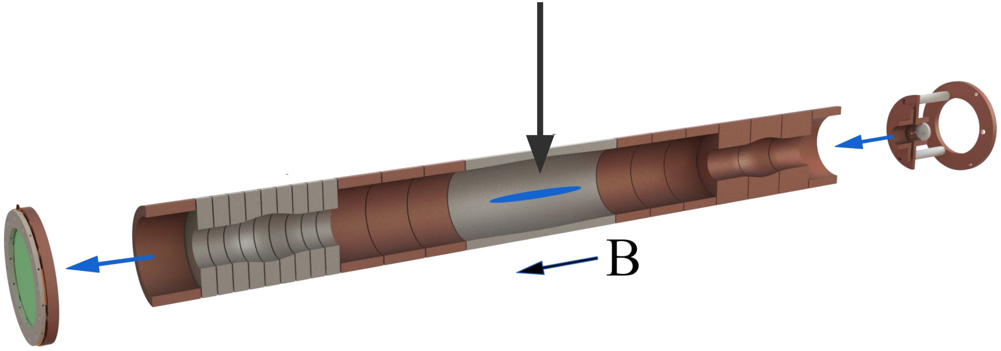
Antihydrogen Formation from Cold Nonneutral Plasmas



What

antimatter
hyperfine measurement

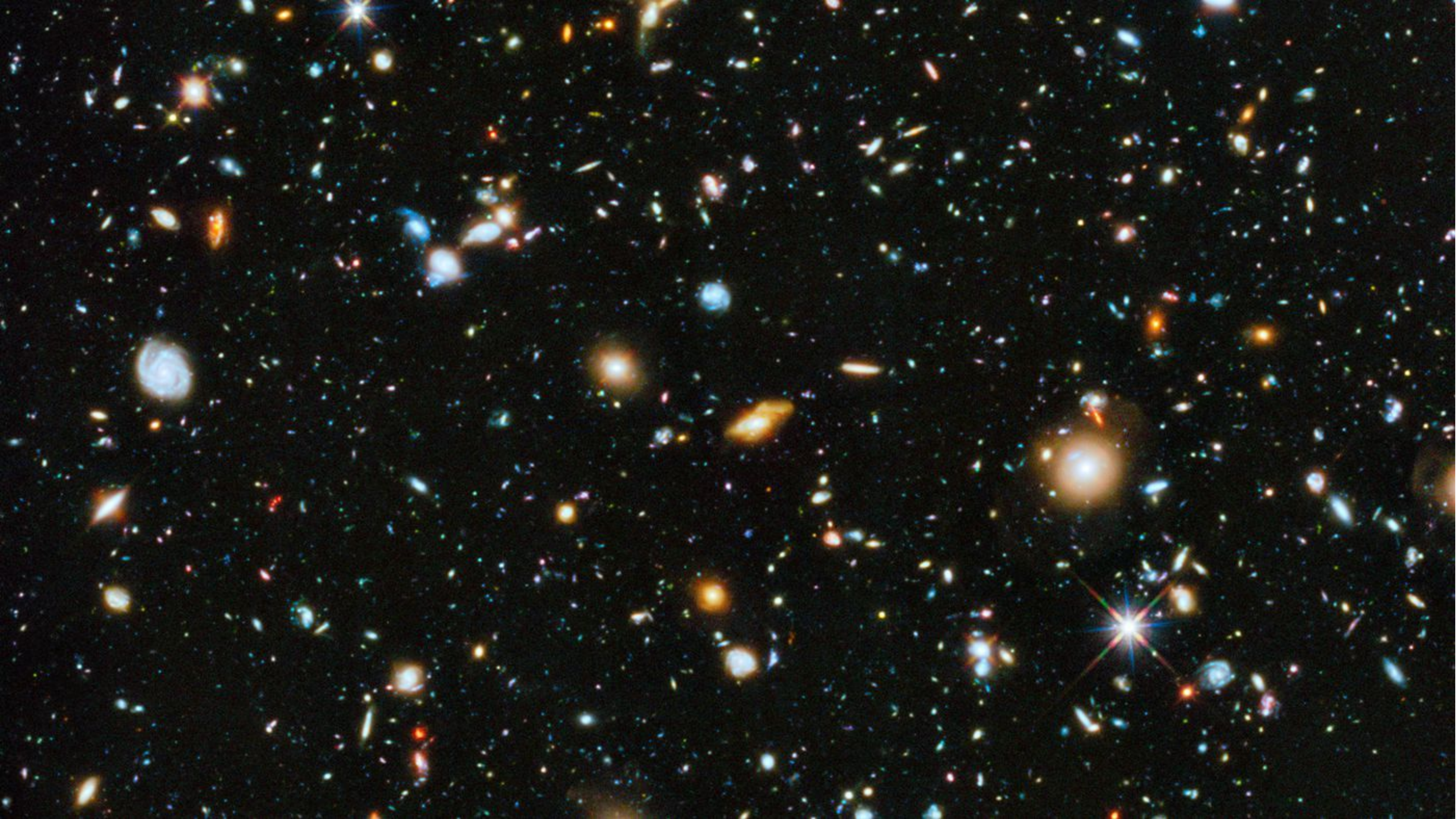
How

getting antiprotons
mixing them with a positron plasma

My contribution

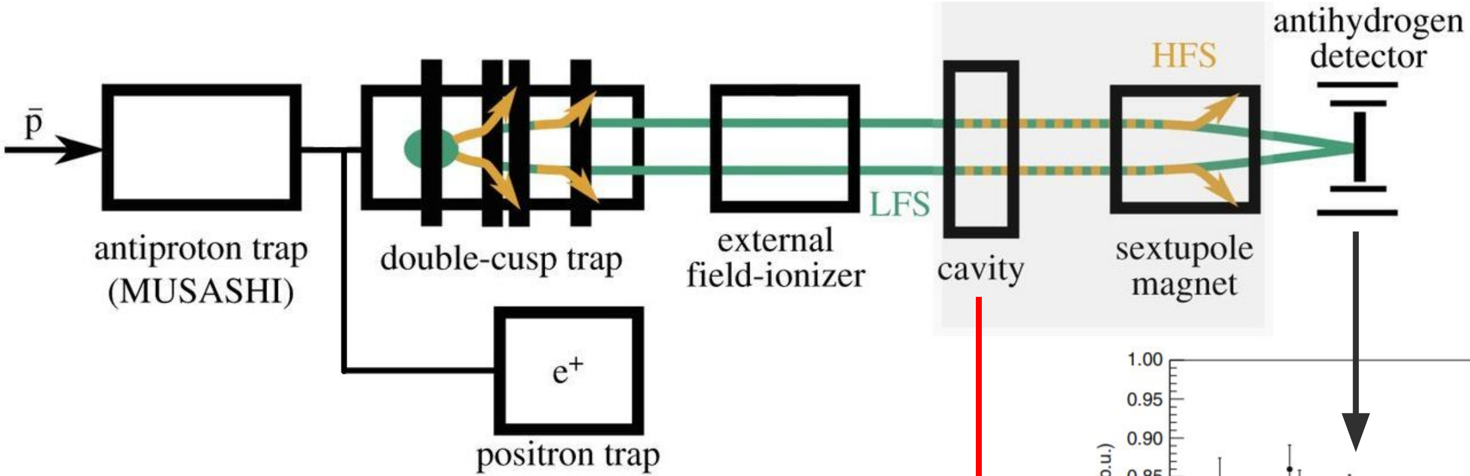
control of plasma shape and density
diagnosis of plasma temperature
minimizing plasma temperature
diagnosis of quantum state distribution

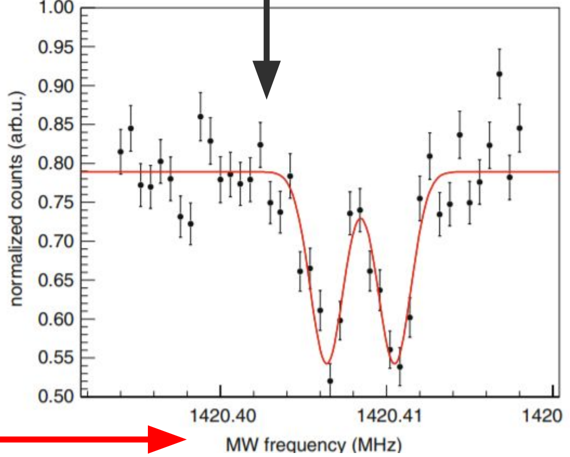
Eric Hunter
for the ASACUSA Collaboration
and the Stefan Meyer Institute




Dark Energy
Dark Matter
Ordinary Matter

ASACUSA's spin flip proposal





1 Cusp forms a polarized H̄ beam

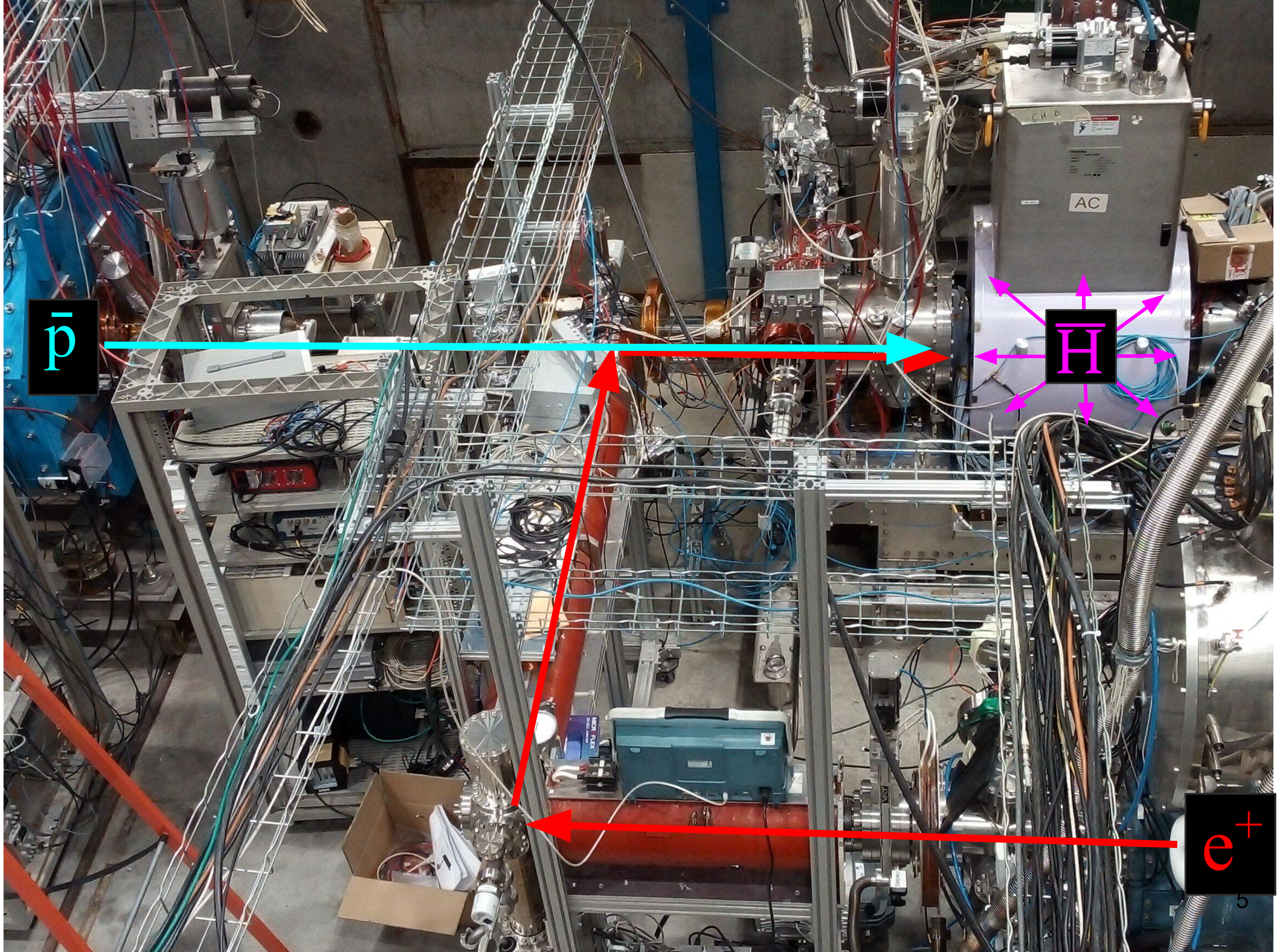
2 Count low-field-seeking H̄ on target

3 Flip the spin with a resonant microwave cavity

Malbrunot, C., Amsler, C., Arguedas Cuendis, S., Breuker, H., Dupre, P., Fleck, M., Higaki, H., Kanai, Y., Kolbinger, B., Kuroda, N. and Leali, M., 2018. The ASACUSA antihydrogen and hydrogen program: results and prospects.

ASACUSA

Atomic
Spectroscopy **a**nd
Collisions **U**sing
Slow **A**ntiprotons

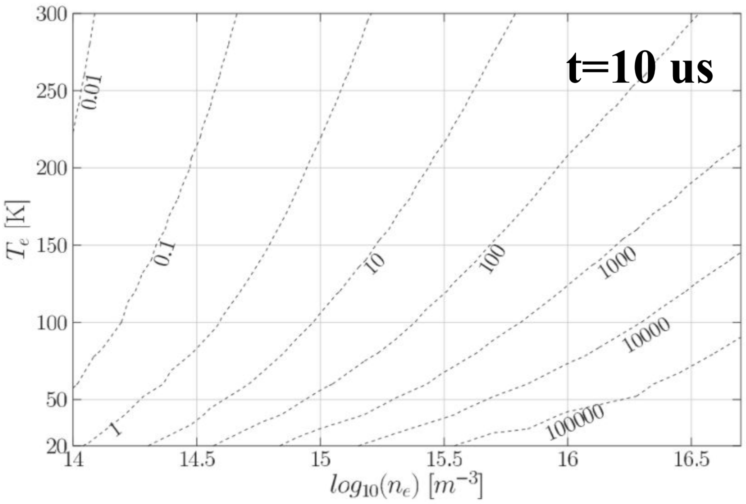


e^+ plasma + $\bar{p}$ plasma → $\bar{H}$ atoms

Simulations of antihydrogen formation suggest:

1 maximize interaction of $\bar{H}$ with e^+

2 minimize plasma temperature



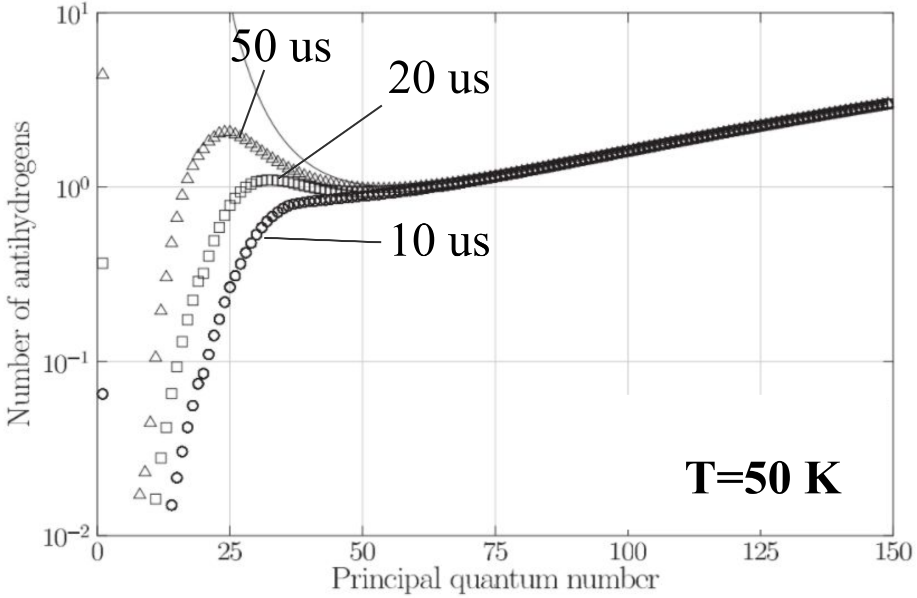


FIG. 1. Antihydrogen bound-state level population distribution after evolution of 10 μs (circle), 20 μs (square), and 50 μs (triangle) and the thermal equilibrium level population distribution (solid line) for positron temperature of $T_e = 50$ K and positron density $n_e = 10^{14}$ m^{-3}(with 10^6 antiprotons).

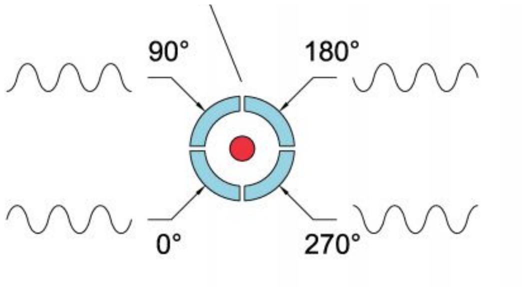
Radics, B., Murtagh, D. J., Yamazaki, Y., & Robicheaux, F. (2014). Scaling behavior of the ground-state antihydrogen yield as a function of positron density and temperature from classical-trajectory Monte Carlo simulations

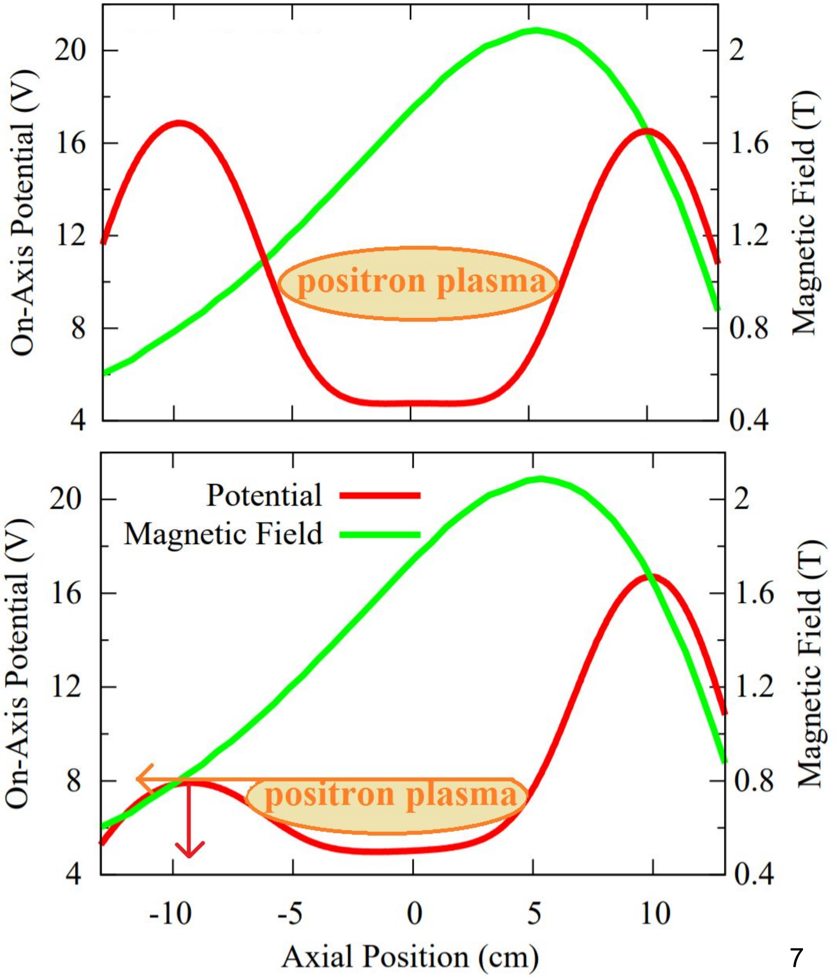
Control of plasma parameters

length
= electrode potentials

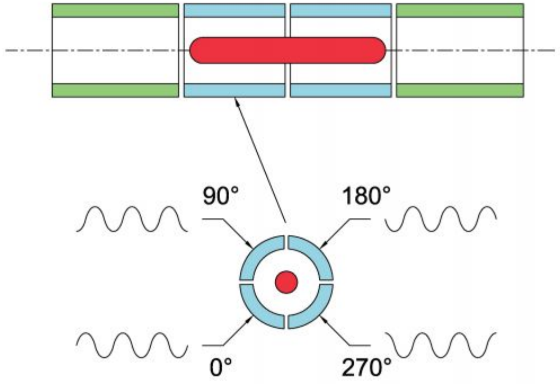
number of particles, temperature
= forced evaporation

density, radius
= rotating wall (next slide)





SDR: Rotating wall in the **S**trong **D**rive **R**egime

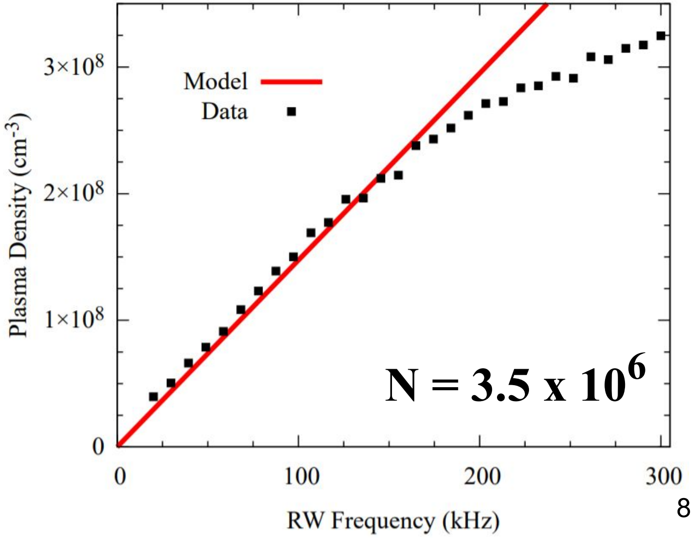


‘Rotating’ electrostatic field creates a torque, when the plasma rotation is slower than the field rotation frequency
→ <u>Plasma rotation frequency asymptotes to RW frequency</u>

The plasma density

$$n_0 = \frac{2\varepsilon_0 m}{q^2}\omega_r(\Omega_c - \omega_r)$$

is proportional to the plasma rotation frequency
→ <u>Plasma density proportional to RW frequency</u>



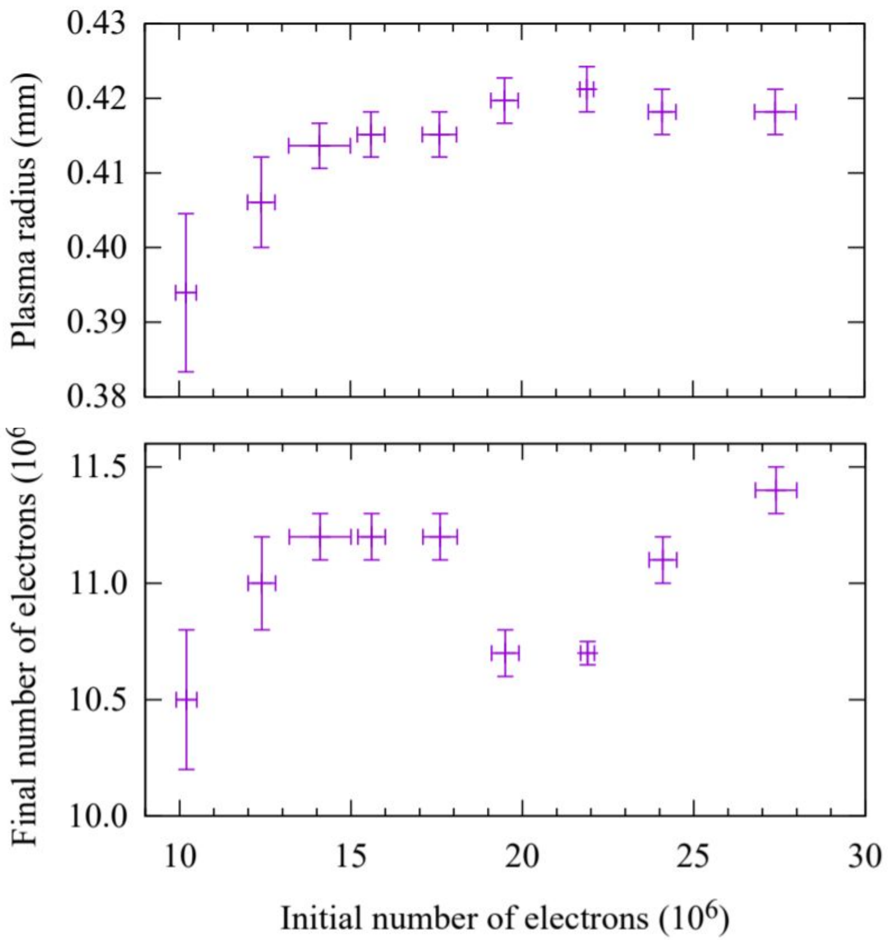
Danielson et al. (2015). Plasma and trap-based techniques for science with positrons

SDR + **EVC** = SDREVC

→ Simultaneous control
of all plasma parameters

→ Reproducible results
independent of initial state

Property	Mean	SD
r_p (mm)	0.417	0.003
T (K)	360	30
N_f (10^6)	11.0	0.3



Newton's law of cooling

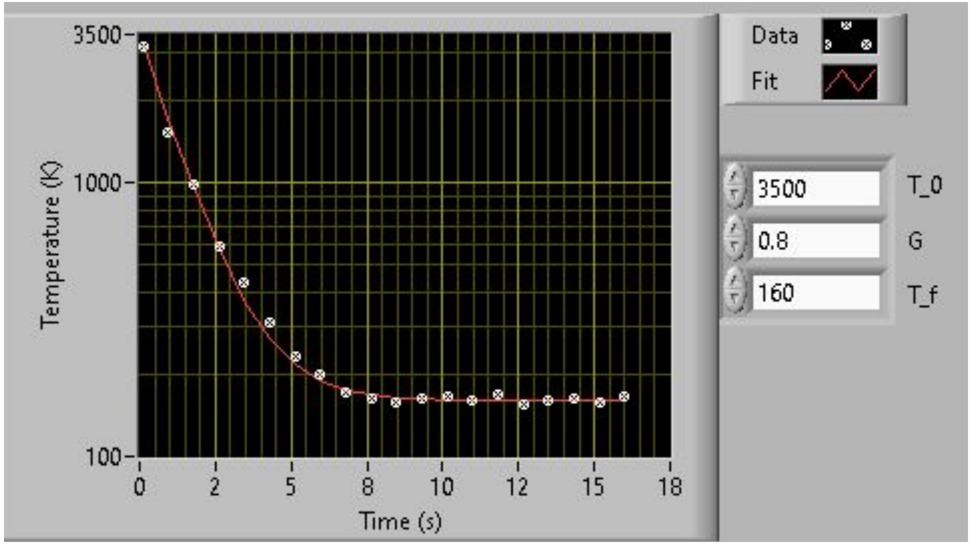
$$dT/dt = -\Gamma(T - T_w) + H$$

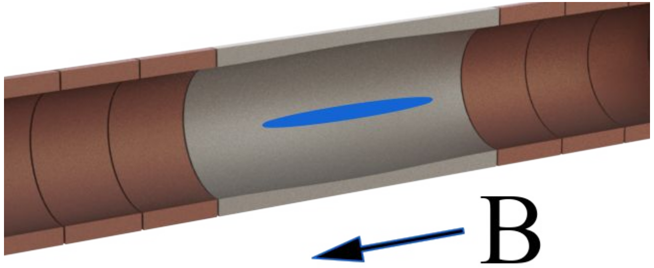
$$\Rightarrow \quad T_f = T_w + H / \Gamma$$

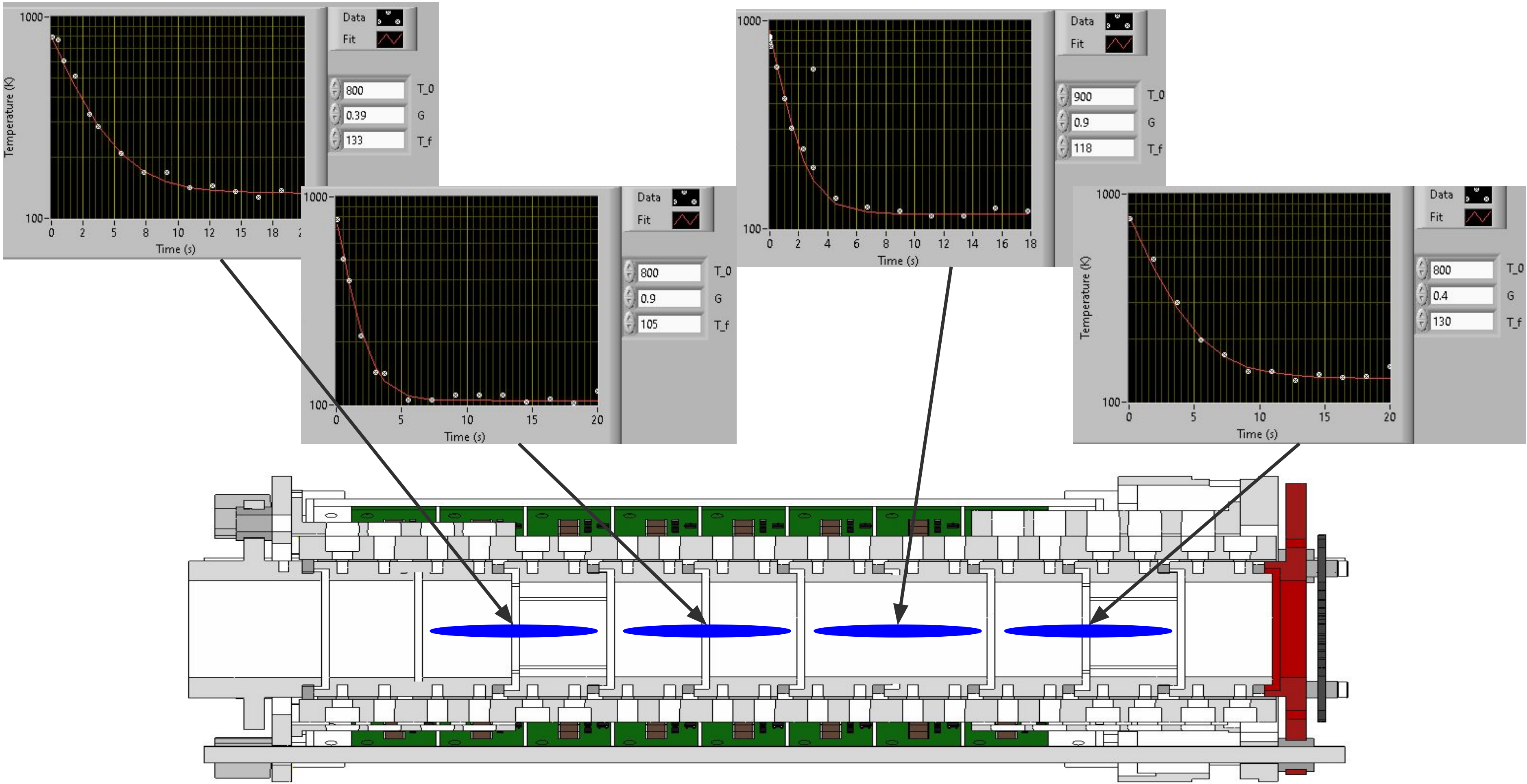
Electrode Temperature

Plasma Heating Rate
(expansion and electrode noise)

Cyclotron Cooling Rate





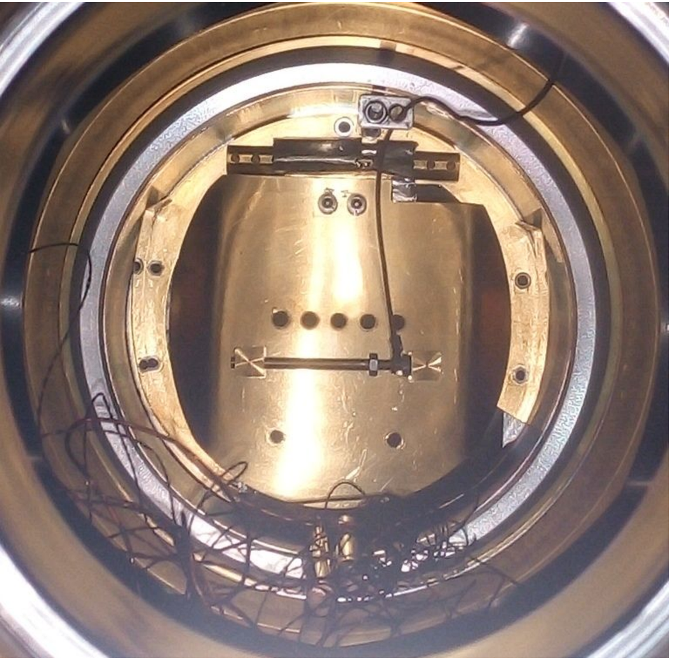


Name:	u13	u12	u11	u10	u9	u8	u7	u6	u5	u4	u3
Filter:	pulsed	slow	slow	none	slow	slow	slow	slow	none	slow	slow

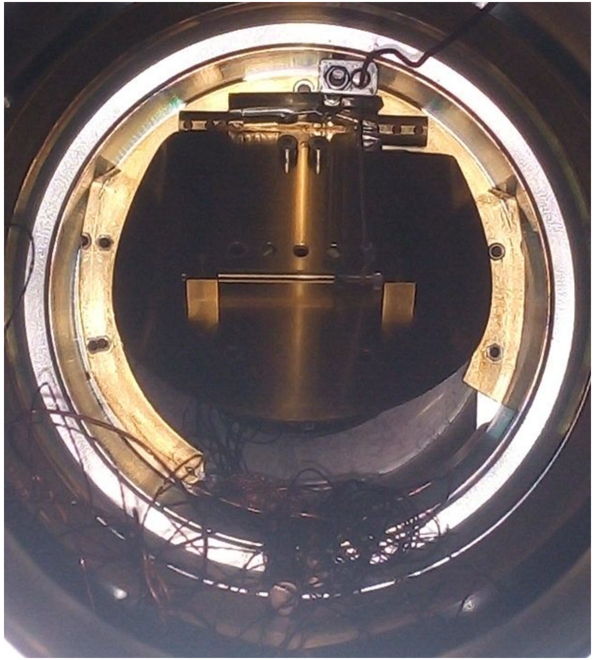
What if the radiation environment is hotter than the ~35 K electrodes?

Measure the temperature of the plasma with the thermal shield in different positions

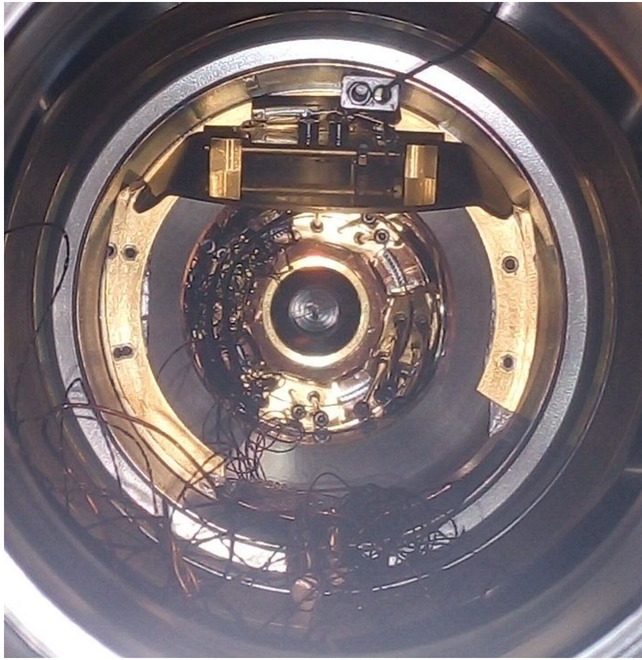
closed

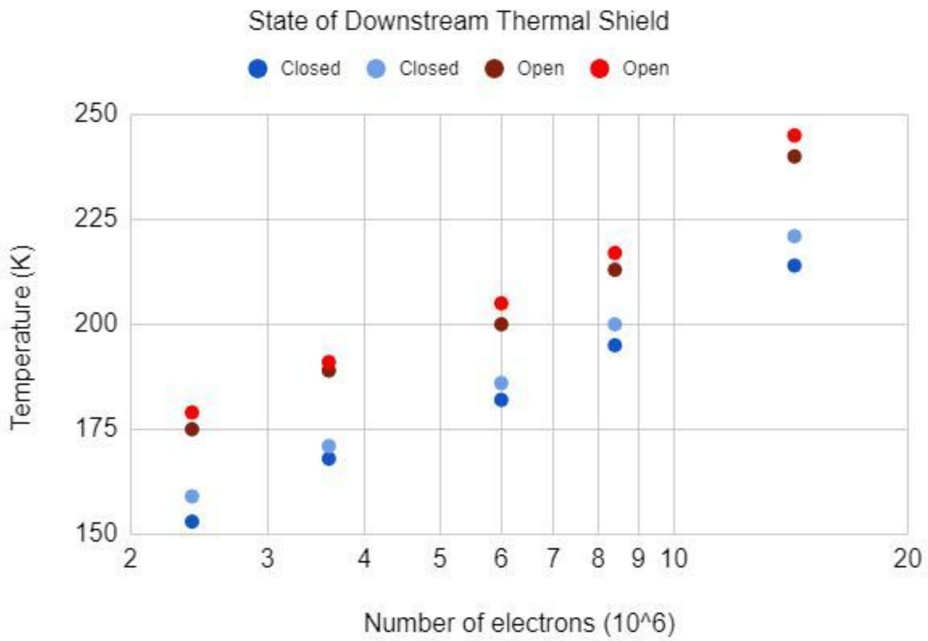


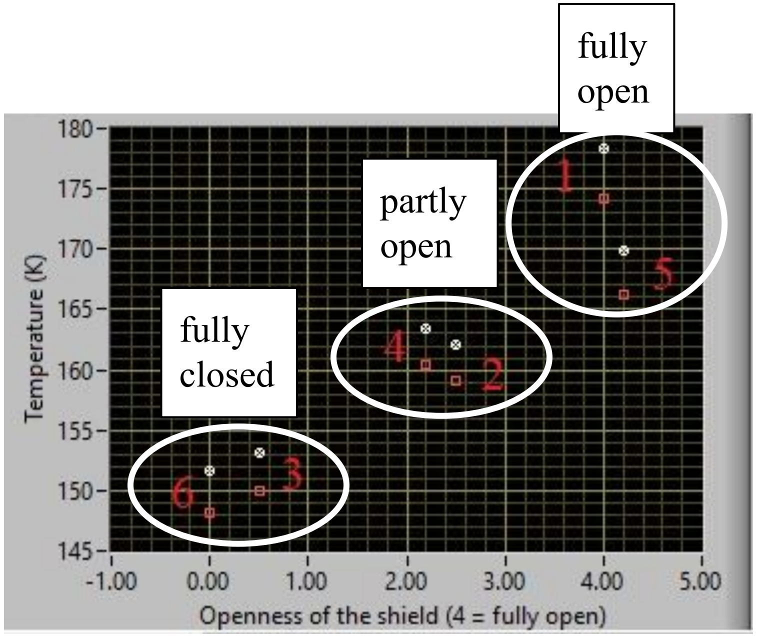
partly open



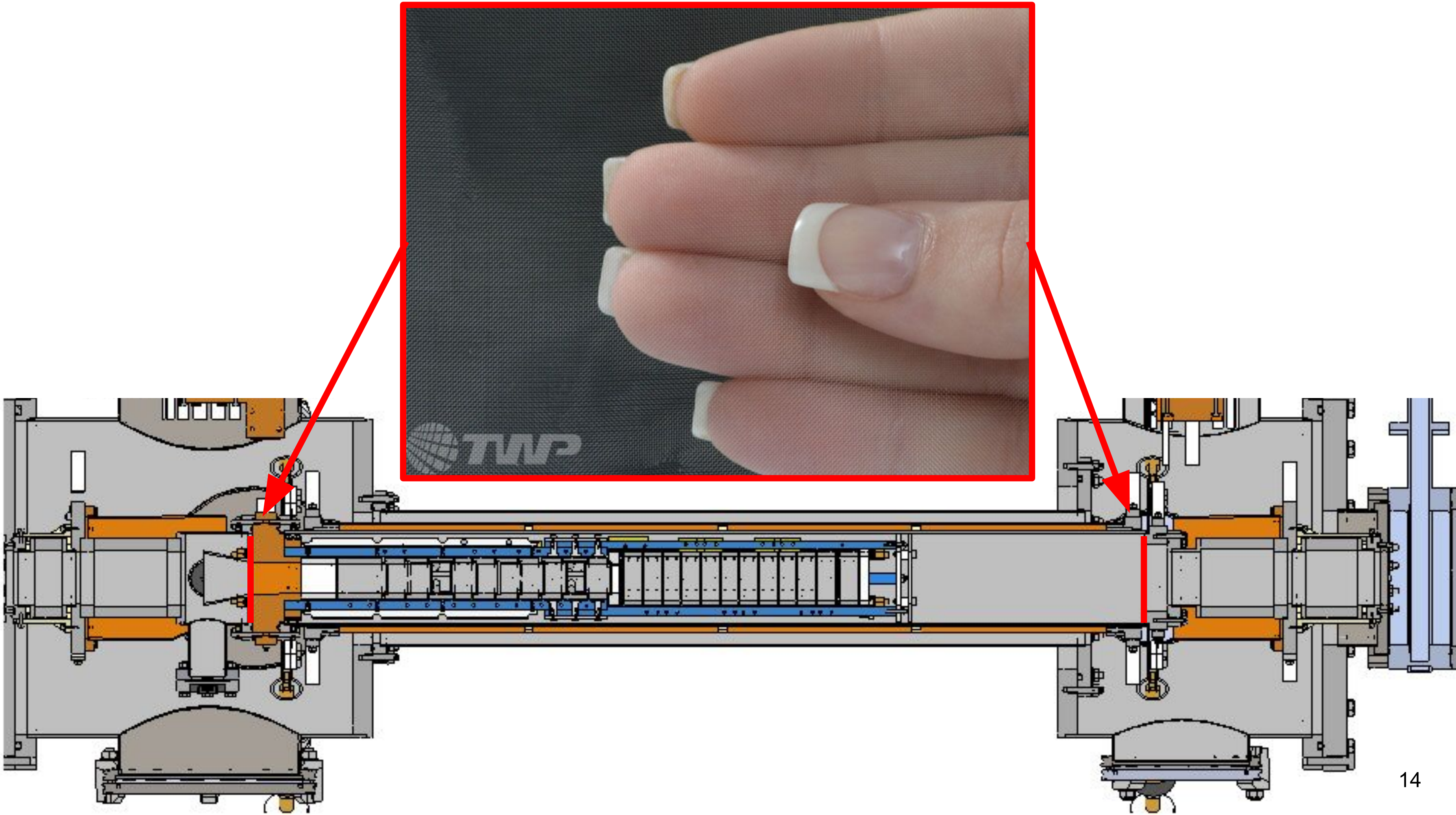
fully open




State of Downstream Thermal Shield
Closed
Closed
Open
Open
Temperature (K)
250
225
200
175
150
2
3
4
5
6
7
8
9
10
20
Number of electrons (10^6)


fully open
partly open
fully closed
Temperature (K)
180
175
170
165
160
155
150
145
-1.00
0.00
1.00
2.00
3.00
4.00
5.00
Openness of the shield (4 = fully open)
1
5
4
2
6
3

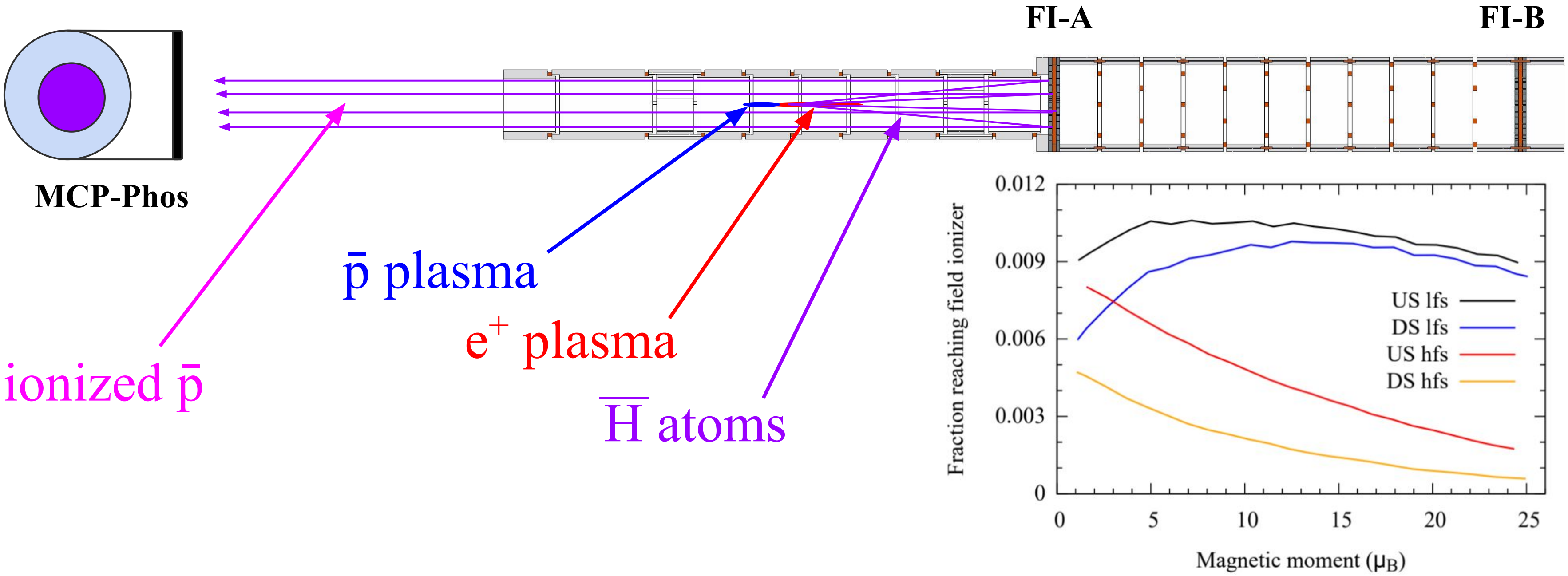

150.1
plasma
Higaki shield


TWP

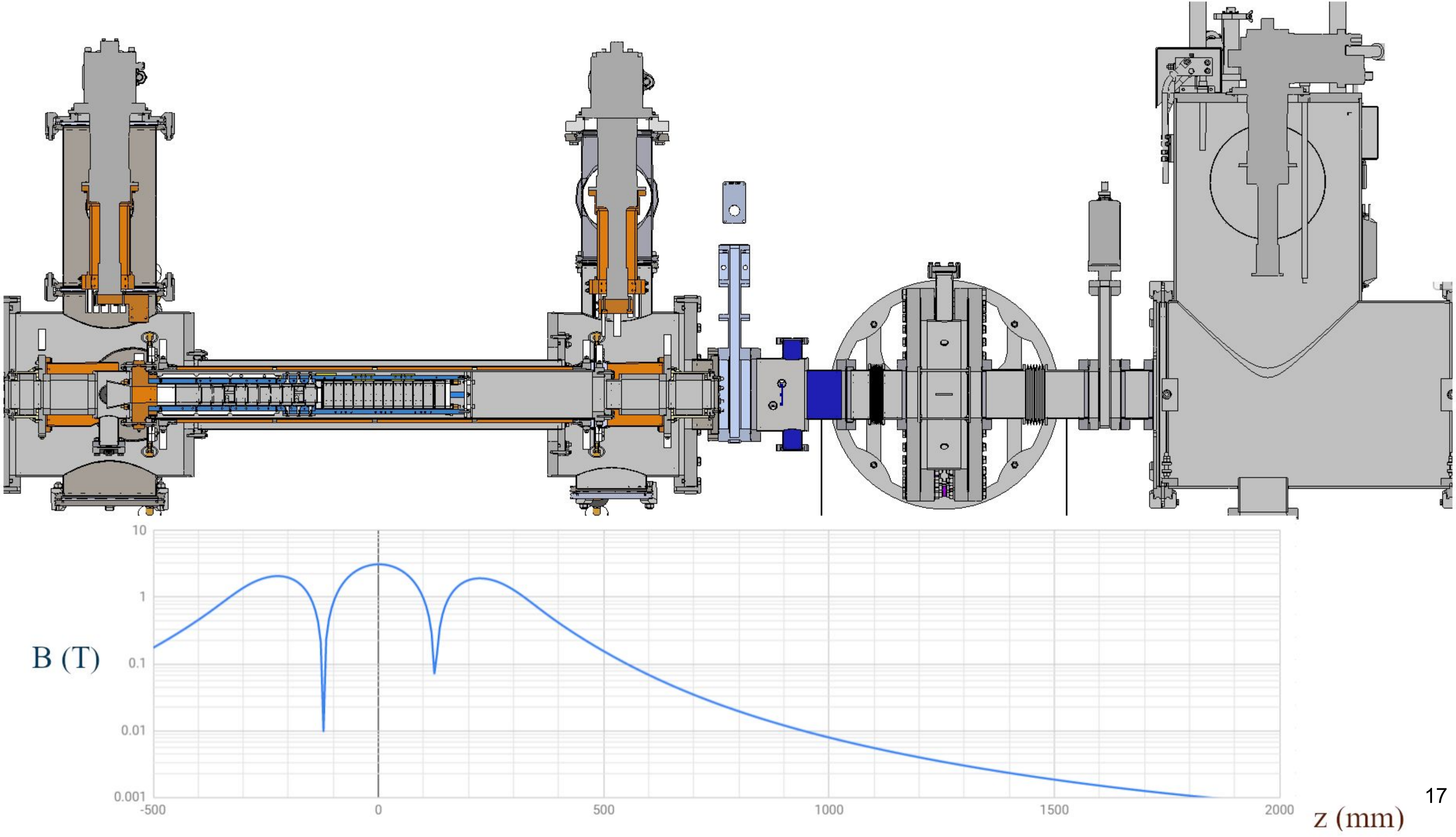
Field ionizers

One ionizer: measure n-state distribution (# ionized atoms vs. applied voltage)

Two ionizers: measure antihydrogen temperature (time of flight)



Backup slides



10
1
0.1
0.01
0.001
B (T)
-500
0
500
1000
1500
2000
z (mm)

Temperature measurement

$$f(E) \propto e^{-E/kT}$$

$$I(t) = G \cdot f(E(t)) \frac{\mathrm{d}E}{\mathrm{d}t}$$

$$\propto a + be^{ct}$$

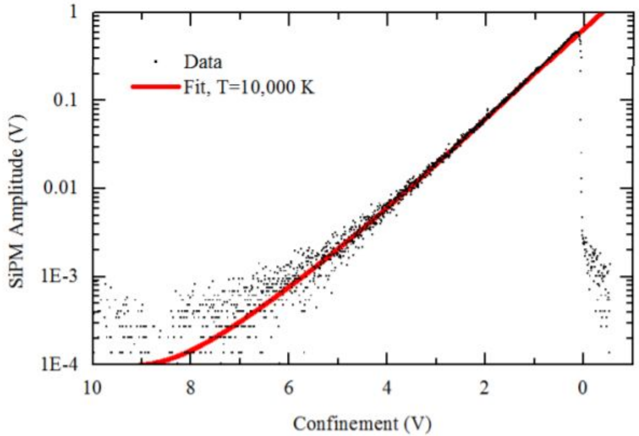
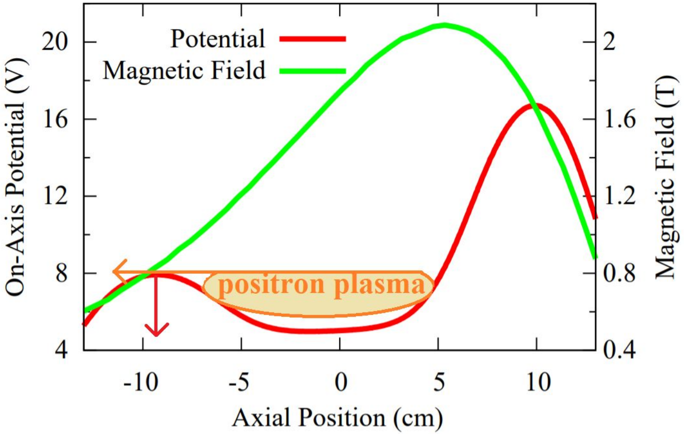
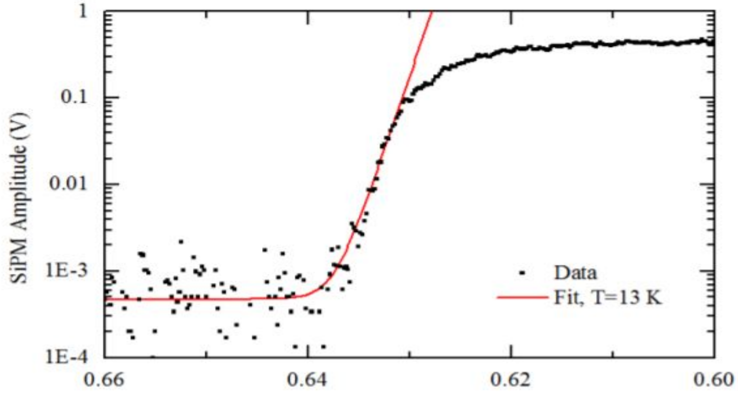


Figure 3.6: Extraction trace for a hot, $N = 3 \cdot 10^6$ e$^-$ plasma. y axis is the voltage on the





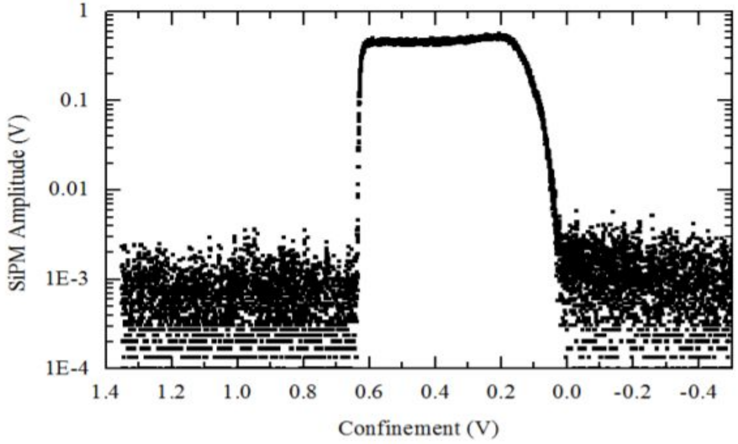
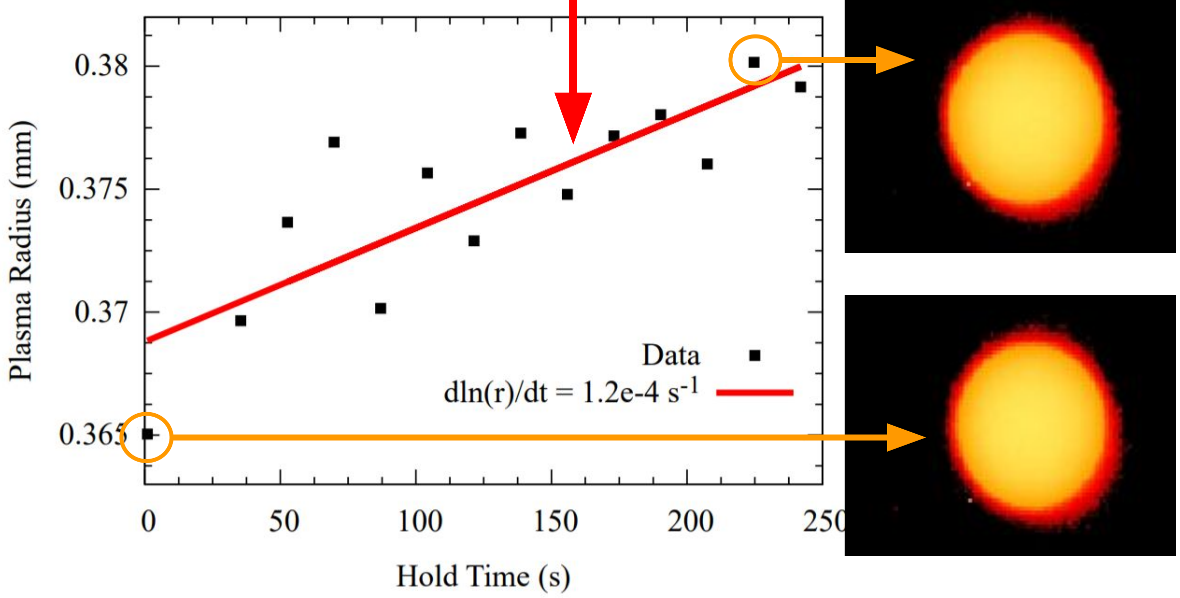
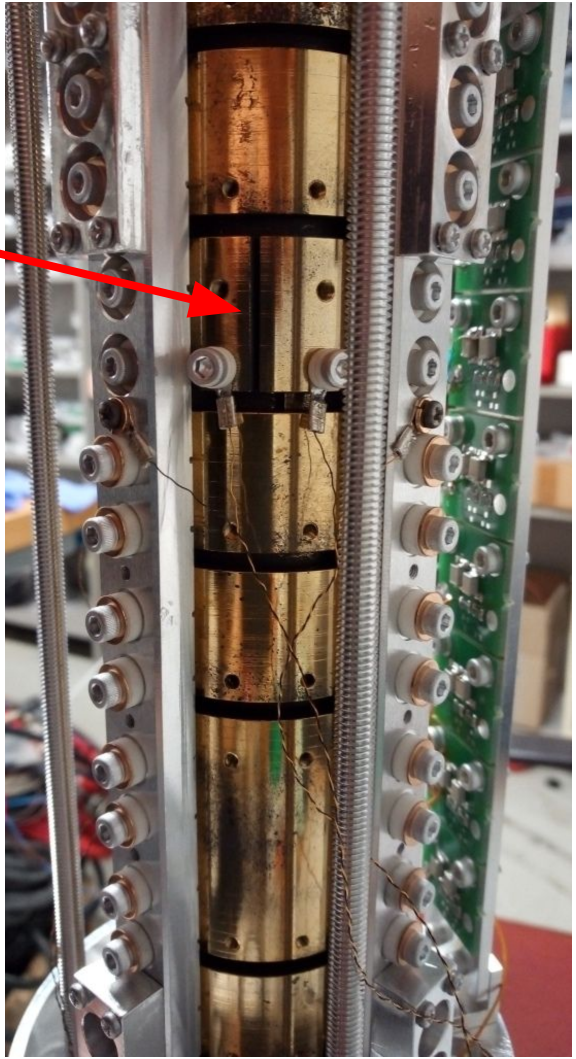


Figure 3.7: Extraction trace for a cold, $N = 3 \cdot 10^6$ e$^-$ plasma. This is the “same” plasma as in Fig. 3.6 after 8 s of resonant cooling.

Plasma temperature is usually reduced by reducing RF noise on the electrodes and the plasma expansion rate





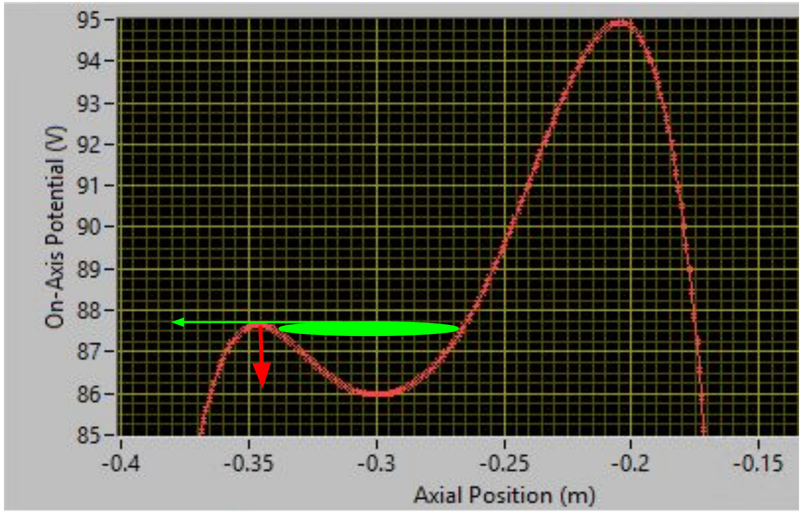
These are both very low in our trap.

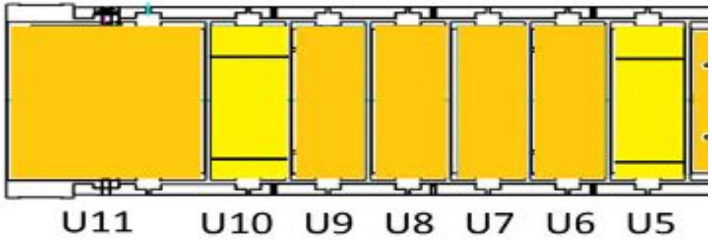
EVC: EVaporative Cooling

Slowly reduce axial electrostatic confinement potential. The most energetic particles escape first
→ Plasma temperature is reduced
→ Plasma space charge set by final well depth

$$\phi(r) = \frac{qnr_p^2}{4\varepsilon_0}\left[1 + 2\ln\left(\frac{r_w}{r_p}\right)\right] - \frac{qnr^2}{4\varepsilon_0}$$

but plasma radius is not controlled

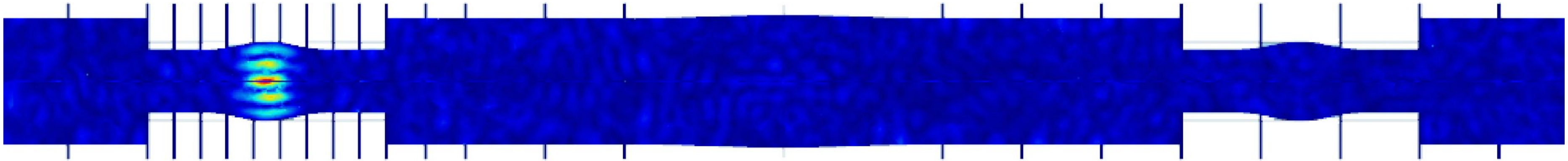




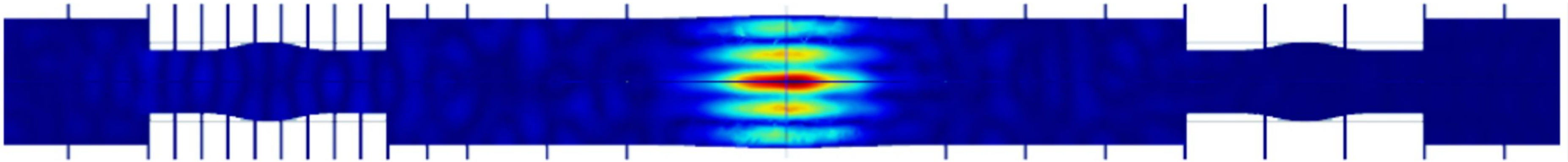
Purcell Effect

Resonant interaction with cavity modes can increase the cyclotron cooling rate

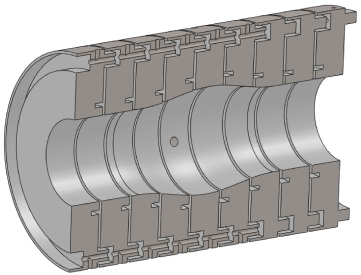
Cavity 1 -- TE_{131} -- 34.1 GHz -- qB/m at 1.22 T)

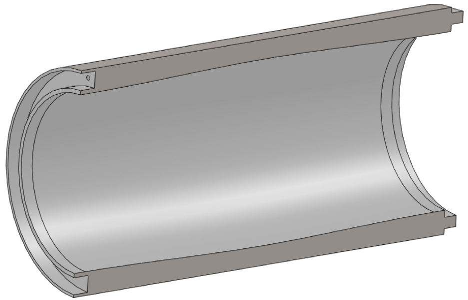


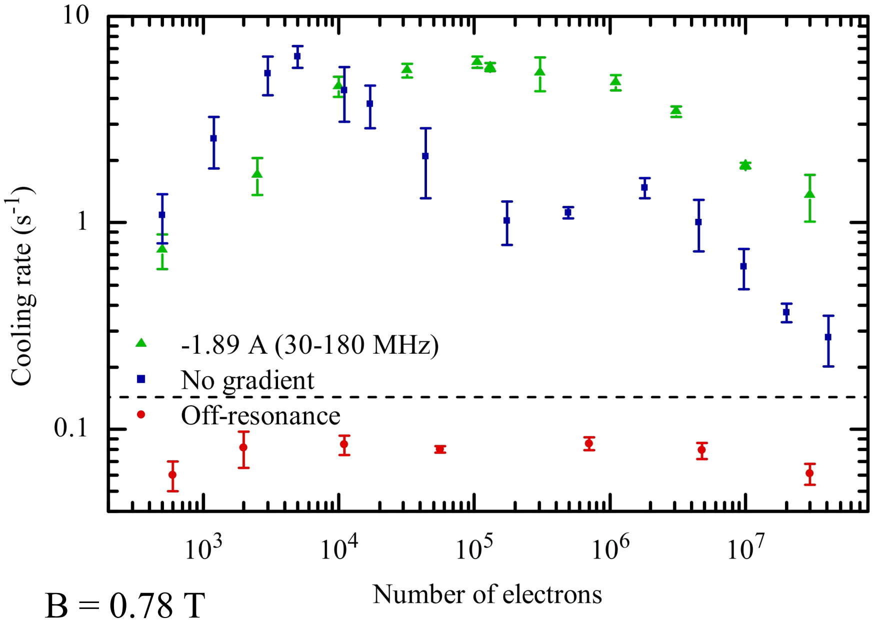
Cavity 2 -- TE_{131} -- 19.6 GHz -- qB/m at 0.70 T)



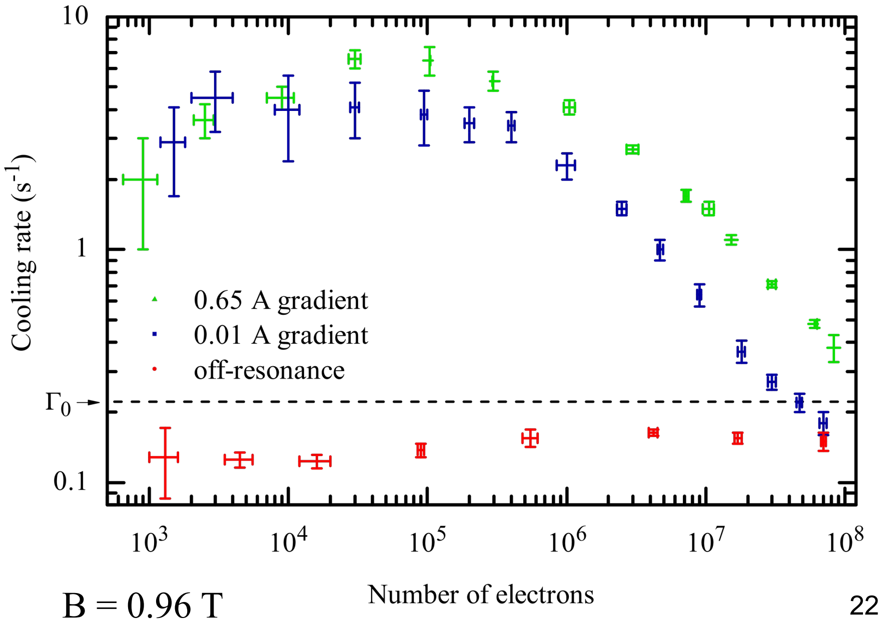
Cooling Rate





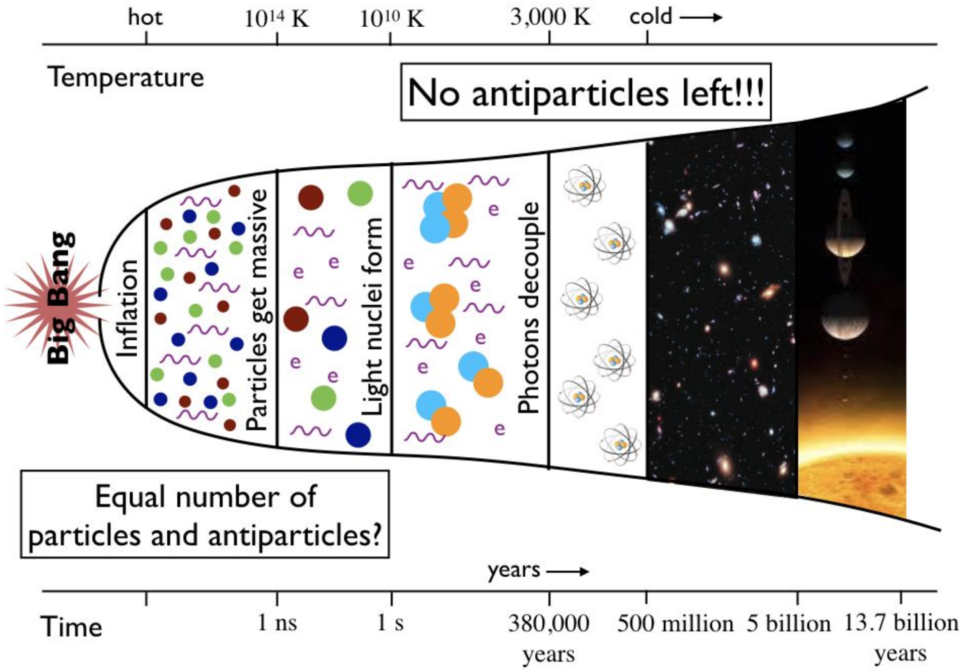


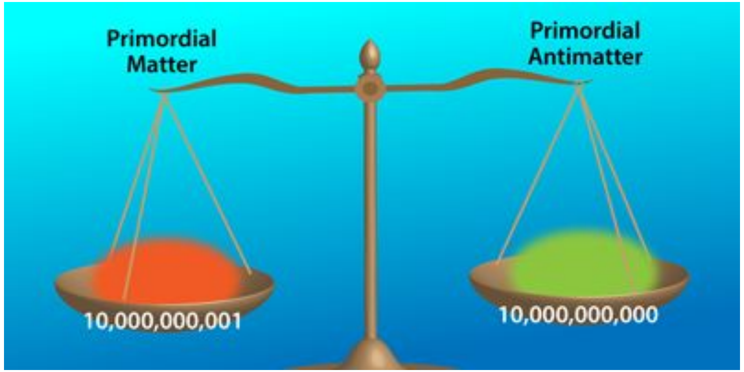
B = 0.78 T



B = 0.96 T

Antimatter and matter in the universe: broken symmetry





Images accessed at https://seydaipek.com/research/ and https://physics.aps.org/articles/v8/s17

The Antiproton Decelerator (AD) at CERN