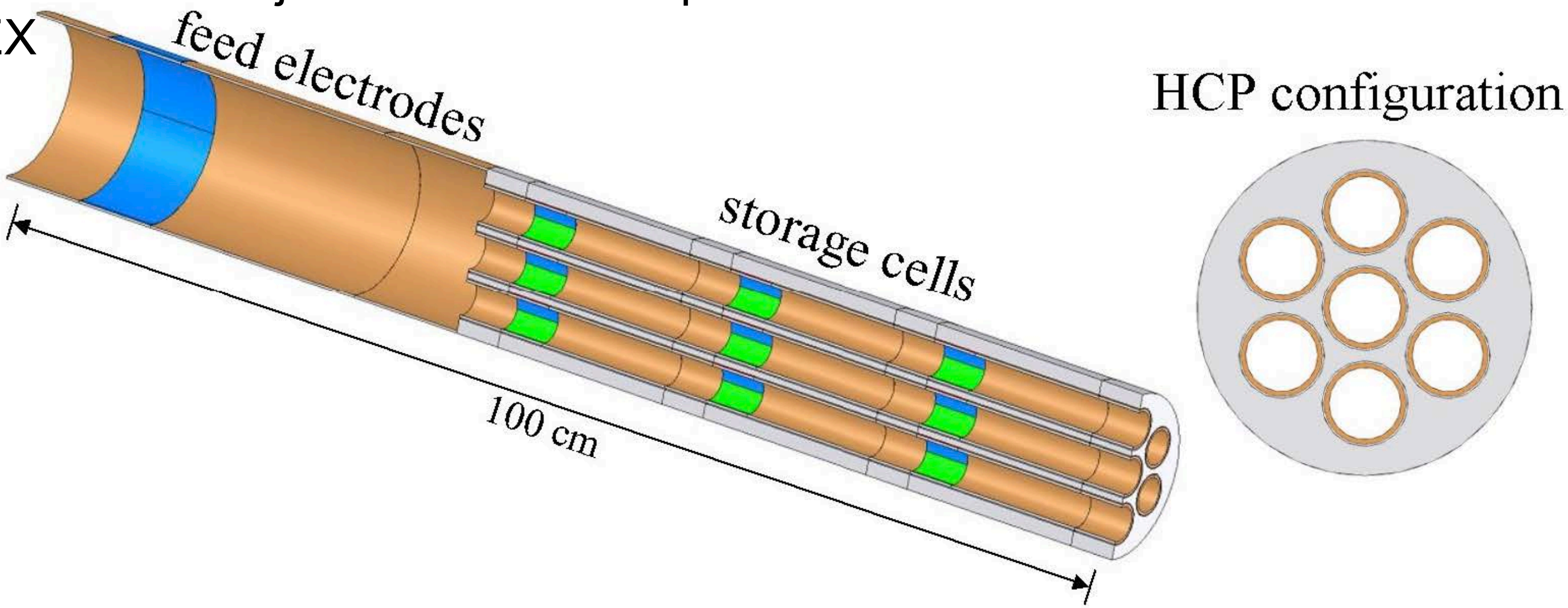
The grand scheme, and pieces thereof



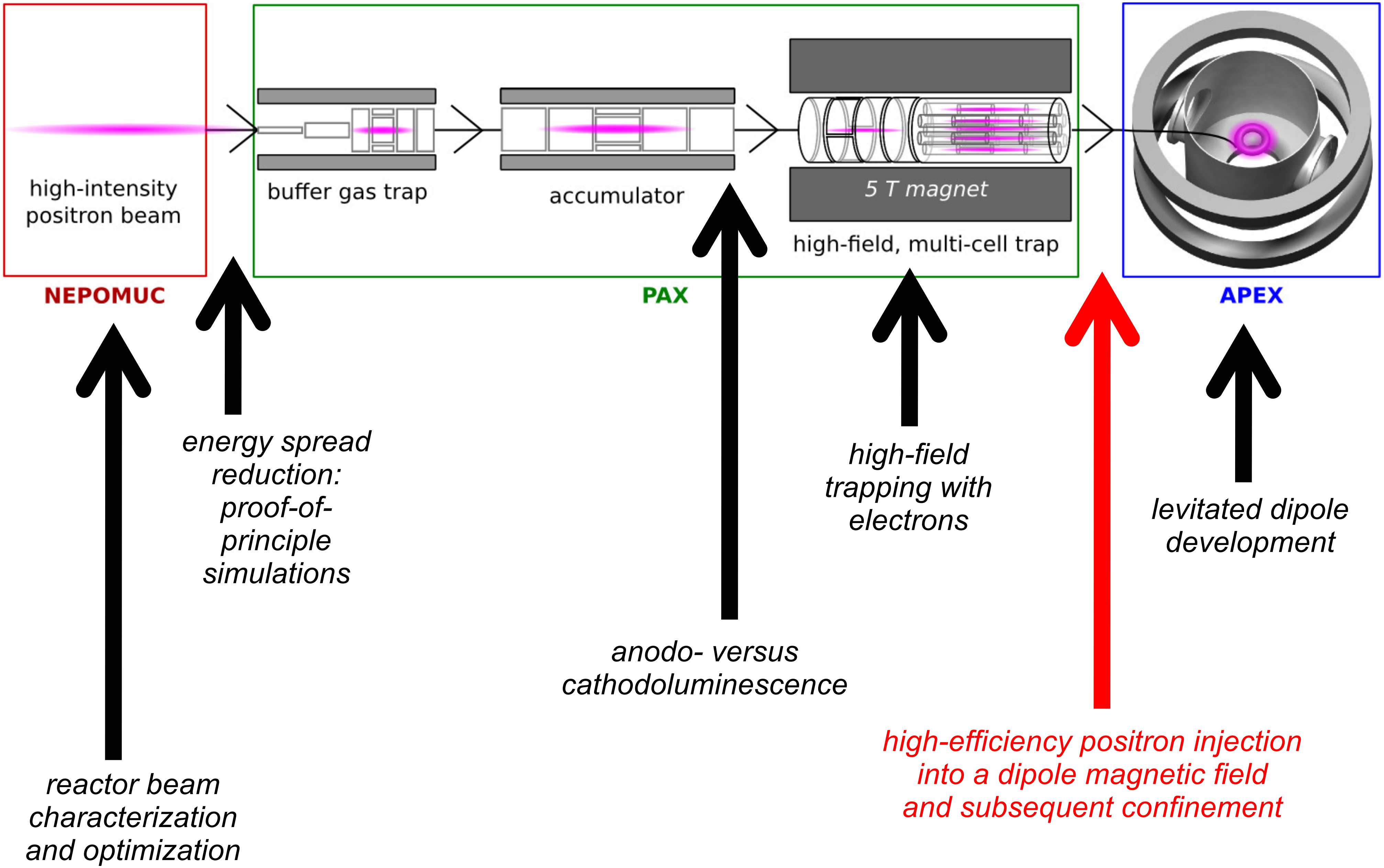
Development of a multicell trap

- we will likely need a positron accumulation stage
- the stored number of positrons (10^{11}-10^{12}) will be larger by one to two orders of magnitude than earlier achieved: Many separate short traps
    - Collaboration with Cliff Surko and James Danielson, UCSD
    - buffer gas trap fills multicell Penning trap array
    - PAX positrons are injected as massive pulses into APEX

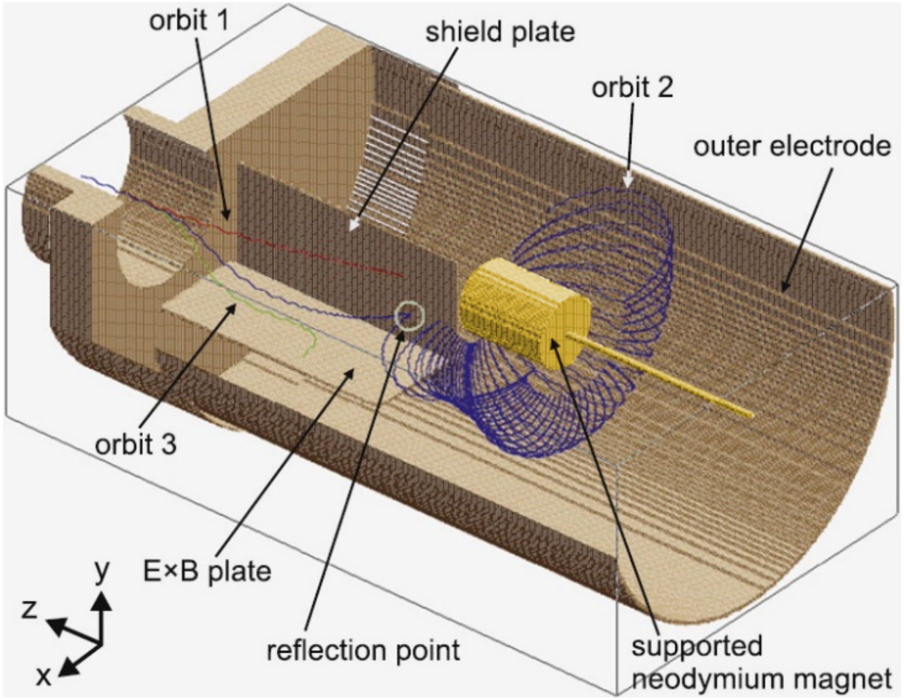




The grand scheme, and pieces thereof



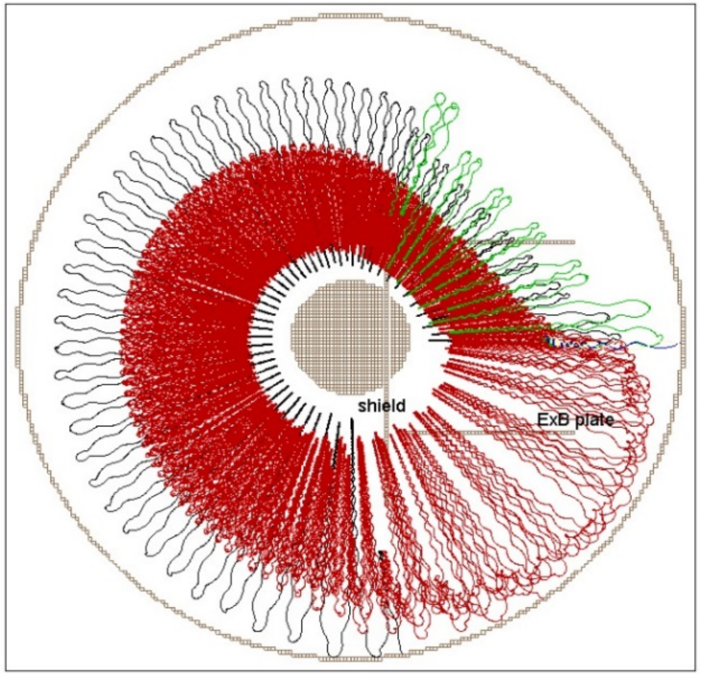
Prototype dipole trap: injection and trapping

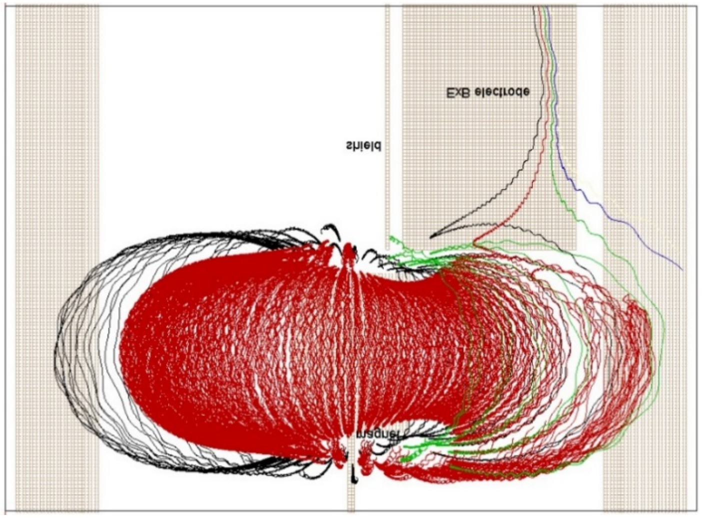


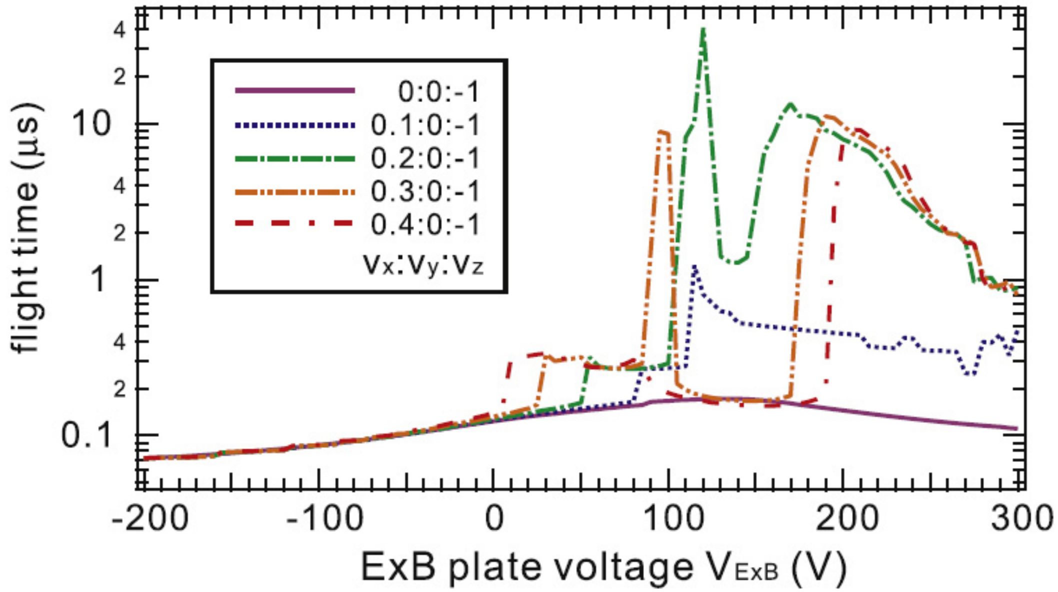
A permanent magnet device with…
- ExB and shield plates, steering coils
- magnet and outer wall electrodes

Magnet biased positively to electrostatically reflect positrons
ExB drift injection was numerically optimized (orbit 2)

Simulation studies for positron injection



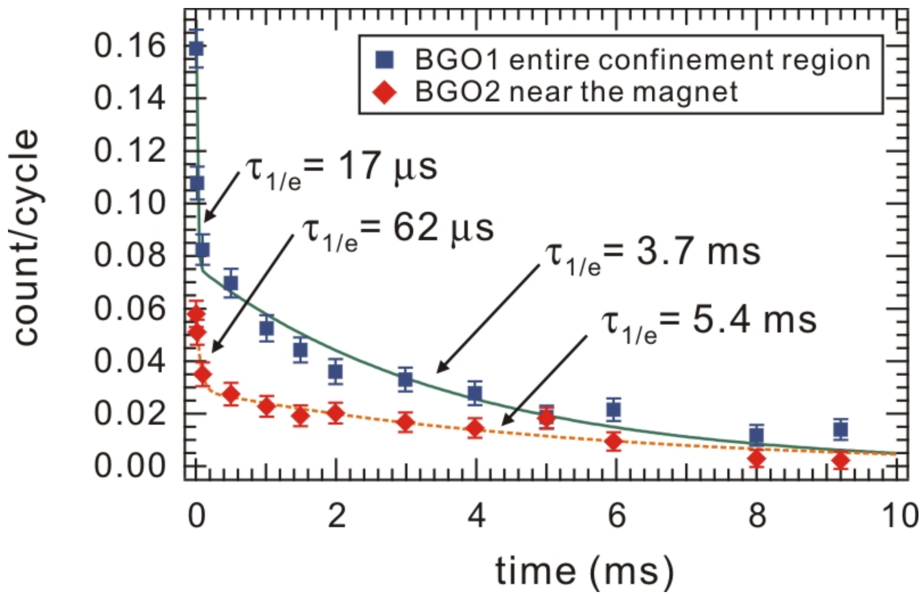




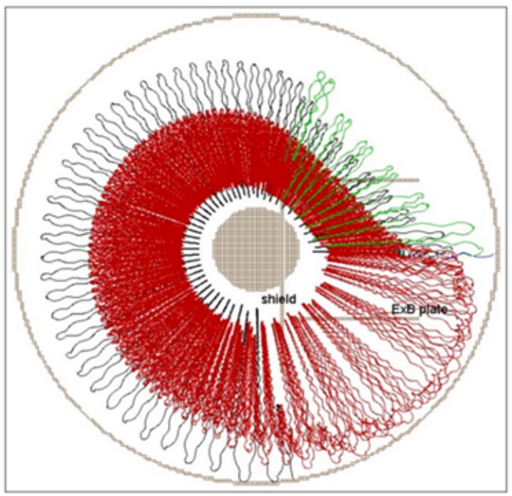
Typical orbits of positron in dipole field trap

- single-orbit analysis with different V_{ExB} and different initial positions (i.e. steering)
- injection is realized with wide V_{ExB} range
- finite v_{perp} is important for mirror trapping
- shield plate reduces error field, realizing long orbits in the trapping region

Experimental results:



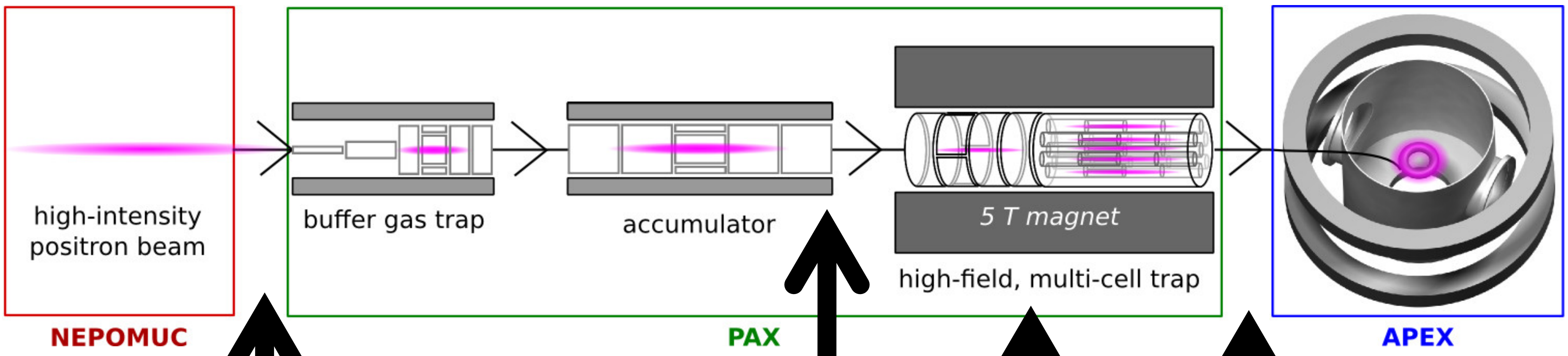
Decay of γ after stopping positron injection



- ExB drift injection of NEPOMUC beam
  - steering, ExB bias, E_r optimization
  - injection and 180° rotation confirmed
  - 35% injection efficiency reported earlier
  - To be published: Nearly 100% injection efficiency
- Confinement
  - 5 ms in strong field region (2015)
  - Recently 1 second (preliminary result)
  - improvement is expected in superconducting, levitated dipole

H. Saitoh, et al. **New Journal of Physics** (2015)

The grand scheme, and pieces thereof



reactor beam characterization and optimization

energy spread reduction: proof-of-principle simulations

anodo- versus cathodoluminescence

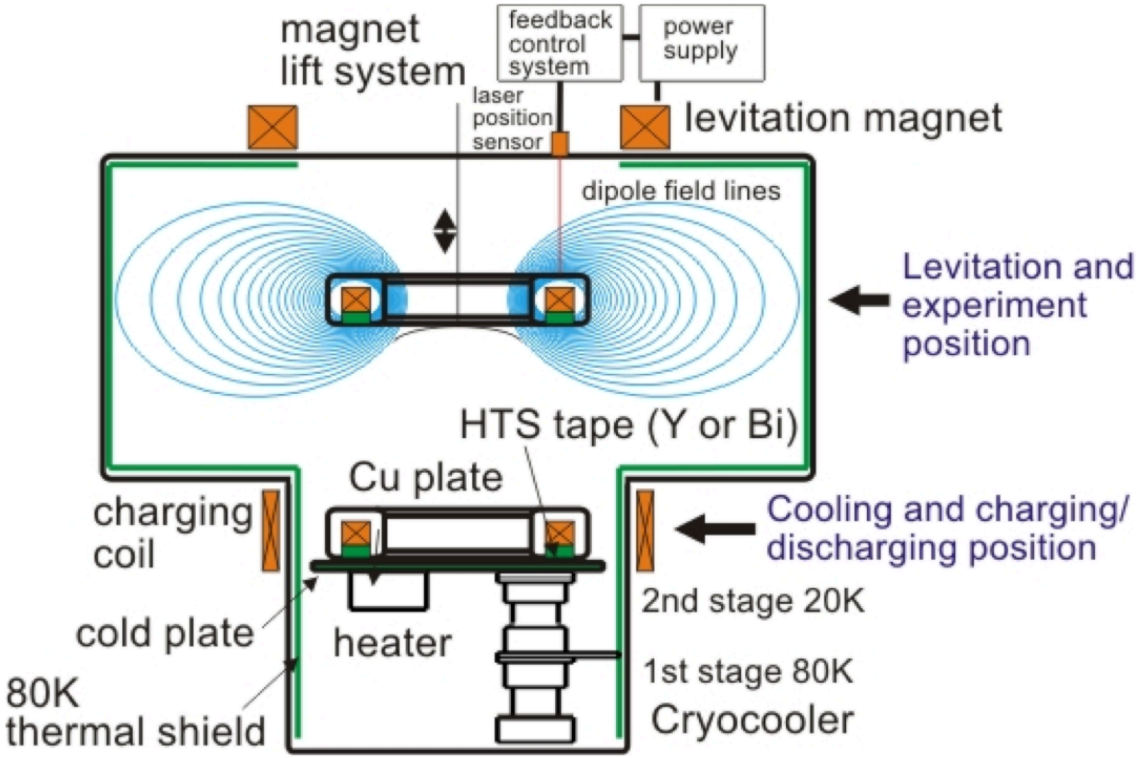
high-field trapping with electrons

high-efficiency positron injection into a dipole magnetic field and subsequent confinement

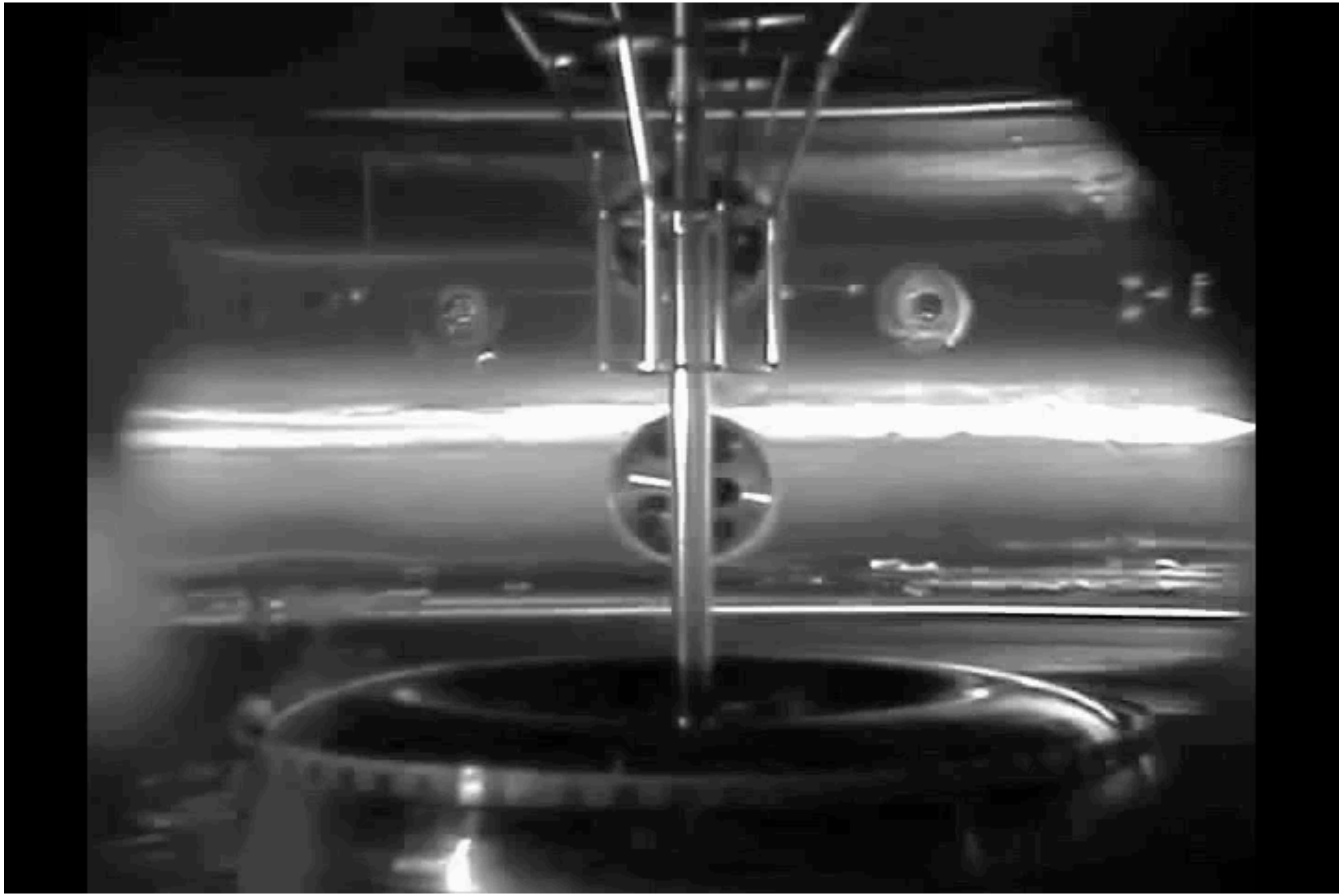
levitated dipole development

Design studies for a levitated dipole trap

- realization of closed and unperturbed magnetic field lines
- compared to other levitated dipoles: smaller, lighter, less heat load
- levitation control (key issue) simplifies to 1D stability problem:
    - If one picks the coil setup correctly, the tilt and slide motions are stable but vertical motion must be feedback-controlled

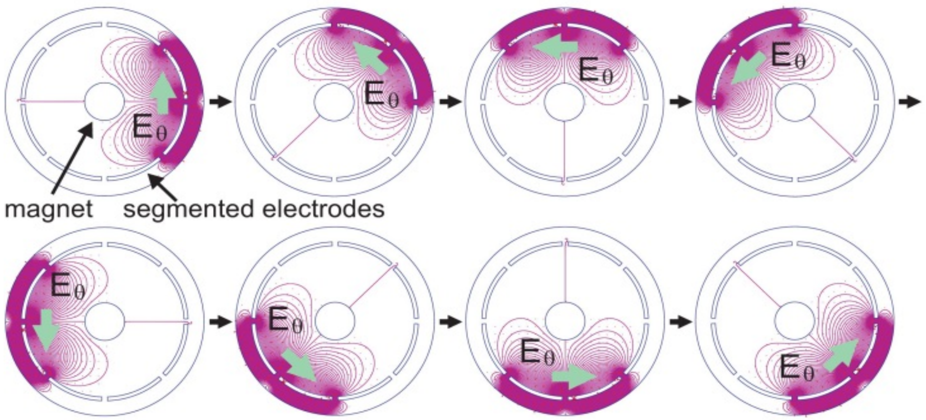


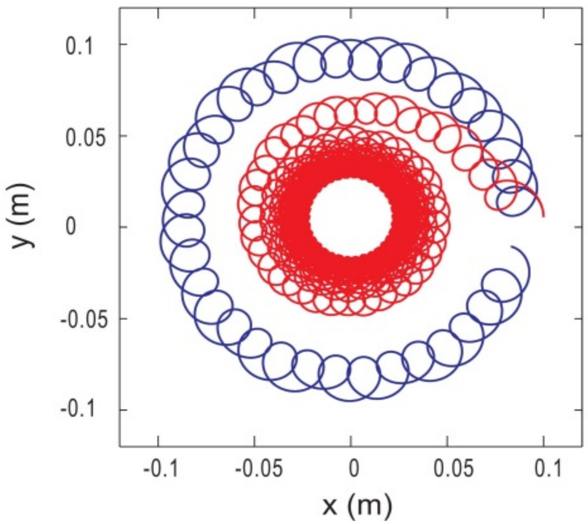
Levitation works here (LDX, MIT)



Compression techniques

- Applying rotating wall technique to dipole trap
- Simultaneous confinement of electrons and positrons
- Investigate alternative injection schemes using
    - *in-situ* remoderation of high-energy positrons
    - drift of positronium across closed magnetic field lines and subsequent laser-ionization
    - Radial inward transport due to plasma-generated inward pinch (re. LDX, Hasegawa)





Summary

Electron-positron plasmas have unique properties that ought to be studied experimentally

- Astrophysically relevant
- Have unique basic plasma properties
- Are particularly easy to analyze (by plasma standards) both theoretically and numerically

Experiments are coming online now

- First laser-produced, relativistic plasmas created, capable of electromagnetic “inner life”
  - Extremely short life (less than a picosecond), unconfined
- Plans for long-lived, confined, small-Debye length pair plasmas are progressing: This should allow tests of the startling predictions of a practical absence of instabilities