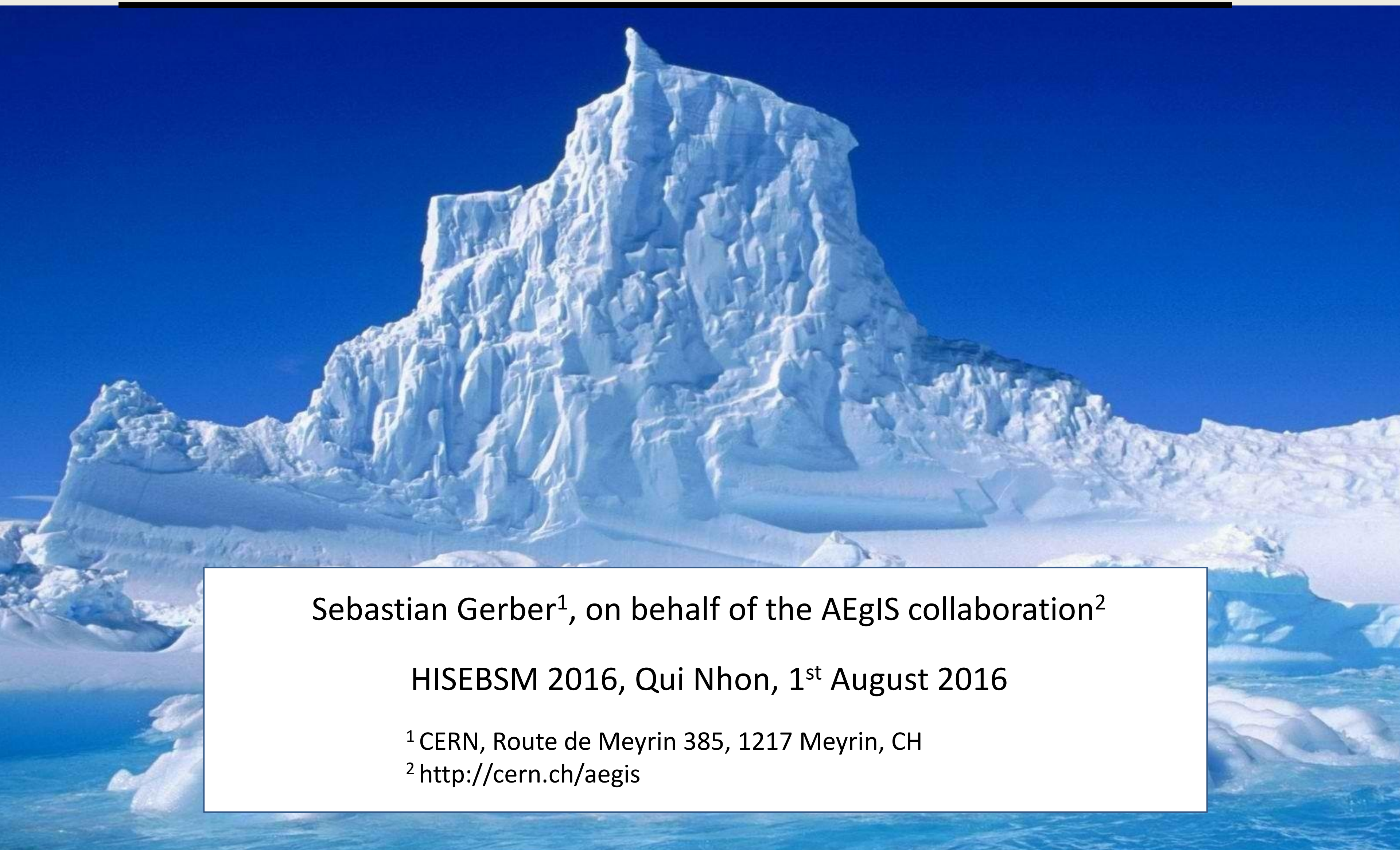
AEgIS – preparing for antihydrogen gravity measurements



Sebastian Gerber[1], on behalf of the AEgIS collaboration[2]

HISEBSM 2016, Qui Nhon, 1st August 2016

[1] CERN, Route de Meyrin 385, 1217 Meyrin, CH

[2] http://cern.ch/aegis

Collaboration

AEgIS

- Stefan Meyer Institute
- CERN
- Czech Technical University
- INFN sections of: Genova, Milano, Padova, Pavia, Trento
- University of Genova
- University of Milano
- University of Padova
- University of Pavia
- Institute of Nuclear Research of the Russian Academy of Science
- Max-Planck Institute Heidelberg
- Politecnico di Milano
- University College London
- University of Bergen
- University of Bern
- University of Brescia
- Heidelberg University
- University of Lyon 1
- University of Oslo
- University of Paris Sud
- University of Trento

Motivation

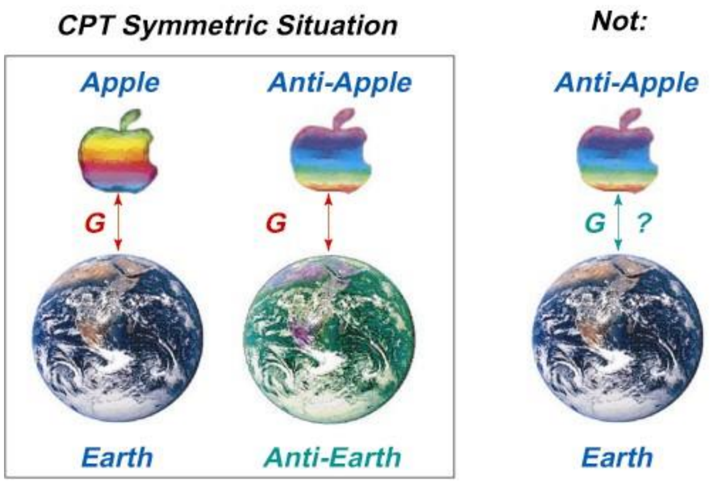
Currently <u>no experimental WEP test available for antimatter</u> with high precision

normal matter $\Delta g/g$: H. Mueller et al., *Nature*, **463**, 926 (2010)

normal matter WEP: S. Baessler et al., *Phys. Rev. Lett.*, **83**, 3583 (1999)

Three hypotheses of gravitational interaction of matter with antimatter:

- <u>normal gravity</u>, supported by EP
- <u>antigravity</u>
- <u>graviphoton/graviscalar</u> in quantum gravity theory, interaction with slightly different magnitude.
  Kaluza Metric: L. L. Williams, *J. of Gravity*, **6**, 901870 (2015)



→ Neutral antimatter ($\overline{H}$) suitable to reach high precision

Currently hampered by absence of directionally emitted or trapped production in sufficient quantity

→Physics goal of AEgIS: measurement of gravitational interaction between matter and antimatter, $\overline{H}$ spectroscopy,…

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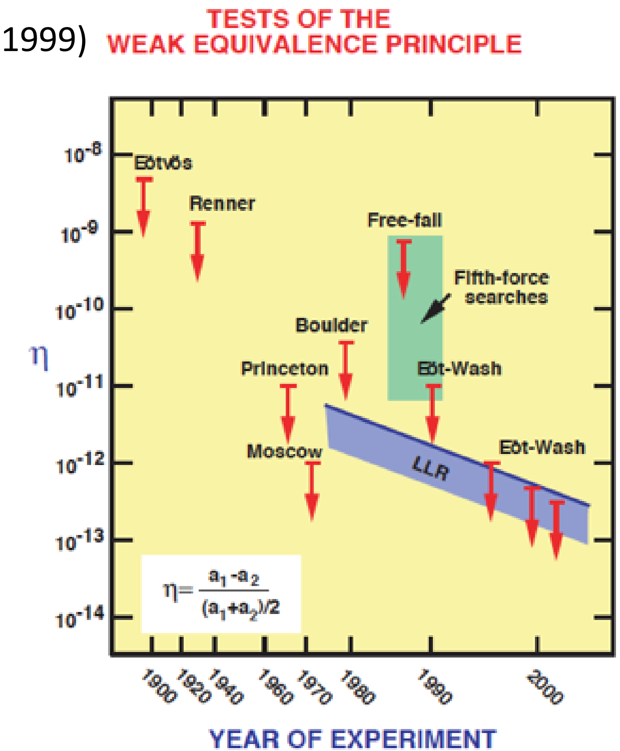

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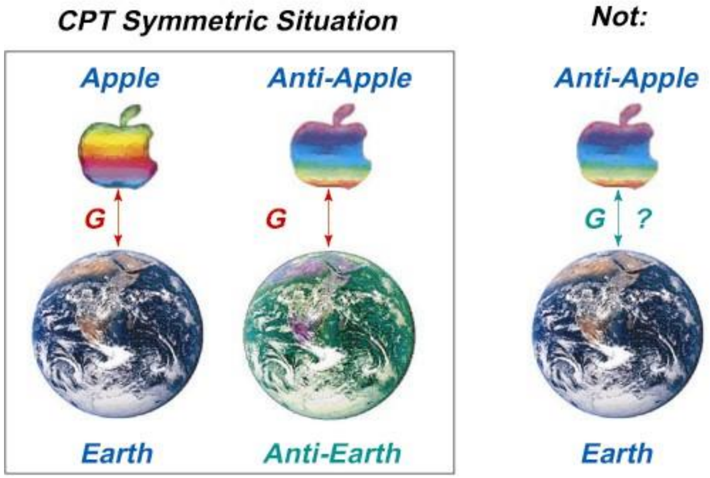

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Method

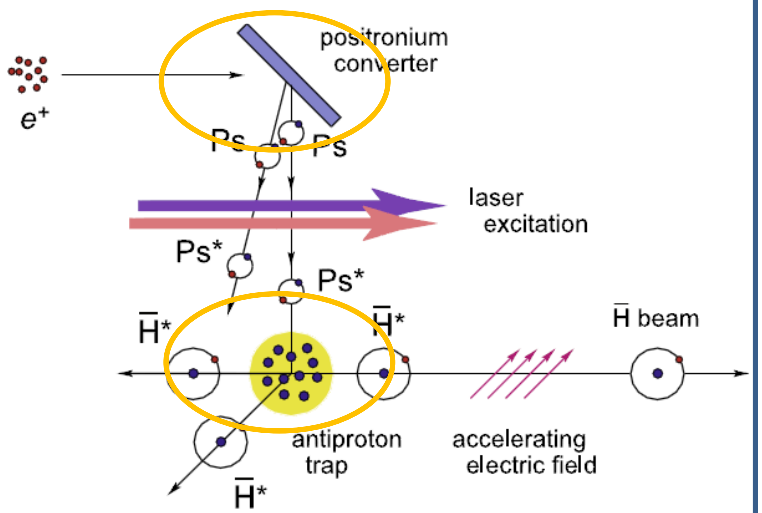
→ AEgIS proposal: *http://cdsweb.cern.ch/record/1037532*

$\bar{H}^*$ formation via resonant charge exchange with o-Ps*

Advantages:

- Pulsed $\bar{H}^*$ production (time of flight)
  laser-excitation to Ps*
- Colder production than via mixing process
  $T_{\bar{H}^*}$ defined by $T_{\bar{p}}$ + momentum of Ps*
- Narrower $\bar{H}^*$ n-state distribution $n_{\bar{H}^*} \approx n_{Ps^*}$
- Rate: $\sigma \sim a_0 {n_{Ps}}^4 {T_{Ps,\bar{p}}}^{-1}$, $N_{\bar{H}^*} \approx N_{Ps^*} \left(1 - e^{\sigma\rho L}\right)$

$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$



Kellerbauer, A., et. al. (2008). Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 266(3), 351–356.

→ How do we intend to measure g($\bar{H}$)?

Method

Route to WEP measurement using atomic physics techniques:

Split and recombine the atomic wave function in presence of gravity

A. Peters et al., *Nature,* **400**, 849 (1999)

$$\Delta\phi_g = kg\tau^2 = \frac{2\pi}{d} g\tau^2$$

Quantum interference if:

P. R. Berman et al., Academic, Chestnut Hill, 407 (1997)

$$d = \frac{2\pi}{k} \ll \sqrt{\lambda_{DB} L}$$

→ Very cold and collimated $\overline{H}$ atoms required

→ Initial g($\overline{H}$) measurements planned in classical limit: $L \ll \frac{d^2}{\lambda_{DB}}$

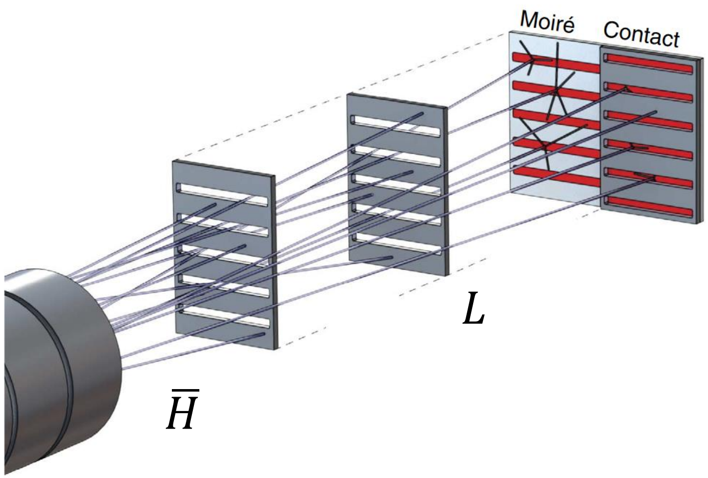
Method

→ AEgIS proposal: *http://cdsweb.cern.ch/record/1037532*

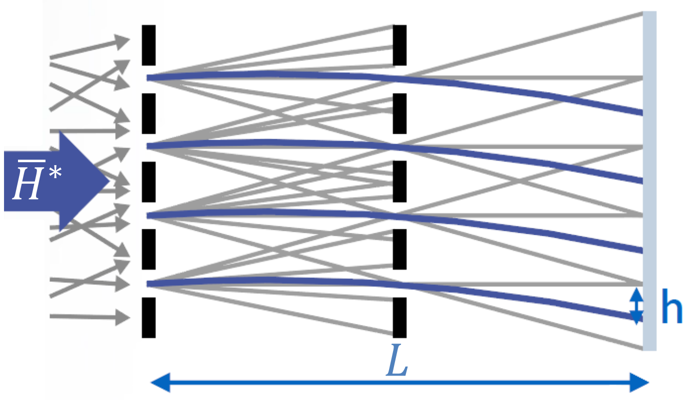
Measure g for $\overline{H}$ using gravitational deflection in two-grating Moiré deflectometer

- First direct measurement of g($\overline{H}$), without assumptions. Initial order of %
- Falling height: $h = g\tau^2 = \frac{g}{2}\left(\frac{L}{v_{\overline{H}^*}}\right)^2 , L \sim T_{\overline{H}^*}^{-1/2}$
- Requires velocity information of $\overline{H}$ and t_0
- Min. detectable acceleration: $a_{min} = \frac{d}{2\pi\, \vartheta\, \tau^2 \sqrt{N}}$
- tune a_{min} (Visibility ϑ, opening fraction, grating periodicity d, L, $T_{\overline{H}^*}$, N...)
- Requires high detector resolution

S. Aghion et al., *Nat. Commun.* **5**, 4538 (2014)



M. Oberthaler et al., *Phys. Rev. A,* **54**, 3165 (1996)



AD, Experiment

1. Antiproton production

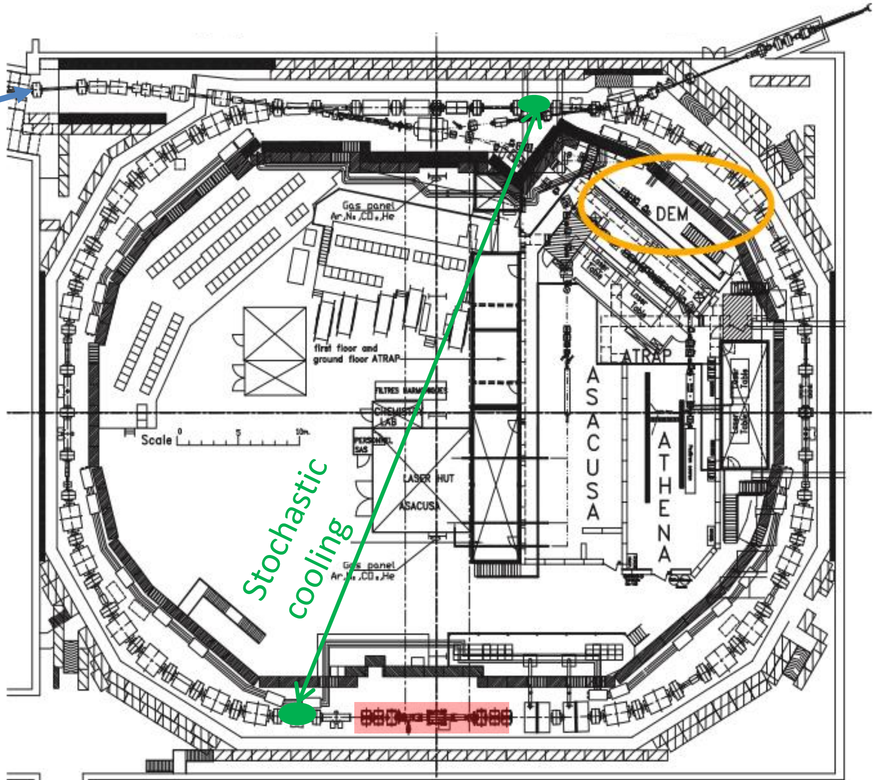
$$p(26\ GeV/c) + p_{\mathrm{Ir-target}} \rightarrow p + p + p + \bar{p}$$

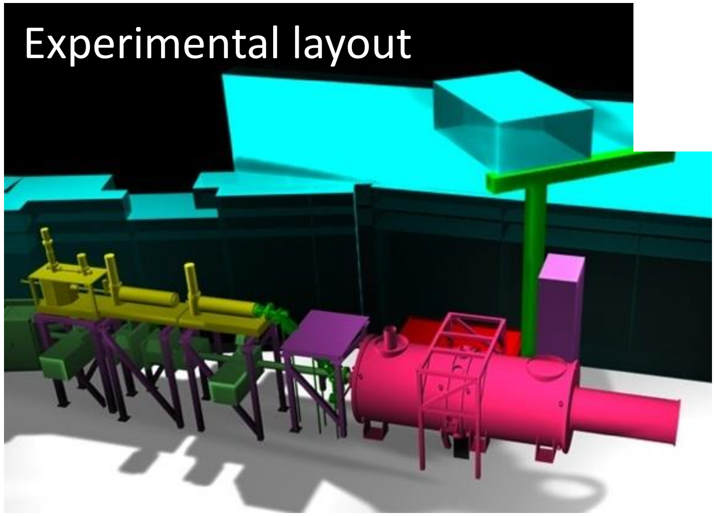
2. $\bar{p}$ cooling energy cascade:

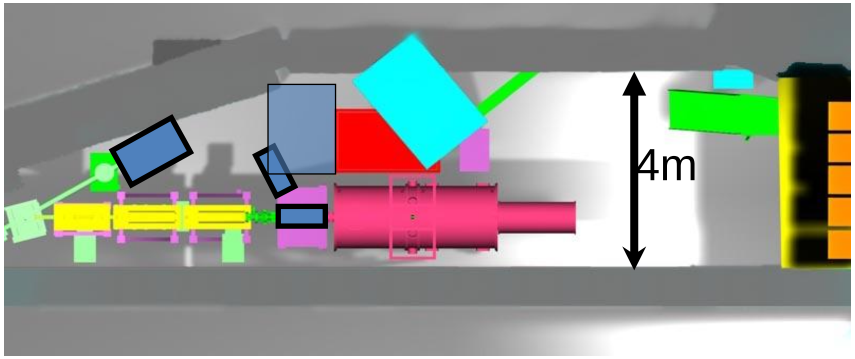
Target: 3.5 GeV/c → AD cooling: 100 MeV/c
→ AD cooling: 5.3 MeV/c

3. AD extraction (~2x10^{7} in 200 ns)

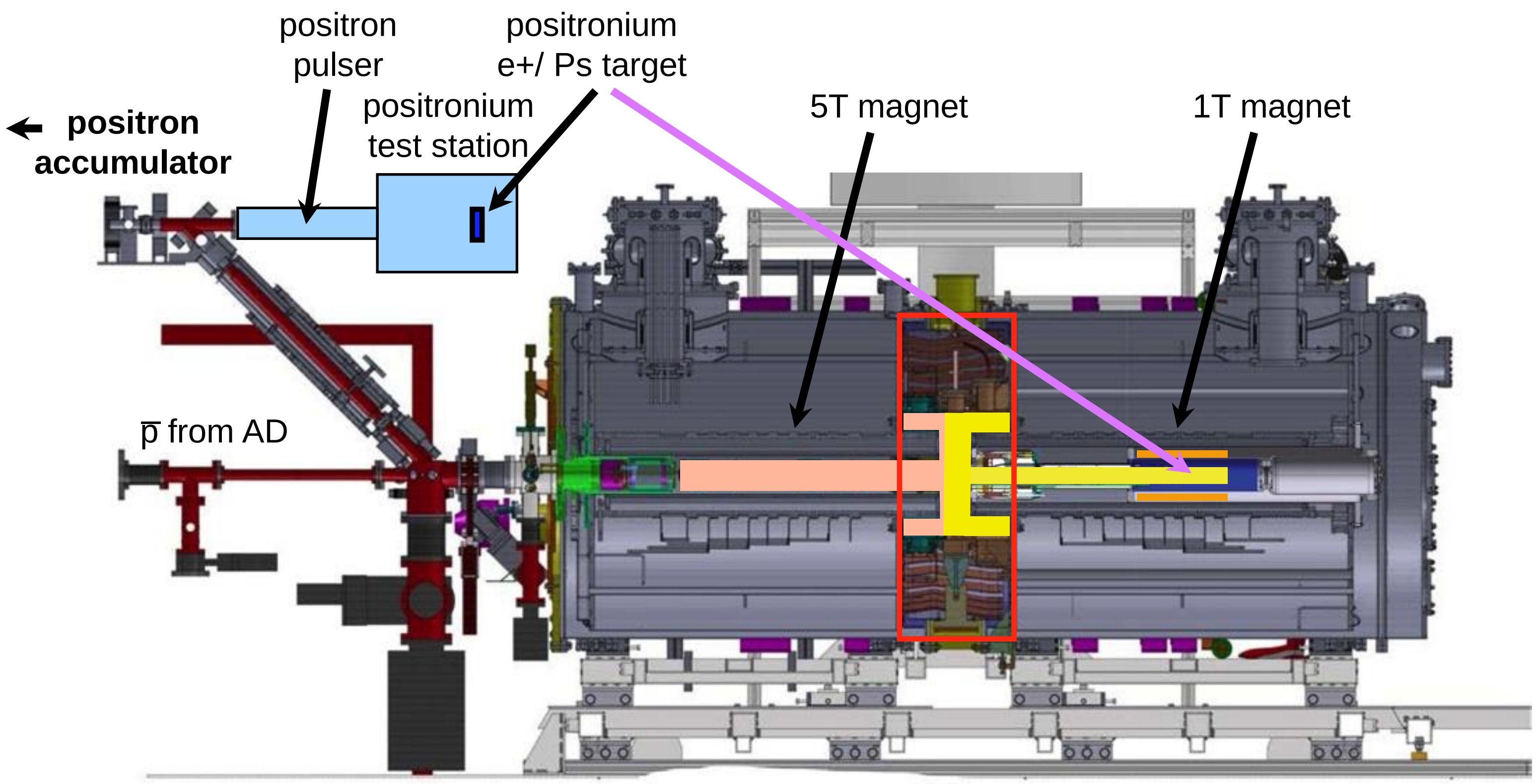
→ Degrader: 9 keV → Trapping
→ e^- cooling in Penning Trap: 30 K (2.5 meV)







The central Apparatus



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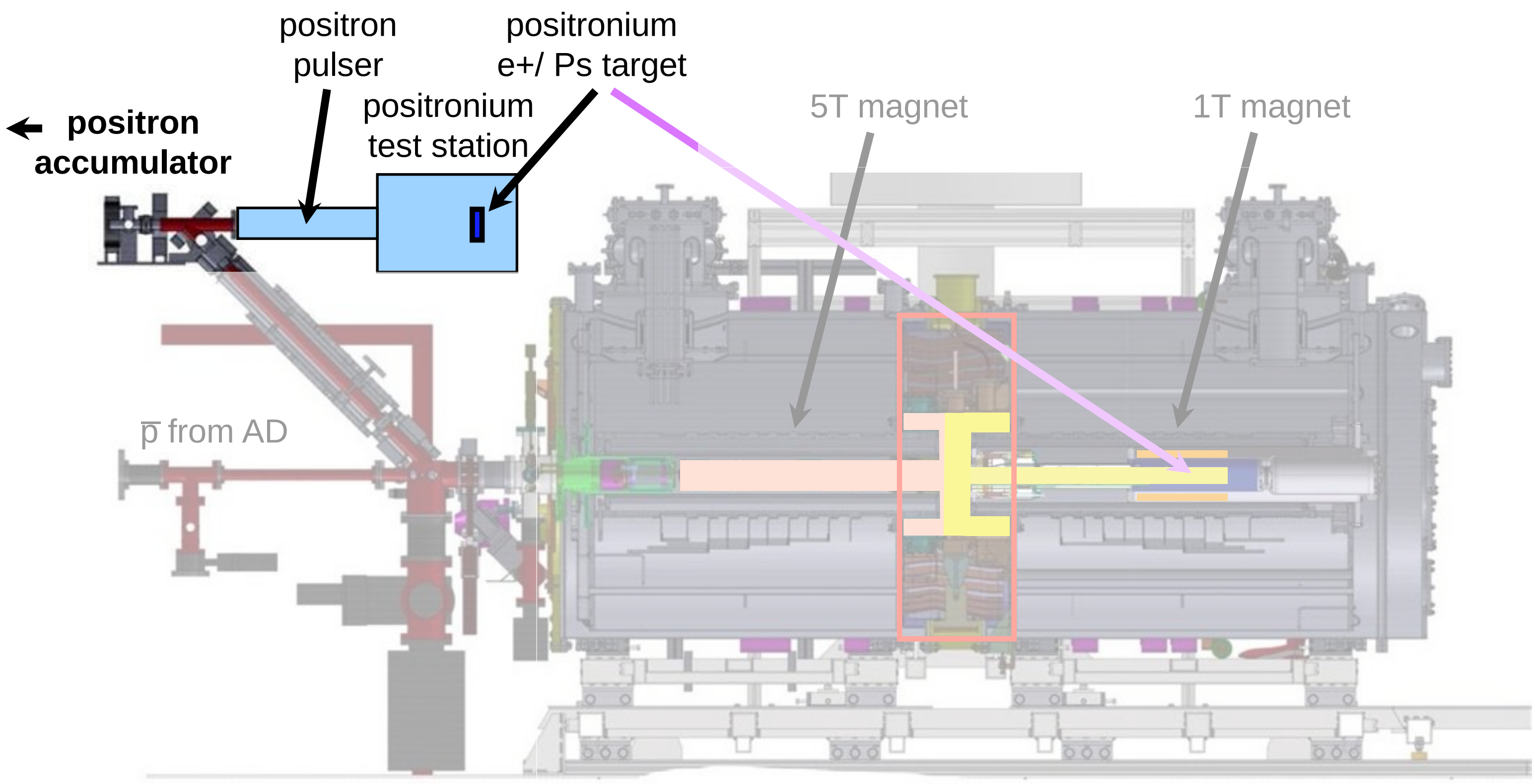
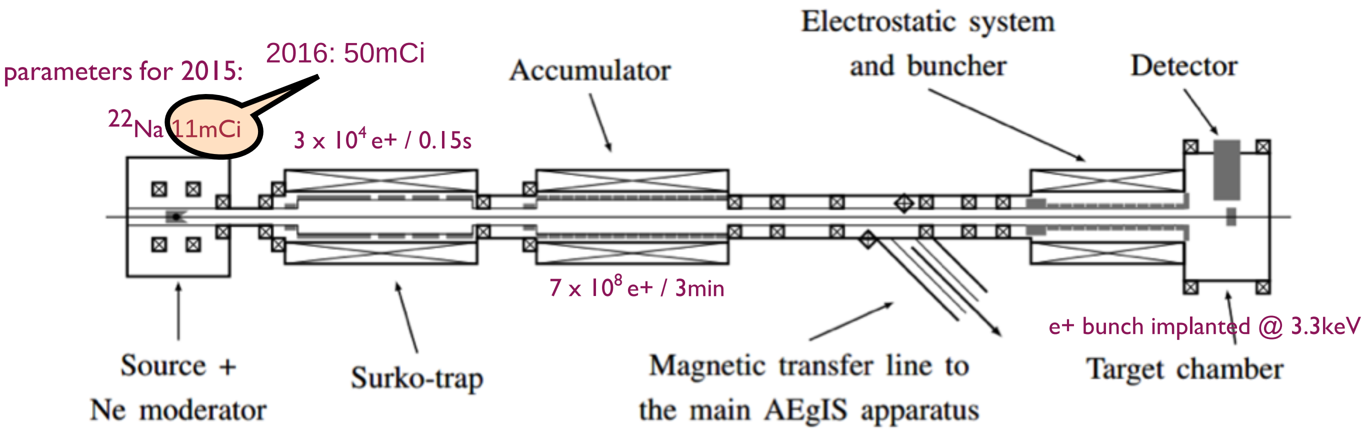
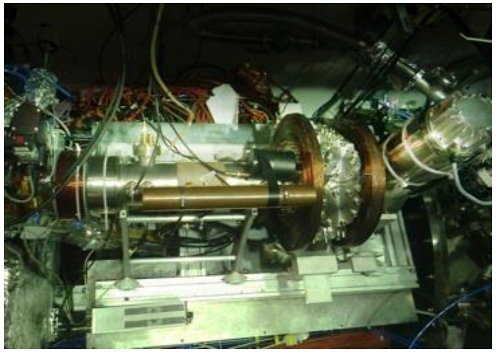
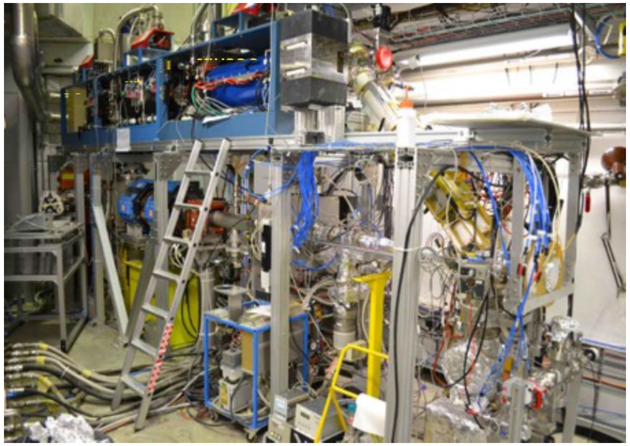


Study of Ps formation

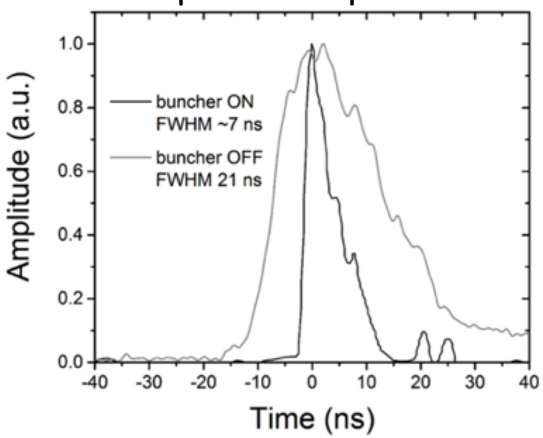
The e⁺ beam line:



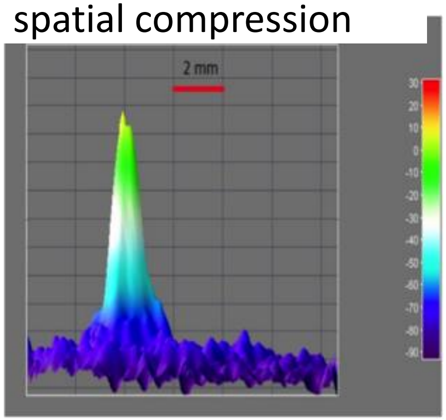




temporal compression



spatial compression



position

S. Mariazzi et al., *Phys. Rev. B* **81**, 235418 (2010)

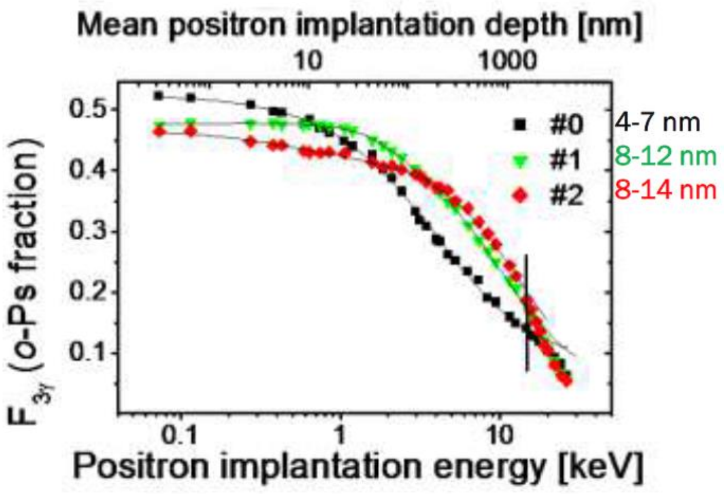
Study of Ps formation

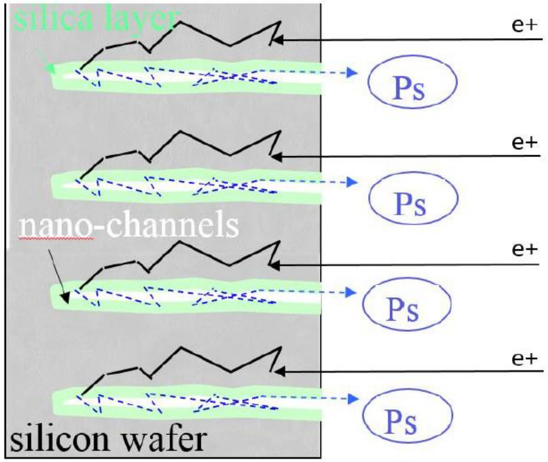
AEgIS

e⁺ implantation in nano-porous silica (8-15 nm)

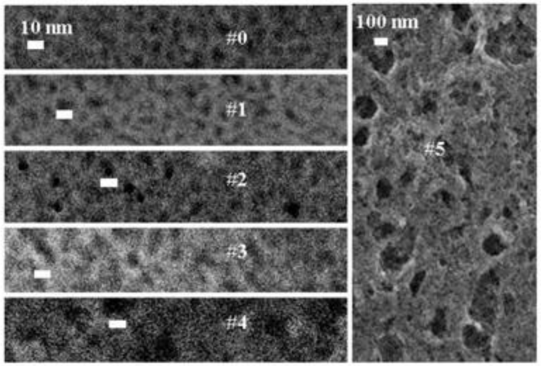
- ~75 K o-Ps required (for Ps to reach $\bar{p}$ plasma)
- Tune of nano-channels to change Ps temperature
- Possible production of Ps in reflection and transmission

S. L. Andersen et al., *Eur. Phys. J. D*, **68**, 124 (2014)



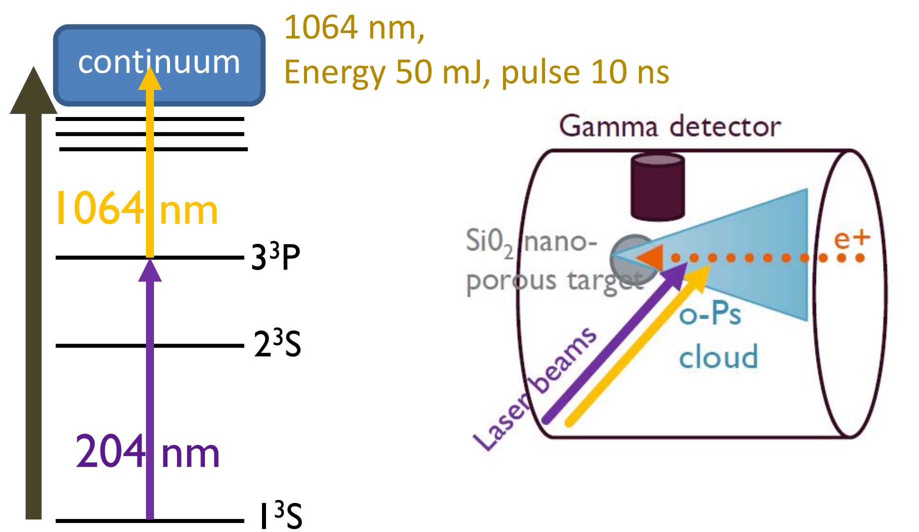


Silica-based nano-porous target (SEM image)



S. Mariazzi et al., *Phys. Rev. B* **78**, 085428 (2008)

Ps laser excitation



Energy 54 μJ, pulse 1.5 ns,
waist 6 mm x 8 mm,
σ ~ 110 GHz

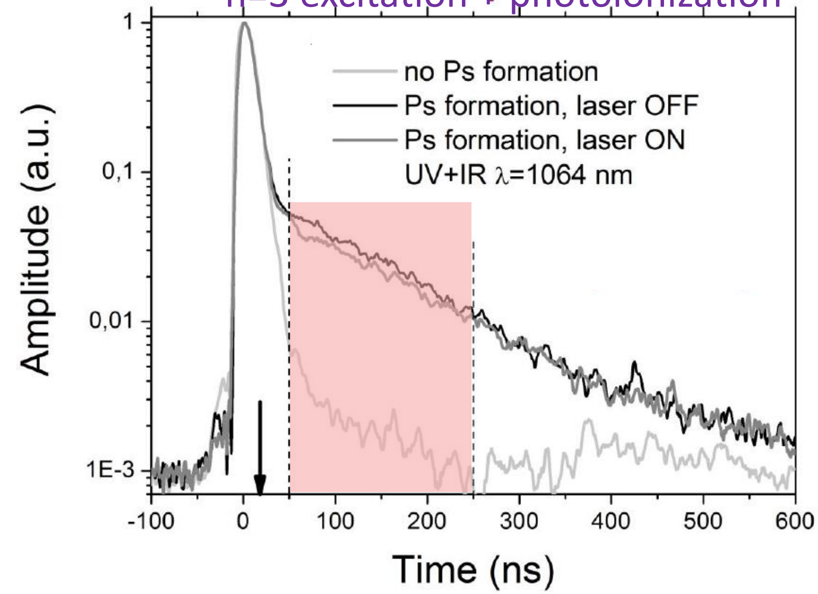
Experimental conditions:
B= 250 G
E= 600 V/cm

SSPALS spectroscopy:
D. B. Cassidy et al., *Appl. Phys. Lett.*, **88**, 194105 (2006)

- expect *decrease* of o-Ps population on resonance
  ➔ *decrease* in (delayed) annihilation rate
- Excitation + photoionization efficiency ~ 15 %
  (limited by laser linewidth)
  o-Ps Doppler broadened profile T ~ 1300 K

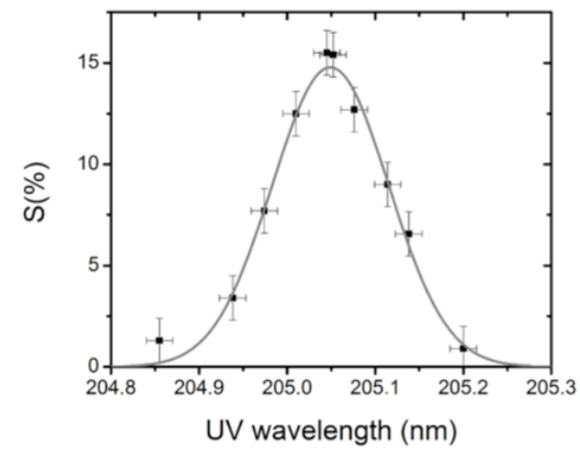
S. Aghion et al., Phys. Rev. A, in print (2016)

n=3 excitation + photoionization

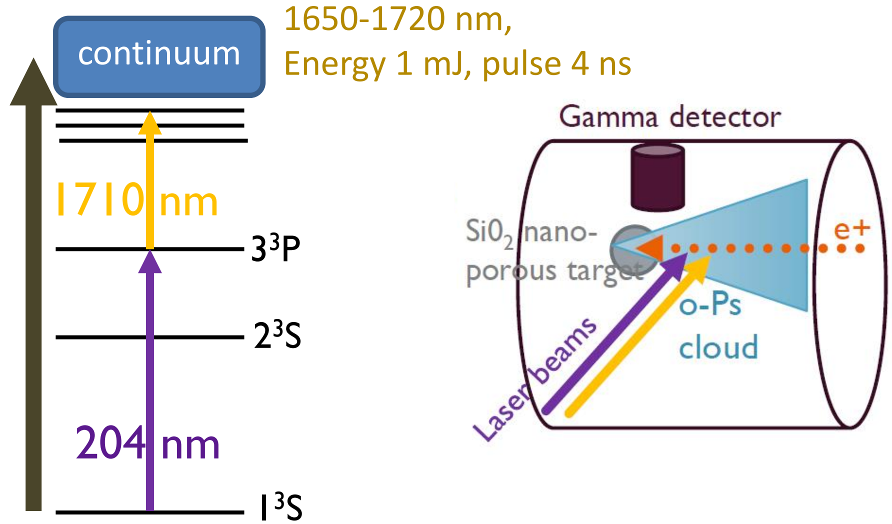


$$S(\%)=\frac{(\text{Area laser OFF}-\text{Area laser ON})}{\text{Area laser OFF}}$$

3P excitation line center at **205.05+-0.02 nm**



Ps laser excitation



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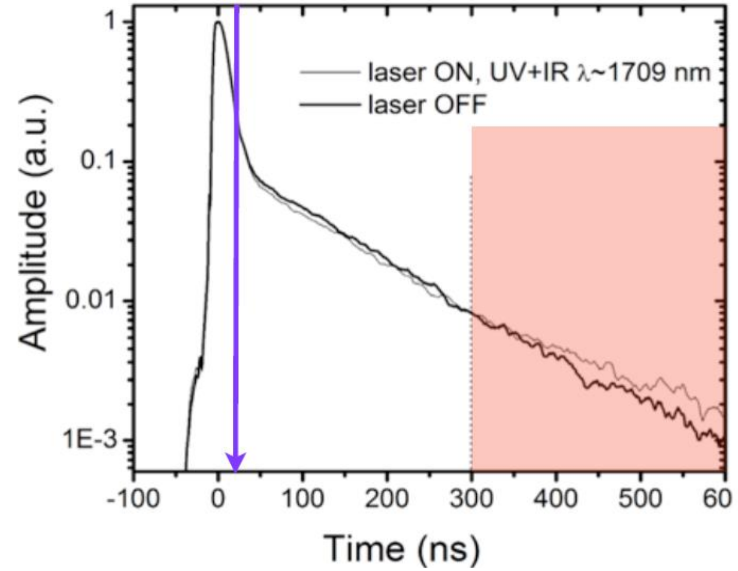
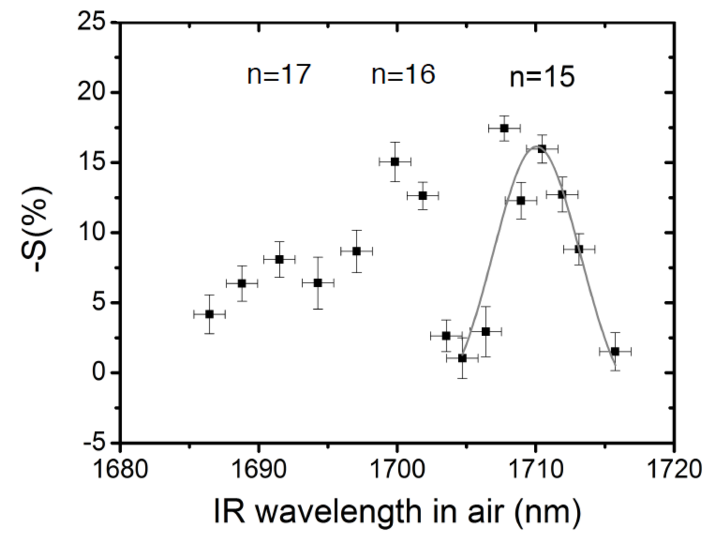
n=3 excitation + Rydberg excitation



alternating UV+IR on/off and scanning over IR:

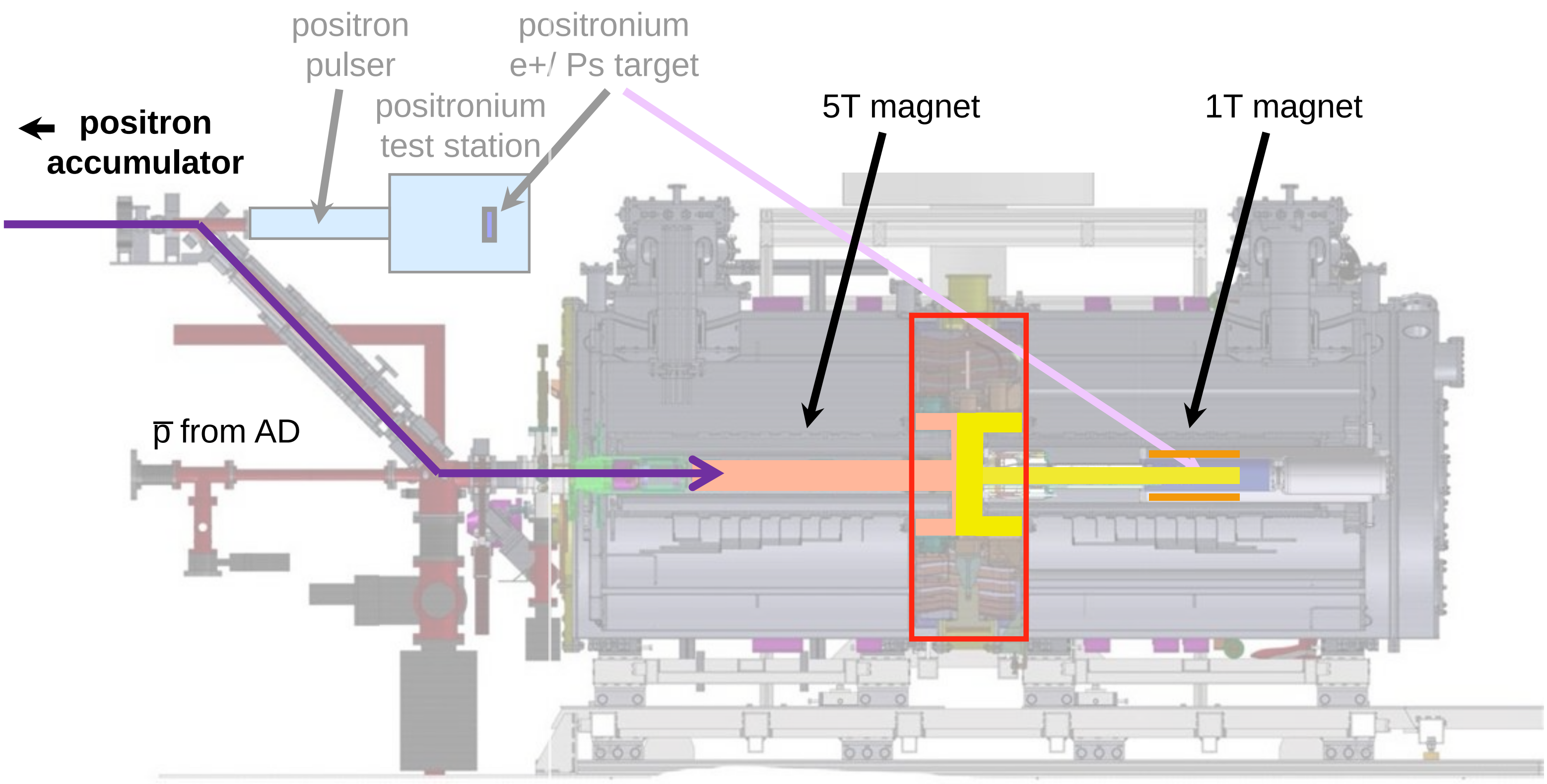


- expect *decrease* of o-Ps population on resonance and appearance of long-lived o-Ps*

  ➔ *increase* in (very delayed) annihilation rate

S. Aghion et al., Phys. Rev. A, in print (2016)

Positron transfer

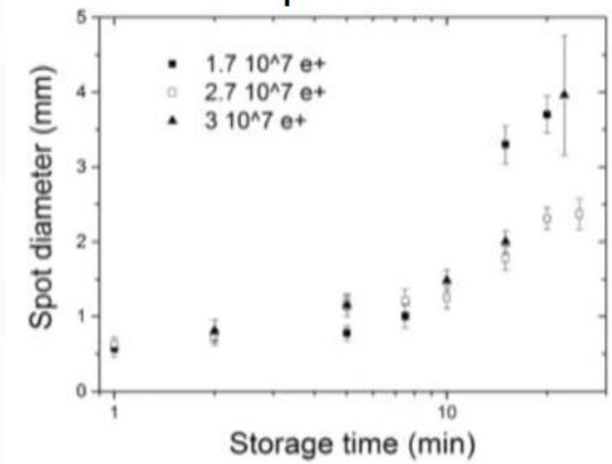


Positron transfer to Penning trap

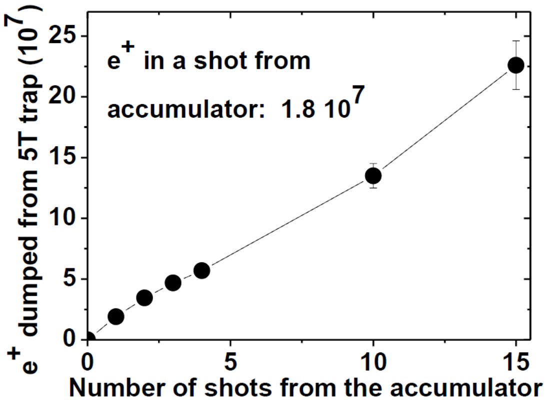
AEgIS

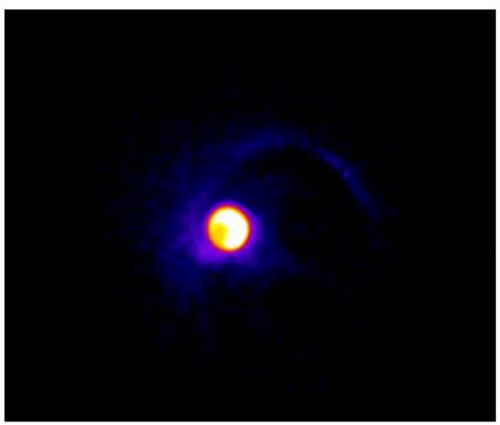
- Transfer, catching and cooling almost lossless: ε > 95%
- Storage times adequate, good control with RW, no losses

Radial expansion in 5T

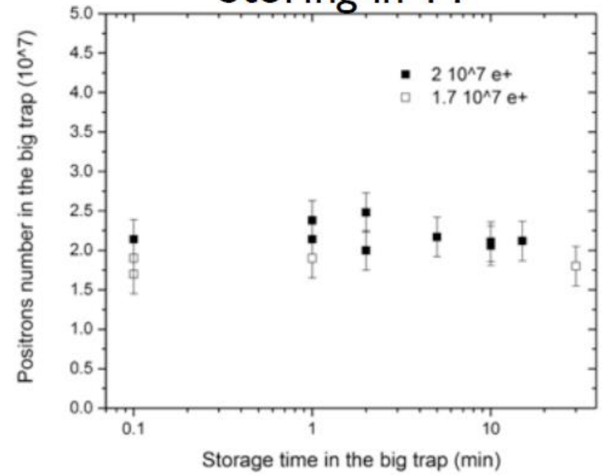


Stacking in 5T





Storing in 1T

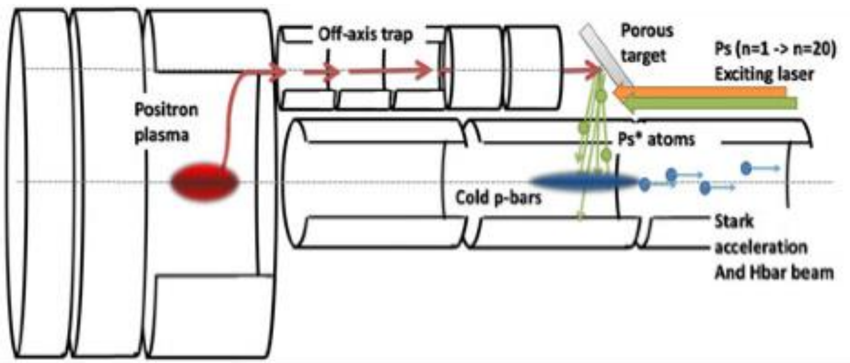


Positron transfer to Penning trap

AEgIS

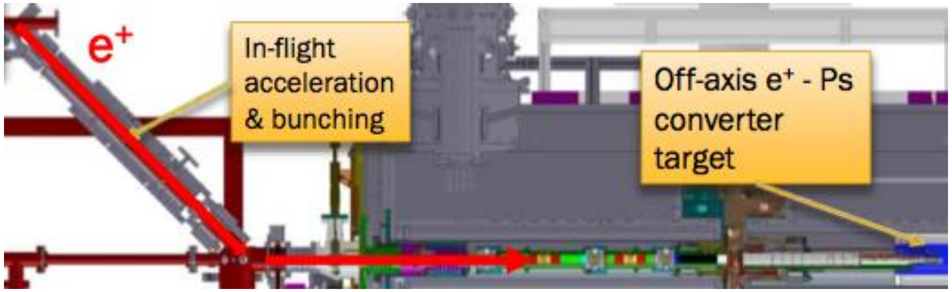
Current scheme:

- Diocotron excitation of e^+
- Acceleration to ~2 keV in off-axis trap

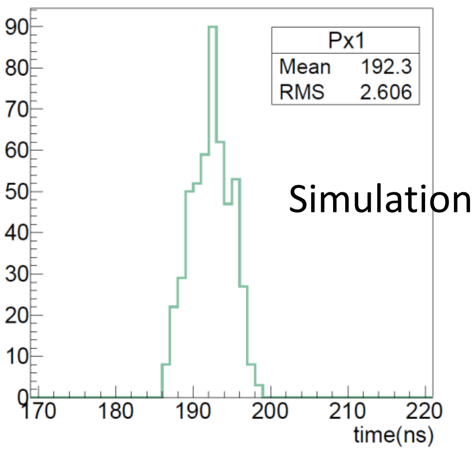


Direct injection:

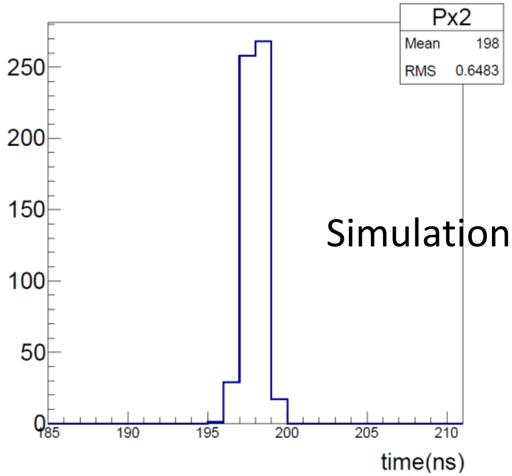
- In-flight acceleration to ~2 keV
- e^+ follow B field lines into trap



→ **Individually, all required Ps technologies are present for $\bar{\mathrm{H}}$ production**

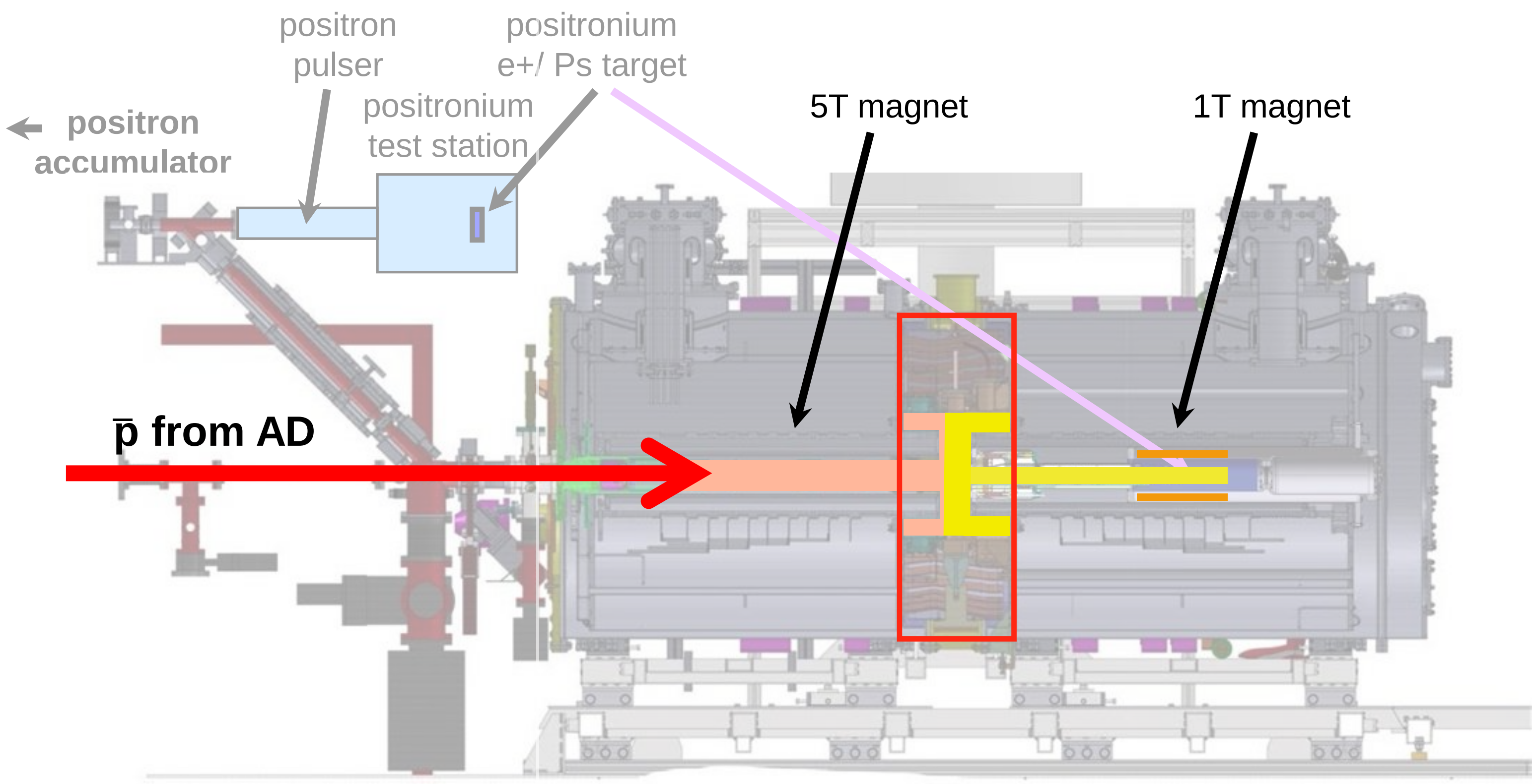


kicker/elevator tube (installed)

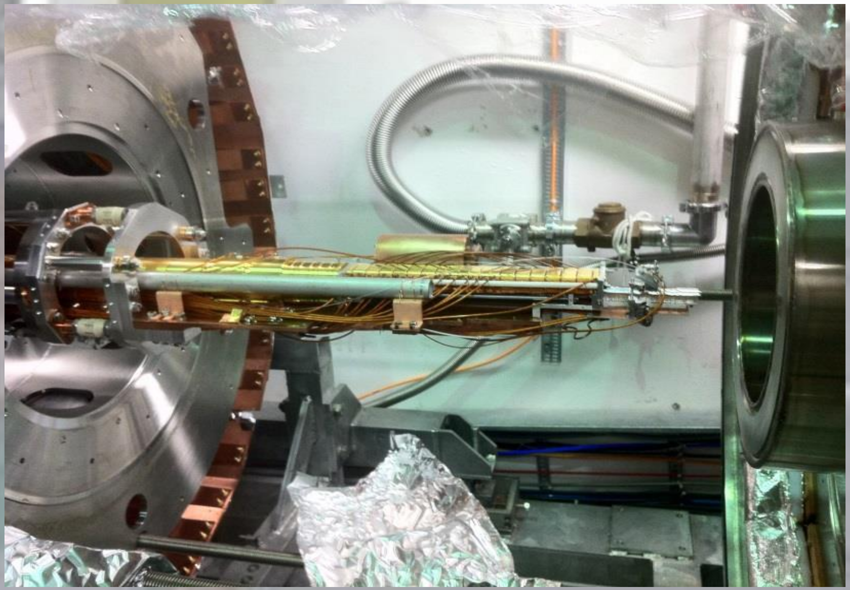


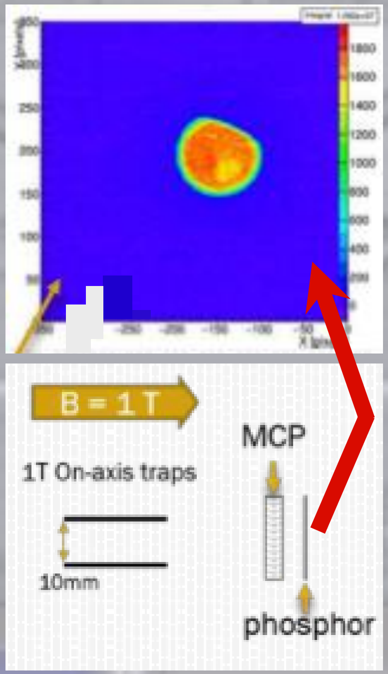
parabolic buncher (designed)

Antiprotons catching and cooling



Antiprotons in Penning trap and MCP

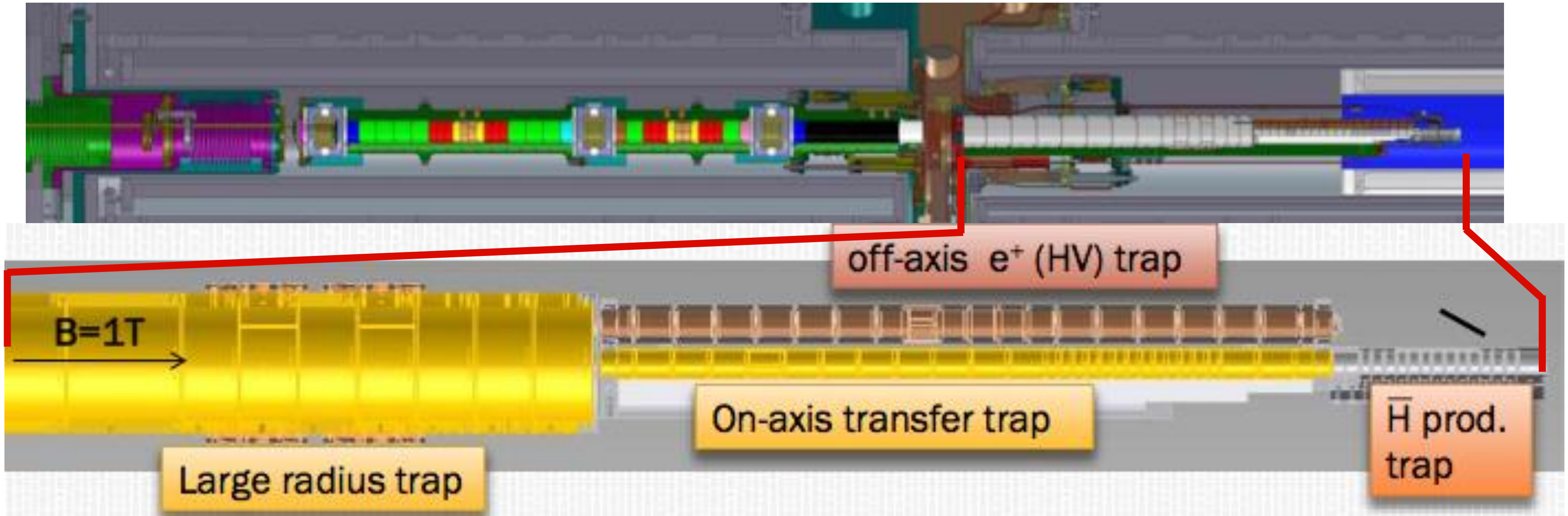




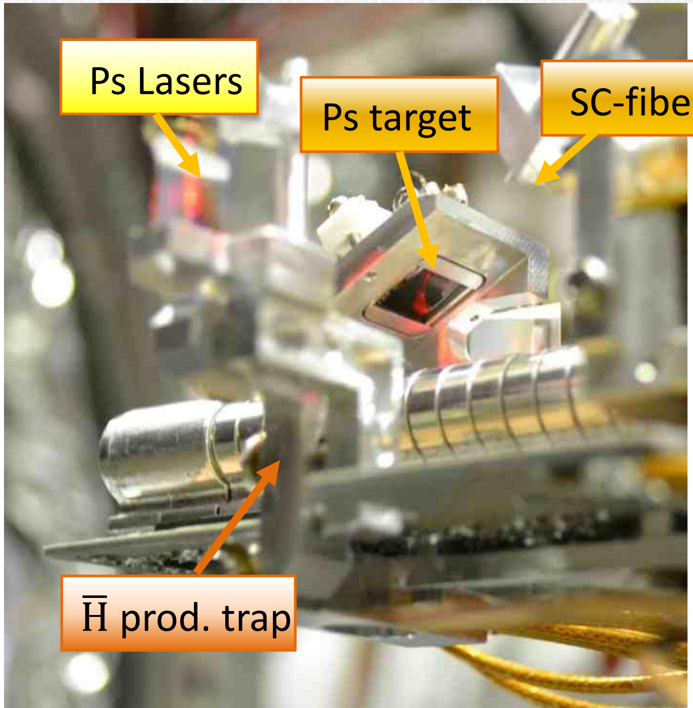
CCD read-out of 2-stage MCP @ 55K in 1T

$\overline{p}$ (and e$^-$) in the Penning trap

AEgIS

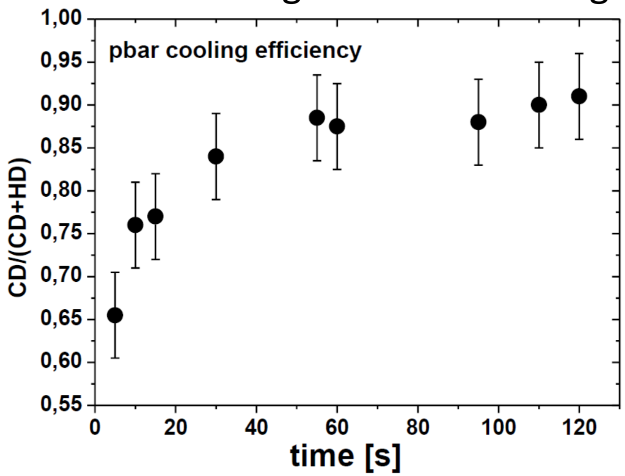


- Large radius trap
  r=40 mm
  RW compression and transfer
- Off-axis trap
  e$^+$ acceleration to Ps target
- $\overline{\mathrm{H}}$ production trap:
  r=5 mm
  RW compression
  Ps target 15 mm away

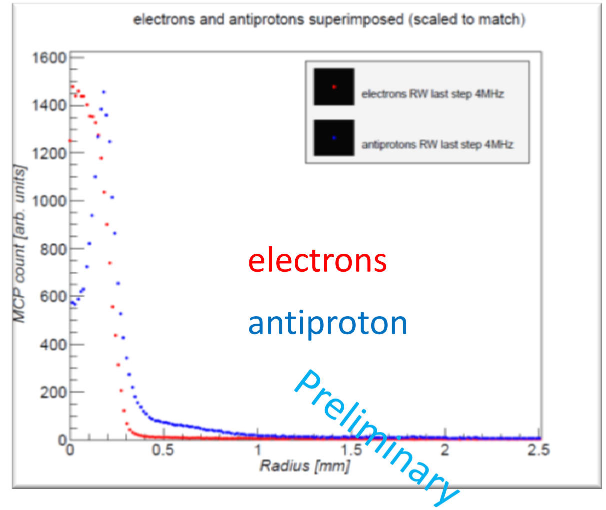


$\bar{p}$ (and e^-) in the Penning trap

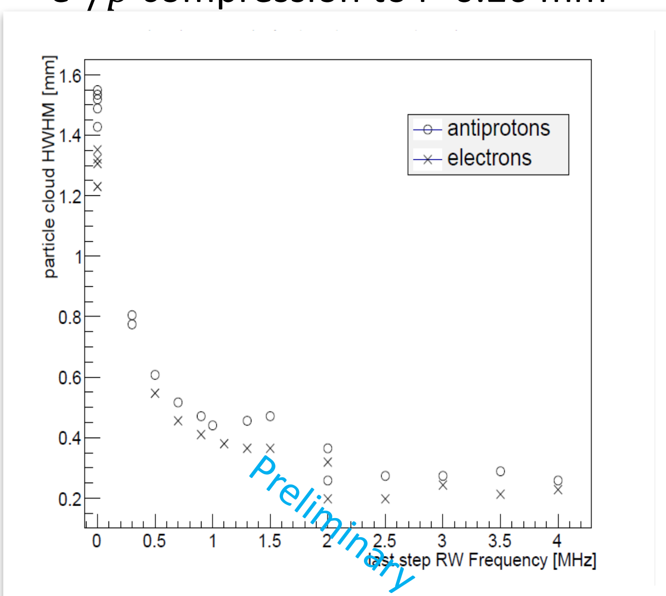
Initial electron cooling after AD catching:



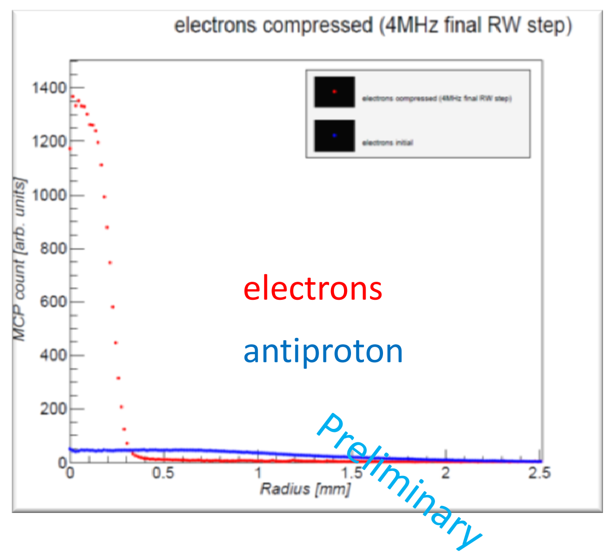
$e^-/\bar{p}$ rotating wall, dipole field (scaled to match):



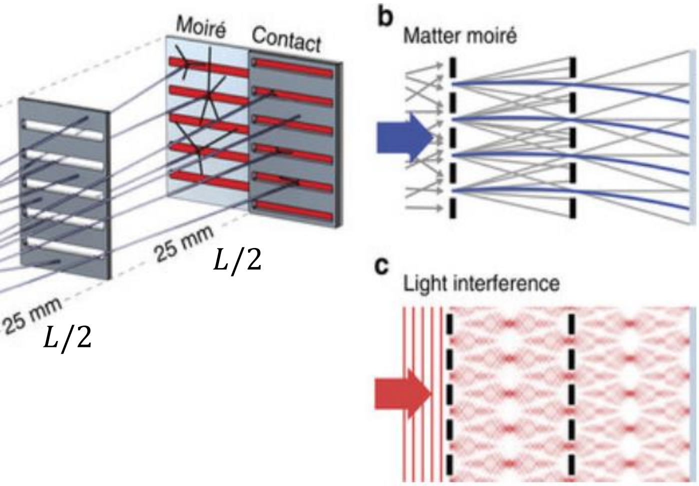
$e^-/\bar{p}$ compression to r=0.26 mm



$e^-/\bar{p}$ rotating wall, dipole field:

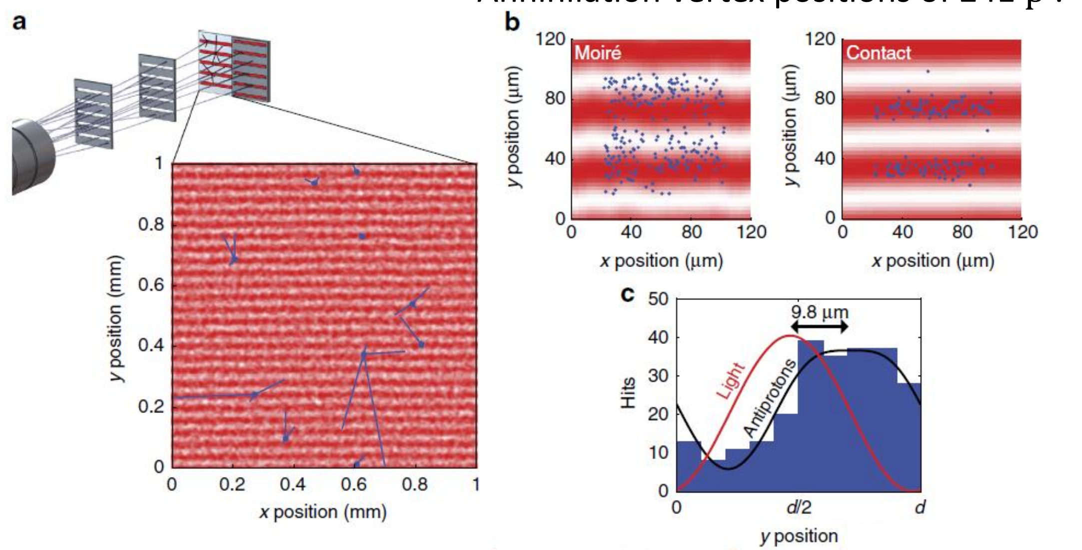


Proof of principle with $\bar{p}$...



…Moiré deflectometer to measure deflection of $\bar{p}$ beam (~100 keV)

Annihilation vertex positions of 241 $\bar{p}$:

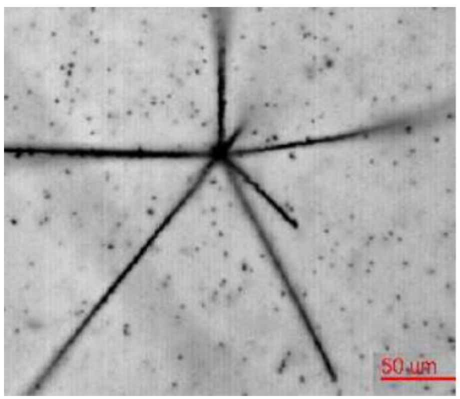


Shift between light and $\bar{p}$: $\Delta y = 9.6 \pm 0.9$ (stat.) ± 6.4 (syst.) µm

Visibility of 71%; mean force of ~530 aN

(Compatible with a Lorentz force from 1 mT or 30 V/cm)

S. Aghion et al., *Nat. Commun*. **5**, 4538 (2014)

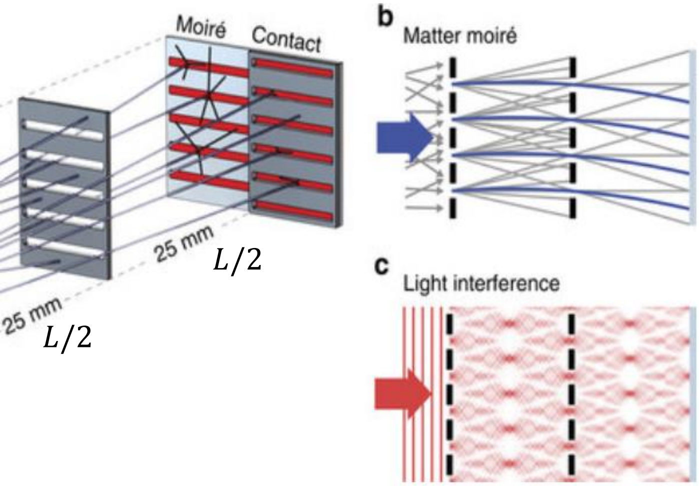


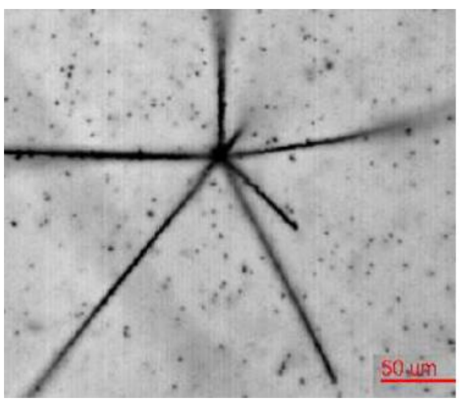
Emulsion detector ~2 µm resolution

P. Scampoli et al., J. Instr., **9,** C01061(2014)

Crucial step towards the direct detection of the gravitational acceleration of antihydrogen with the AEgIS experiment $\Delta z = g\, t^2$

Proof of principle with $\bar{p}$...



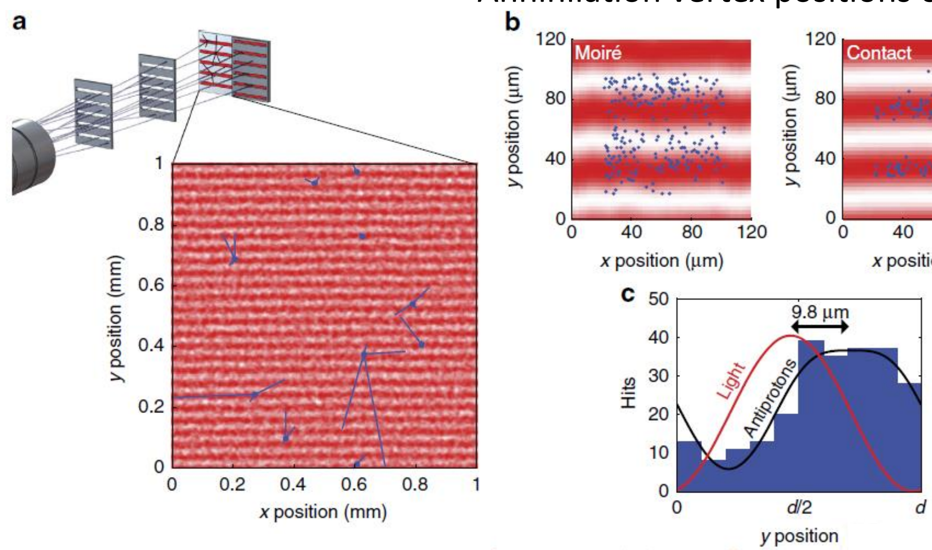


Emulsion detector ~2 µm resolution

P. Scampoli et al., J. Instr., **9,** C01061(2014)

...Moiré deflectometer to measure deflection of $\bar{p}$ beam (~100 keV)

Annihilation vertex positions of 241 $\bar{p}$:



Shift between light and $\bar{p}$: $\Delta y = 9.6 \pm 0.9$ (stat.) ± 6.4 (syst.) µm

Visibility of 71%; mean force of ~530 aN

(Compatible with a Lorentz force from 1 mT or 30 V/cm)

S. Aghion et al., *Nat. Commun*. **5**, 4538 (2014)

→ To measure g: High and <u>cold</u> flux of $\bar{H}$ is needed

$\bar{\mathrm{H}}$ beam - Antiproton cooling

AEgIS

Cold $\bar{\mathrm{p}}$ maximize flux of $\bar{\mathrm{H}}$: $T_{\bar{H}^*}$ defined by $T_{\bar{p}}$ + momentum of Ps* ; higher $\bar{\mathrm{H}}$ rate via $\sigma \sim a_0 n_{Ps}{}^4 T_{Ps,\bar{p}}{}^{-1}$;
shorter deflectometer via $L \sim T_{\bar{H}^*}^{-1/2}$

Goal/Scenario for $\bar{\mathrm{H}}$ beam $T_{\bar{H}^*} \sim 100\ \mathrm{mK}$:

<u>axial</u>: with $T_{\bar{p}} \sim 10\ \mathrm{mK}$ limited by 100 K Ps momentum transfer to 100 mK $\bar{\mathrm{H}}$

<u>radial</u>: 10 mK ($n_{\bar{\mathrm{p}}}$=10^6 cm^{-3} $f_{\mathrm{ExB}} = \frac{q n_{\bar{\mathrm{p}}}}{4\pi\epsilon_0 B(1T)}$ =1.4 MHz , $v = f_{\mathrm{ExB}} r$, r →~0.1 mm)

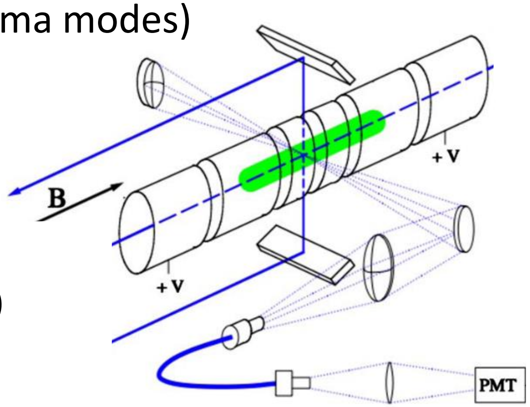
$\bar{p}$ cooling mechanism:

- Sympathetic radiation electron cooling. (Limit ~30 K with trap temperature ~ 10 K)
- Evaporative / adiabatic cooling (limited by $\bar{\mathrm{p}}$ numbers and axial confinement)
- Resistive cooling (proven for single ions, difficult on low-Q plasma modes)
- Sympathetic laser cooling with anions :

Os^- spectroscopy: *U. Warring et al., Phys. Rev. Lett.* ***102*** *043001 (2009)*

La^- spectroscopy: *E. Jordan et al., Phys. Rev. Lett.* ***115*** *113001 (2015)*

C_2^- proposal: *P. Yzombard et al., Phys. Rev. Lett.* ***114*** *213001 (2015)*

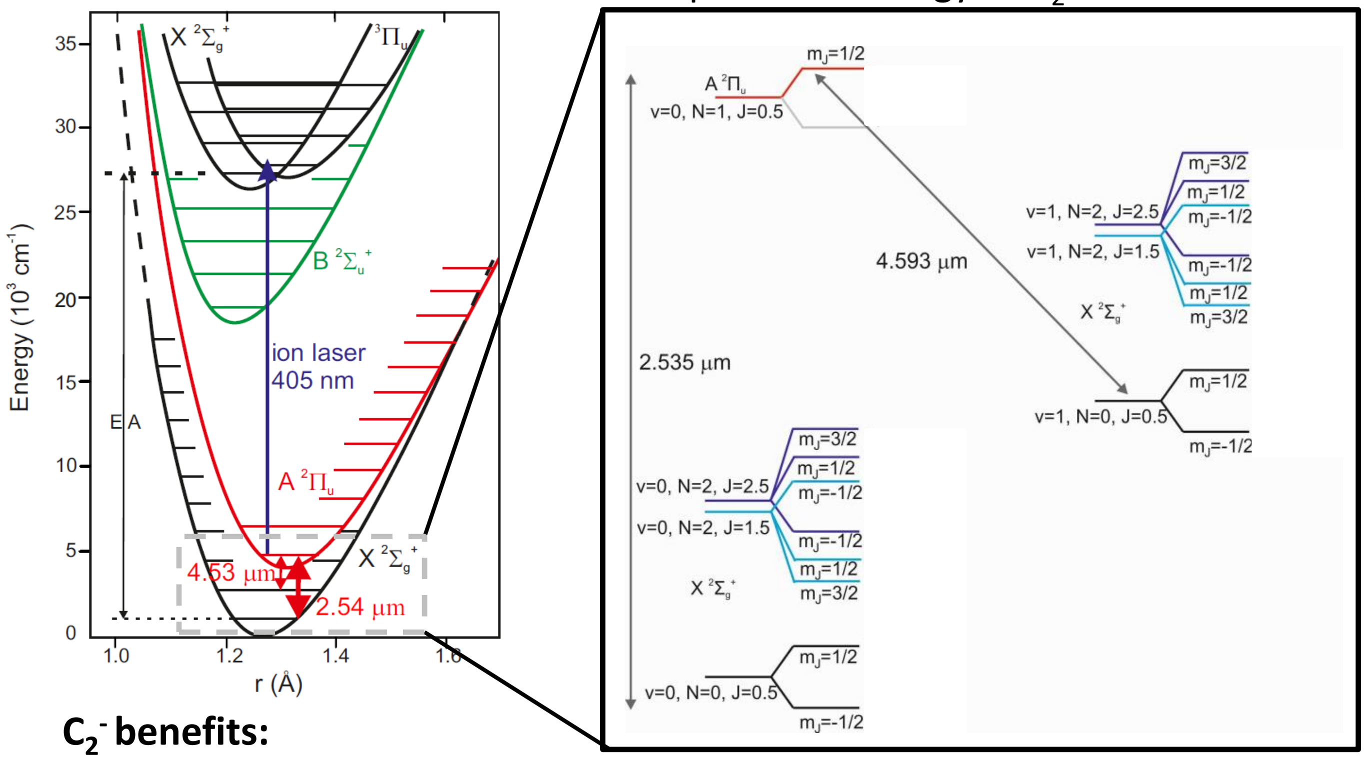


Laser cooling in Penning trap

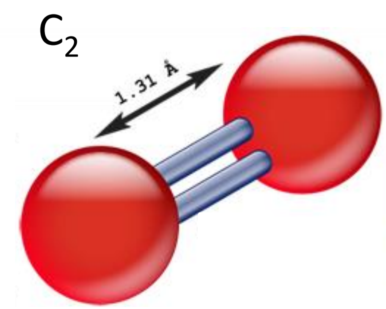
Picture: D. Dubin, O'Neil, http://sdpha2.ucsd.edu/

Molecule C_2^-

Ro-Vib level structure and molecular potential energy of C_2^- in B=5 T :



Homonuclear molecule



C_2^- benefits:

- Completely known level scheme to ν/dν ~100 MHz M. Tulej et al., *J. Raman Spectrosc.*, **41,** 853 (2010), ….
- 2.54 μm and 4.53 μm dipole transition recently accessible with DFB diode lasers
- Easy production in supersonic gas expansion, ~10 meV internal ground-state occupation

For NH_2^-: K. Luria et al., *Rev. Sci. Instrum.*, **80,** 104102 (2009)

C_2^- challenges:

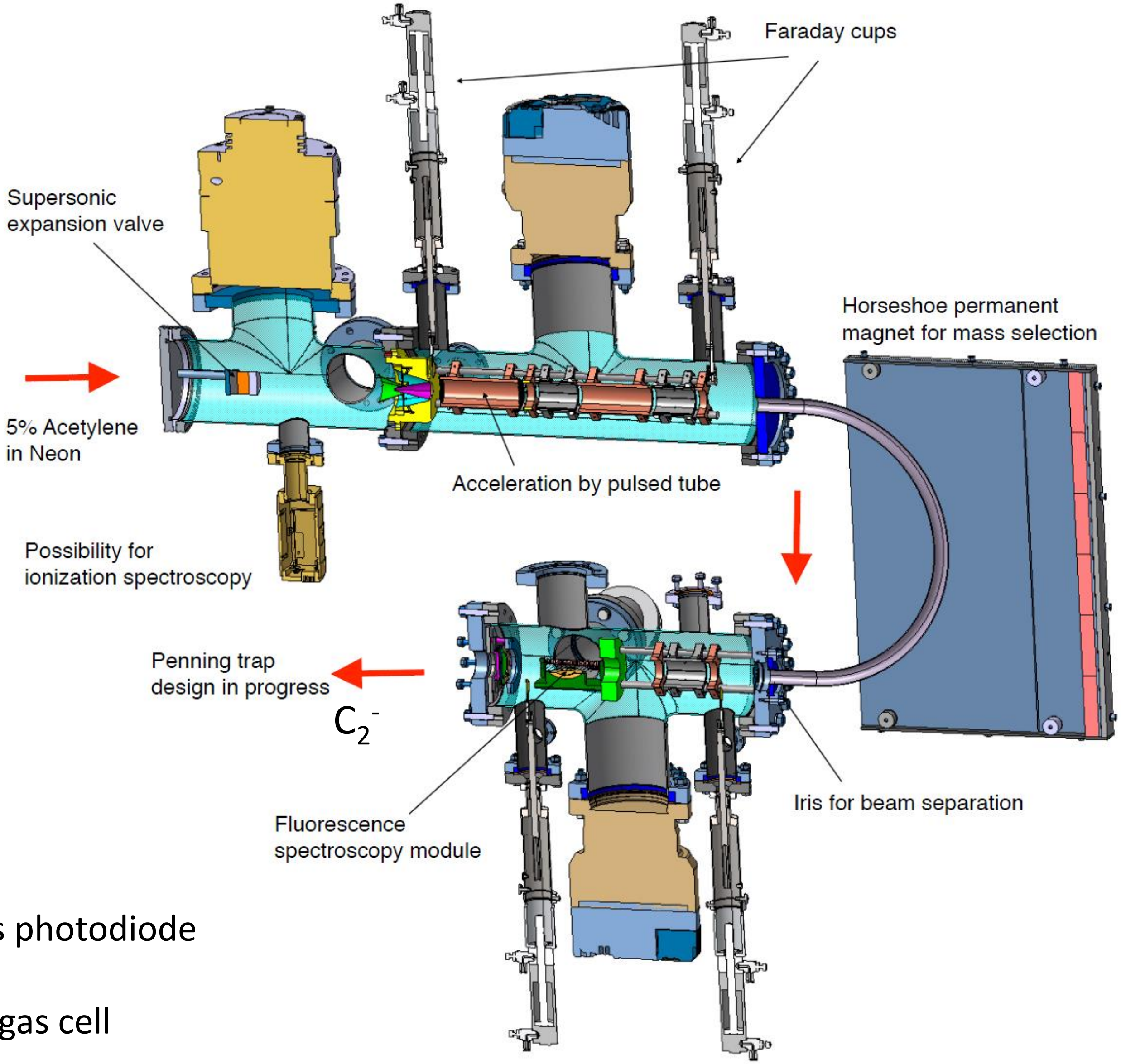
- 16 transitions (8 lasers + sidebands) for closed laser cycle with Zeeman splitting
- 20 kHz linewidth (similar to Os^-, La^-)

C_2^- production and beam

AEgIS

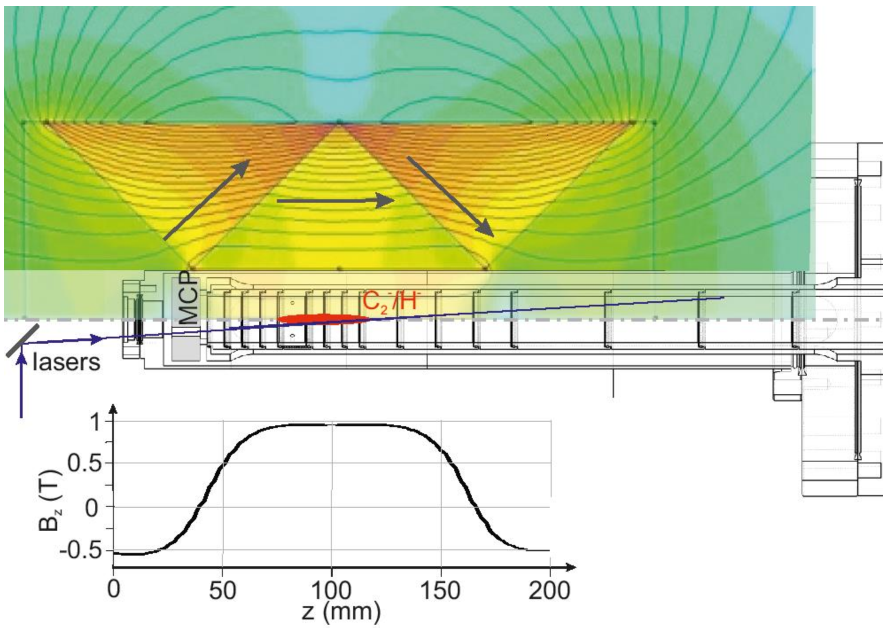
Specifications:

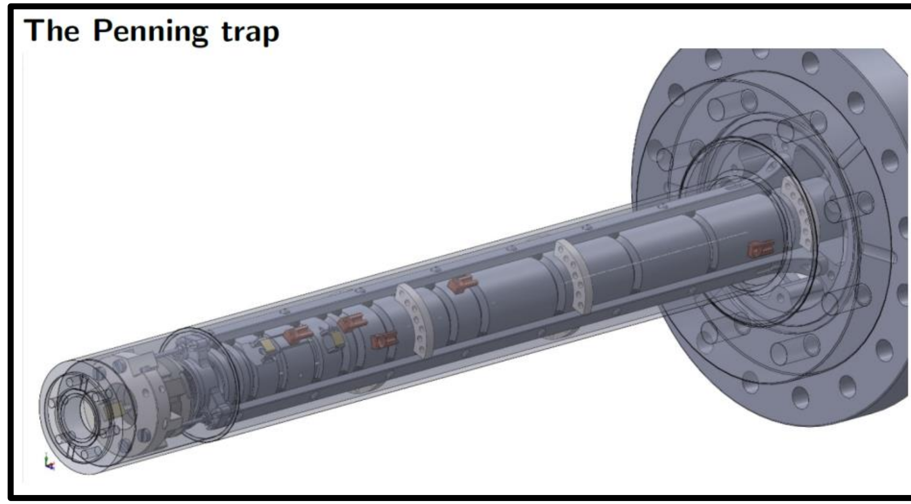
- Even-Lavie valve:
  5% C_2H_2 in 95% Ne at 100 bar
- Acceleration,
  mass spectroscopy:
  100 eV for C_2^-
  2.4 keV for H^-
- Einzel-lens telescope
- Beam diagnostics:
  4 Faraday cups, 1 MCP
- Measure C_2^- state occupation:
  Fly-by spectroscopy
  - Doppler selective
    C_2^- photo-detachment
  - Fluorescence detection
    at 2.54 μm with LN_2 InAs photodiode
- 2.5 μm laser stabilized to H_20 gas cell



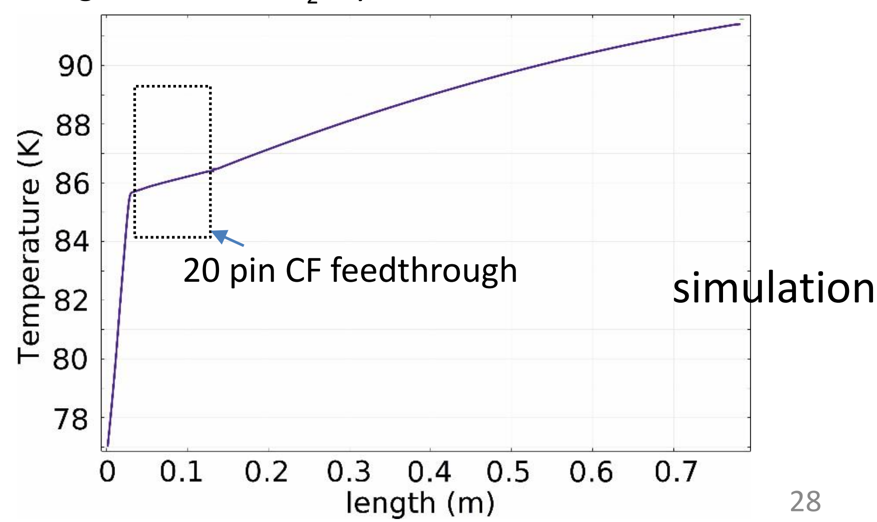
C_2^- test Penning trap

- SmCo permanent magnet configuration:
  - B_z=0.98 T
  - ΔB_z=+-2 mT over z=40 mm
  - ΔB_r=+-1 mT over r=2 mm
- Axial and radial laser access in 50 mm tube





Electrode temperature at 92 K. Cooled by Cu wires guided through 77 K bath LN_2 cryostat



Towards $\overline{p}$ cooling

AEgIS

Three step-plan to reach mK $\overline{p}$ with coolant C_2^- :

1)…

2)…

3)…

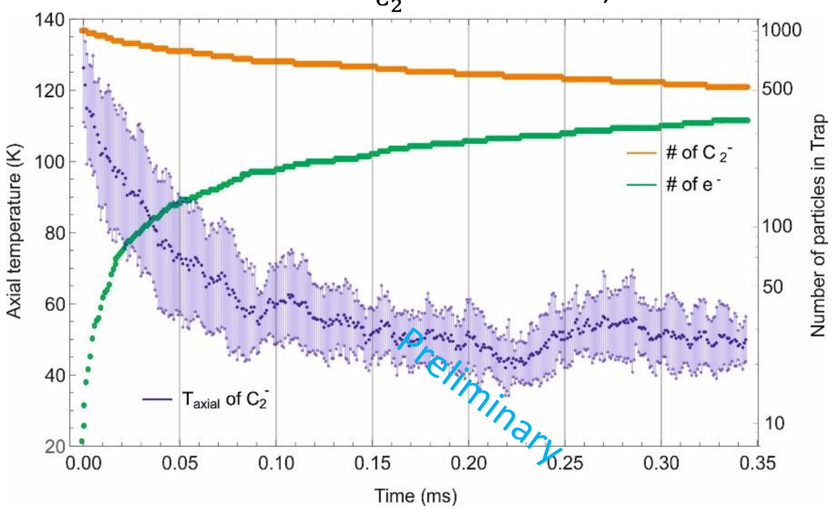
Ionization cooling, simulation

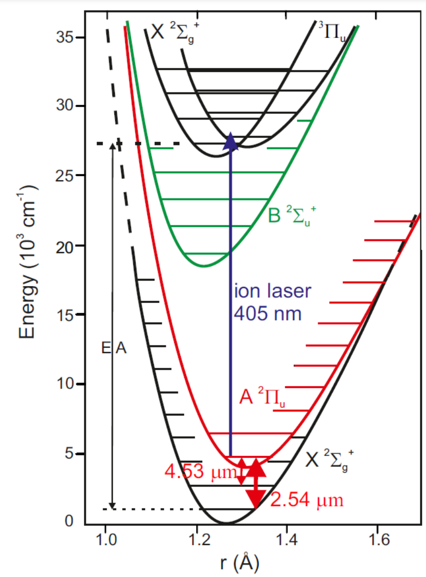
AEgIS

1) Doppler selective photo-detachment (evaporative) cooling:

- 1 x 2.5 μm laser, 1 x detachment laser 405 nm (100 mW enhanced in F~1000 cavity)

$n_{C_2^-}$=5x10^6 cm^{-3} , B=1 T





Rate of photo-detachement:

$$\Gamma = \frac{I}{h\,\nu}\sigma \sim 65\ kHz$$

$$\sigma/cm^2 \sim 1 \times 10^{-18}$$

Cross section calculation Viatcheslav Kokoouline, Uni. Orlando, USA

GPU/C++ based Coulomb interaction calculation of 1000 C_2^-:
For particle-particle interactions Coulomb factor increased by 97.
Simbuca framework : S. Van Gorp and P. Dupre (2013): *http://dx.doi.org/10.1063/1.4796087*

publication in prep.

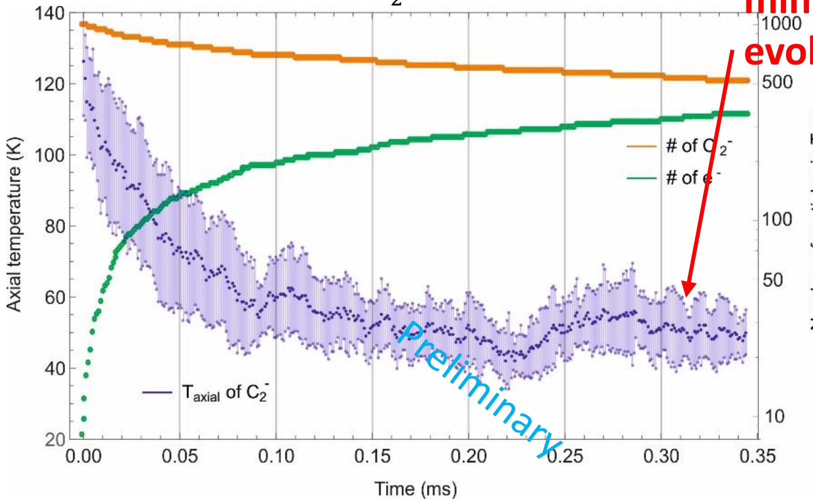
→ Factor ~3 temperature reduction after 0.3 ms, e^- released with binding energy 0.47 eV as: C_2^- + hν → C_2 + e^-

1) Doppler selective photo-detachment (evaporative) cooling:

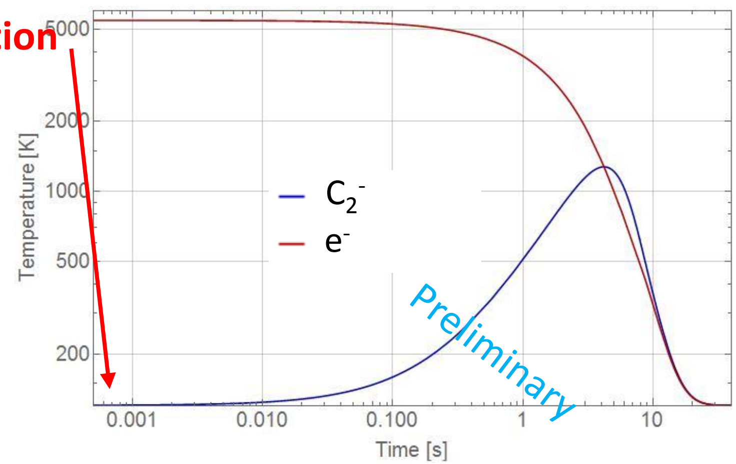
- 1 x 2.5 μm laser, 1 x detachment laser 405 nm (100 mW enhanced in F~1000 cavity)

Time scale <0.5 ms $n_{C_2^-}$=5x10^6 cm^-3 , B=1 T

min. in T evolution



Time scale >0.5 ms



GPU/C++ based Coulomb interaction calculation of 1000 C_2^-:
For particle-particle interactions Coulomb factor increased by 97.
Simbuca framework : S. Van Gorp and P. Dupre (2013): http://dx.doi.org/10.1063/1.4796087

Rate equation including synchrotron radiation:
S. Rolston, G. Gabrielse, *Hyperf. Int.*, **44**, 233 (1988)

publication in prep.

→ Factor ~3 temperature reduction after 0.3 ms, e^- released with binding energy 0.47 eV as: $C_2^- + h\nu \rightarrow C_2 + e^-$

→ Released e^- equilibrate with C_2^- in ca. 10 ms, before thermalizing with 120 K environment after 20 s in 1 T.

→ T measurable with axial charge escape on MCP: $\frac{1}{q}\frac{d\log N(V)}{dV} = \frac{1.05}{kT}$ B. Becks and J. Fajans, *Phys. Plasmas*, **3**, 4 (1996)

→ **Simple to implement but doesn't cool enough…**

Doppler cooling, simulation

AEgIS

2) Doppler cooling, Sympathetic cooling included in simulation for $n_{C_2^-/\bar{p}}$ =10[7] cm[-3]

- 2 x Doppler-selective 2.5 μm laser; locked to optical cavity, reference H_2O gas cell to +- 10 MHz.
- 6 x repumper lasers at 2.5 μm and 4.5 μm

→ Doppler limit: $T_{min} = \frac{h\gamma}{2k} = 0.3\ \mu K$

→ Radial plasma shells at low T minimizable (trap and plasma geometry, B, $\Gamma_{coupling}$)

H. Totsuji et al., *AIP Conf. Proc.*, **498,** 77 (1999)

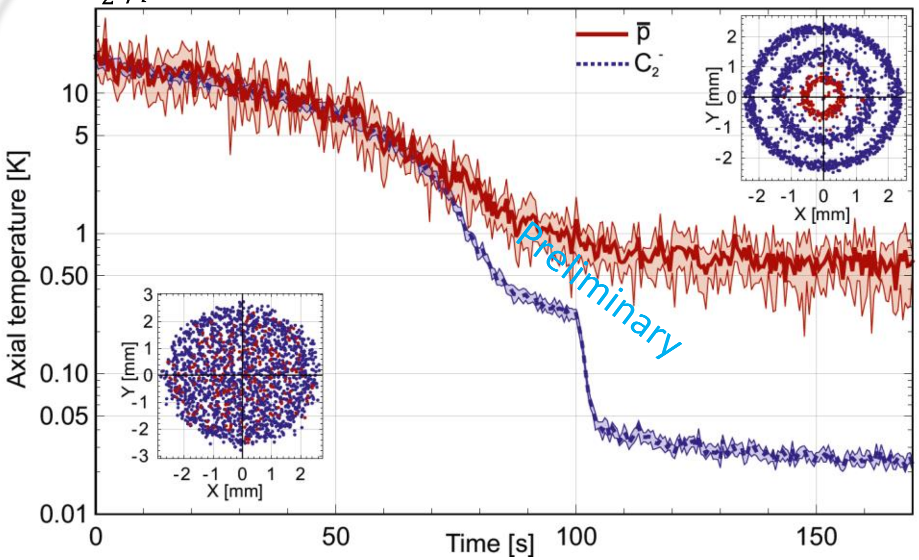
T. Mitchell et al., *Science,* **282,** 1290 (1998)

→ Feasible to reach ~10 mK temperature within minutes range in 10 K AEgIS trap

→ photo-detach C_2^- before $\bar{H}$ production

→ Temperature measurable via Doppler broadened resonance fluorescence

$n_{C_2^-/\bar{p}}$ =10[7] cm[-3] , B=1 T, initialized at 11 K equilibrium



GPU/C++ calculation of 1000 C_2^-/100 $\bar{p}$

For particle-particle interactions Coulomb factor increased by 97

publication in prep.

→ **Possible, but challenging in Penning tap (scatter ~10[7] photons with 8 lasers to <MHz stabilized)**

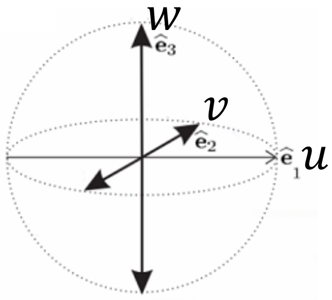
…optimal scheme: AC Sisyphus cooling

AC Stark Sisyphus cooling, simulation

3) Sisyphus AC cooling

- 1 x 2.5 μm ~1.5 GHz detuned dipole laser
- Spontaneous decay lifetime τ_{spon}=50 μs > axial trap motion

Bloch 2 level-system $|\psi\rangle\langle\psi| = \begin{pmatrix} \rho 12 & \rho 12 \\ \rho 21 & \rho 22 \end{pmatrix}$



$u = \rho 12 + \rho 21$ in-phase

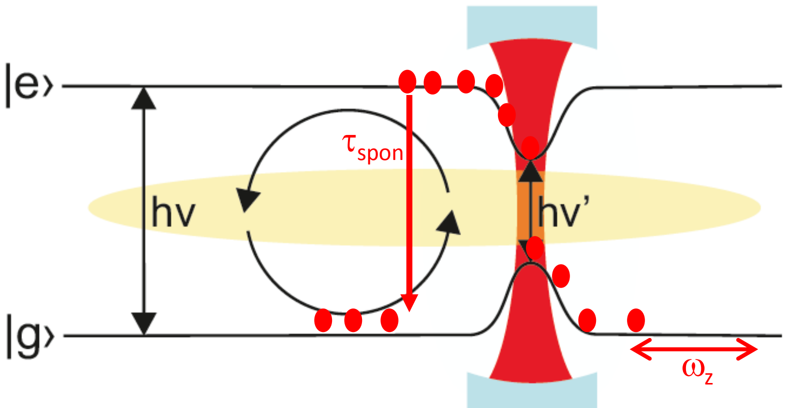
$v = -i(\rho 12 - \rho 21)$ quadrature

$w = \rho 11 - \rho 22$, $|R|^2 = u^2 + v^2 + w^2 = 1$

$$F = \frac{-q\,\chi_{12}}{2}\left[u\frac{\partial E}{\partial z} + vEk\right]$$

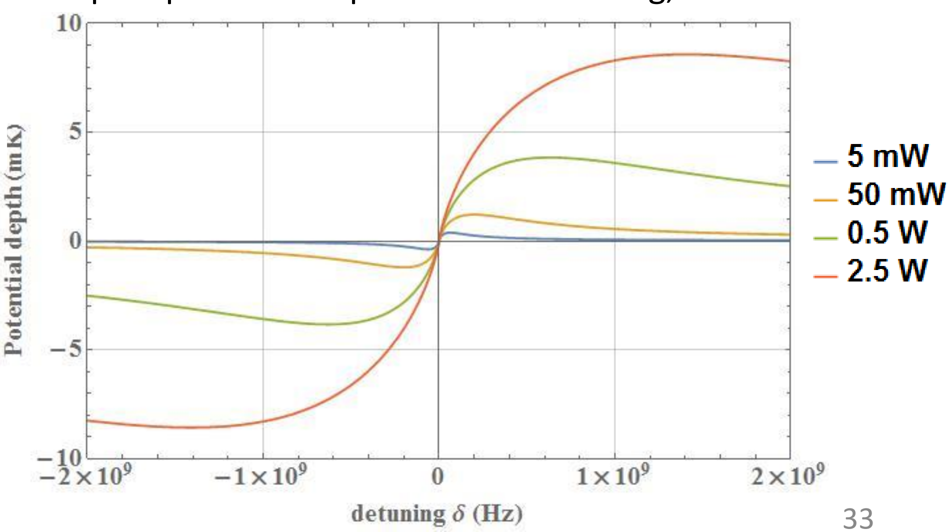
$$F = F_{dipole} + F_{scatter} \;,\; F_{dipole} = \nabla U_{dipole}$$

$$U_{dipole} = \hbar\delta\,\ln\left[1 + \frac{2\Omega^2}{4\delta^2 + \Gamma^2}\right]$$



Sisyphus scheme:
J. Dalibard and C. Cohen-Tannoudji, *J. Opt. Soc. Am. B*, **2**, 11 (1985)

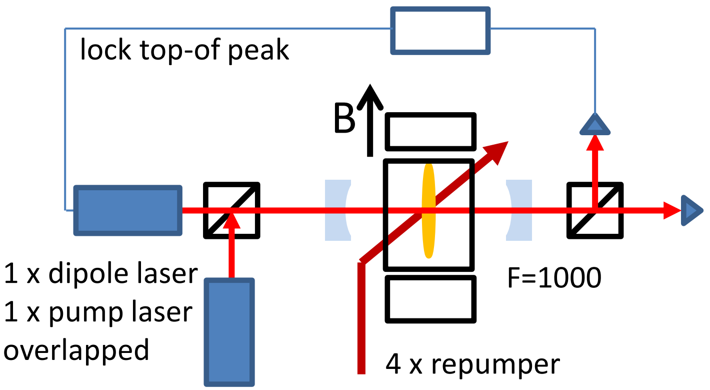
Dipole potential depth vs laser detuning, waist = 0.2 mm



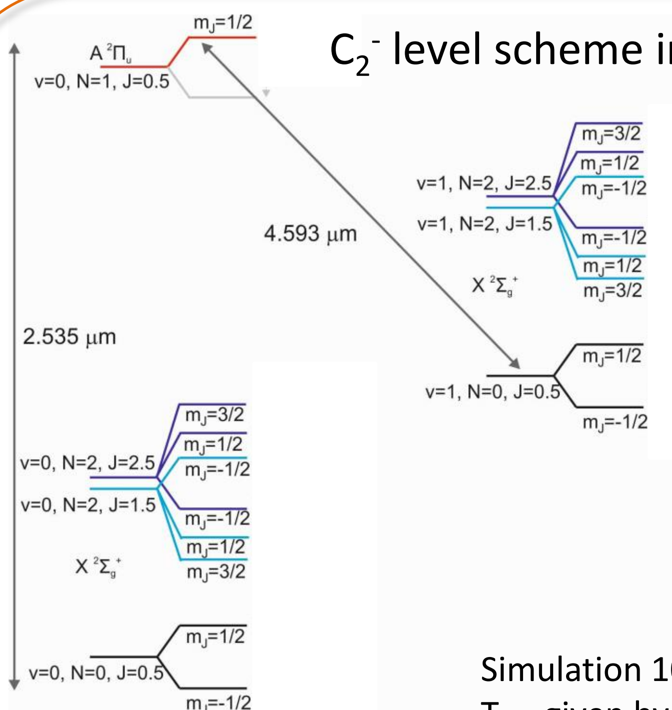
AC Stark Sisyphus cooling, simulation

3) Sisyphus AC cooling - implementation

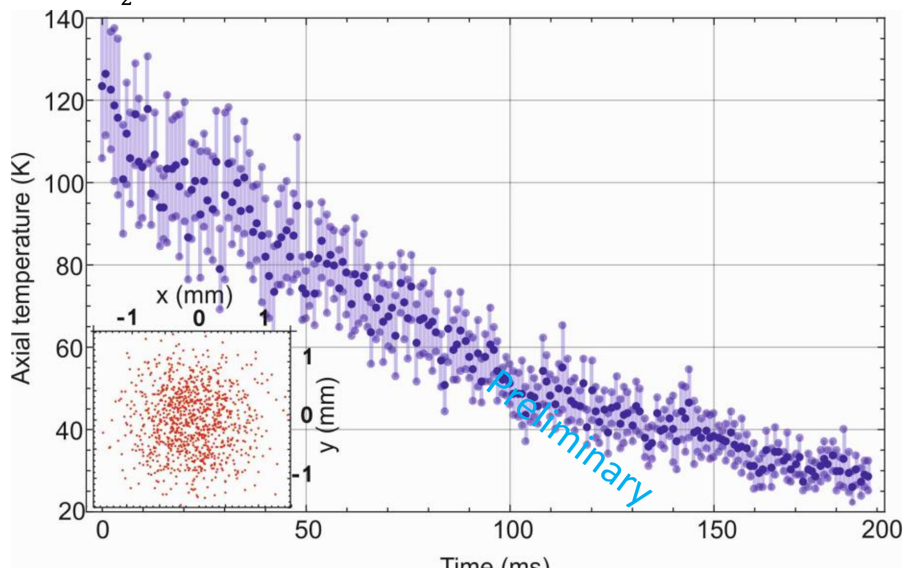
- 1 x 2.5 μm ~1.5 GHz detuned dipole laser (U_{dipole}=7 mK)
- Spontaneous decay τ_{spon}=50 μs > axial trap motion
- 1 x pump at 2.5 μm, 4 x repumper at 2.5 μm and 4.5 μm



C_2^- level scheme in 5 T



$n_{C_2^-}$=10^7 cm^{-3} , B=5 T, initialized at 125 K equilibrium



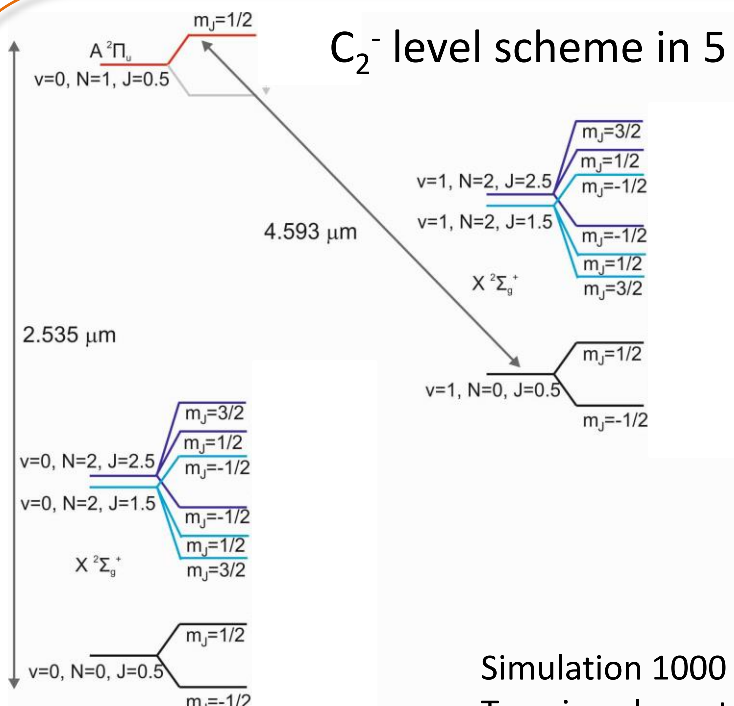
Simulation 1000 C_2^- time 14 h, then stopped. (preliminary plot)

T_{min} given by potential depth U_{dipole} to ~1 mK *publication in prep.*

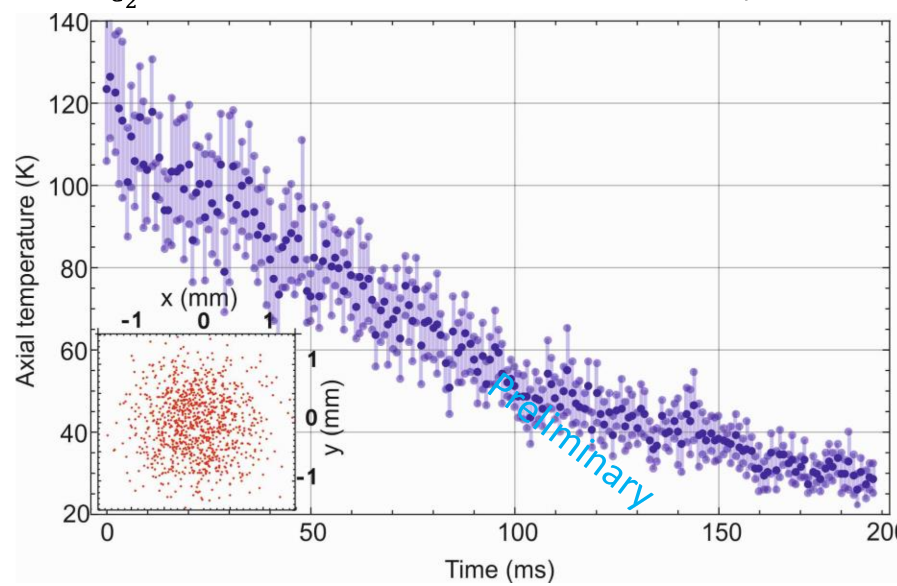
AC Stark Sisyphus cooling, simulation

3) Sisyphus AC cooling - implementation

C_2^- level scheme in 5 T



$n_{C_2^-}$=10^7 cm^{-3} , B=5 T, initialized at 125 K equilibrium



Simulation 1000 C_2^- time 14 h, then stopped. (preliminary plot)

T_{min} given by potential depth U_{dipole} to ~1 mK *publication in prep.*

→at $n_{C_2^-/\bar{p}}$ =10^7 cm^{-3} **simulation indicates that sympathetic cooling of $\bar{\mathrm{p}}$ works**

→**mK $\bar{\mathrm{p}}$ feasible (scatter ~10^4 photons, 6x lasers only drift stabilized to cell/wavemeter)**

→**sub-K $\bar{\mathrm{H}}$ production becomes feasible with current** Ps **technology**

→**First-ever production of trapped sub-K negative ions (impacts on many fields of physics)**

Conclusion and Outlook

Many procedures required for pulsed production of antihydrogen atoms are now working (Ps formation, Ps excitation into Rydberg states, antiproton cooling and compression in 5 T to r=260 μm, fringe shift measurement with deflectometer);

Recent improvements will help (new ^{22}Na source with 10^8 e^+/300 s, substantial antiproton trapping efficiency 4.5×10^5 $\bar{p}$/AD shot, installation of a modified e^+ injection scheme for Ps production in the 1 T magnet, further sympathetic cooling of antiprotons with anions);

...but challenges remain (and beam formation still looms).

We should be in a position for (precision) studies of gravitational interaction of antihydrogen very soon…

Thank you very much for your attention!