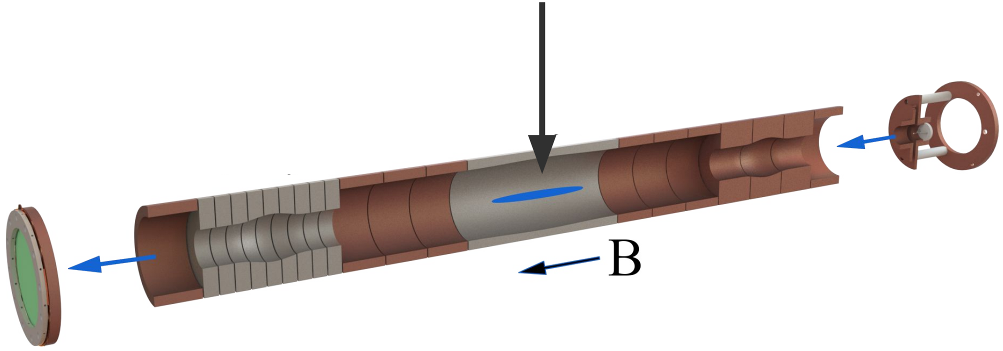
Antihydrogen Formation from Cold Nonneutral Plasmas



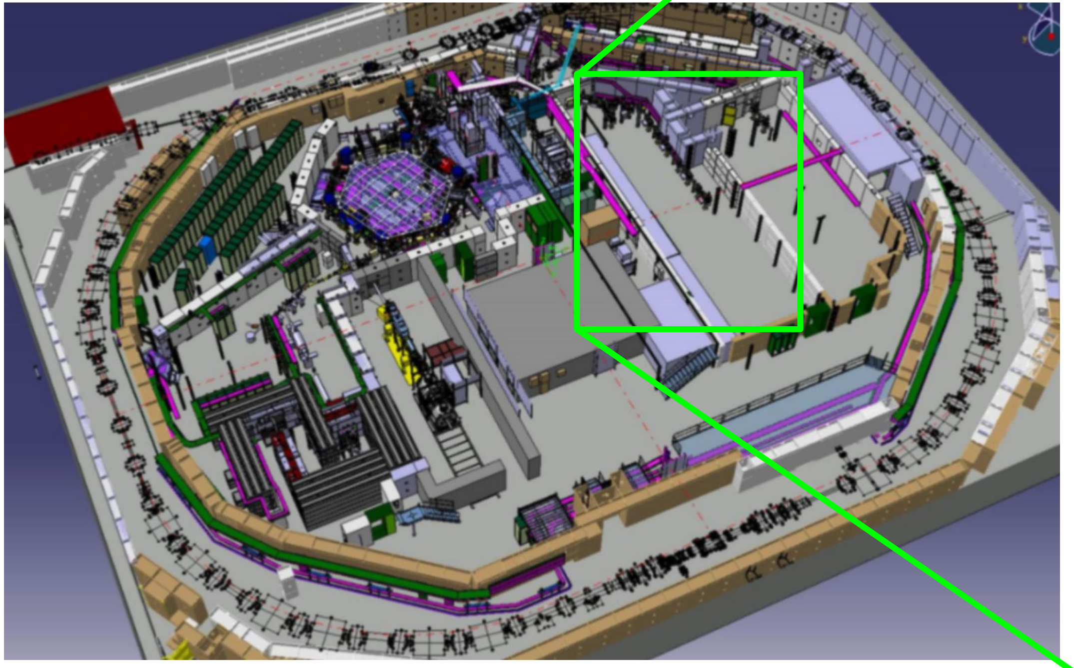
What
antimatter
hyperfine measurement

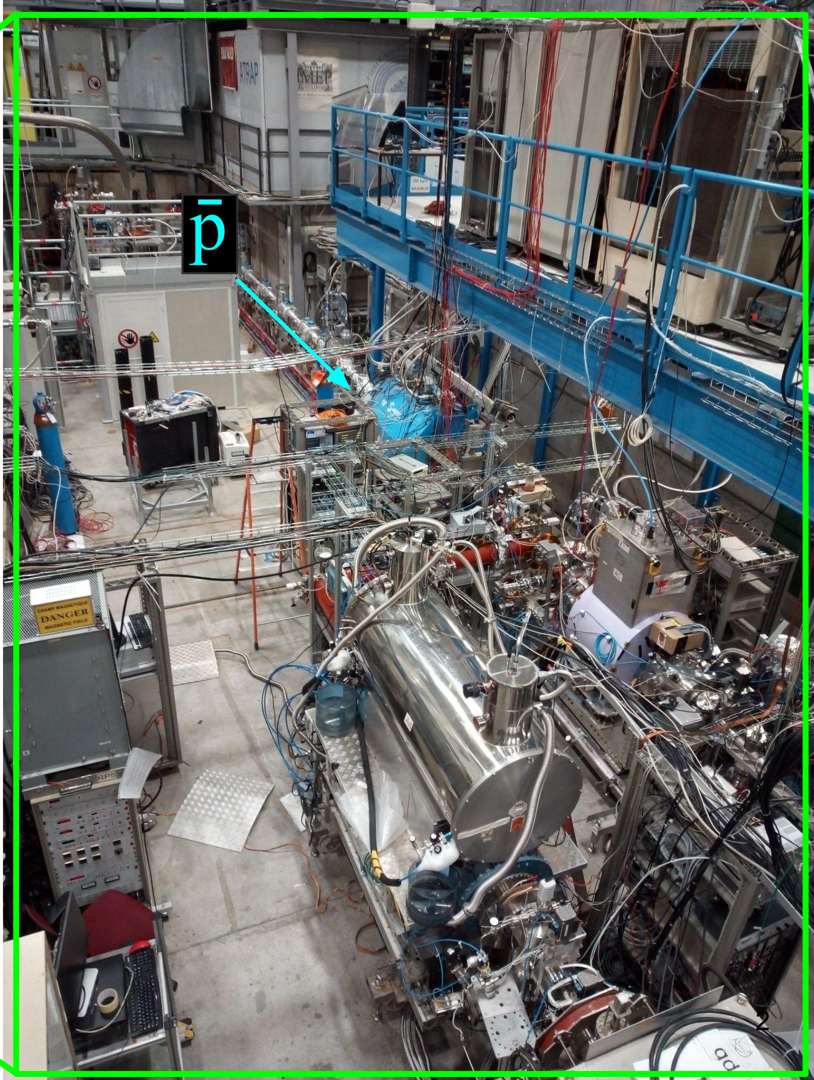
How
catching decelerated antiprotons
mixing them with a positron plasma

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

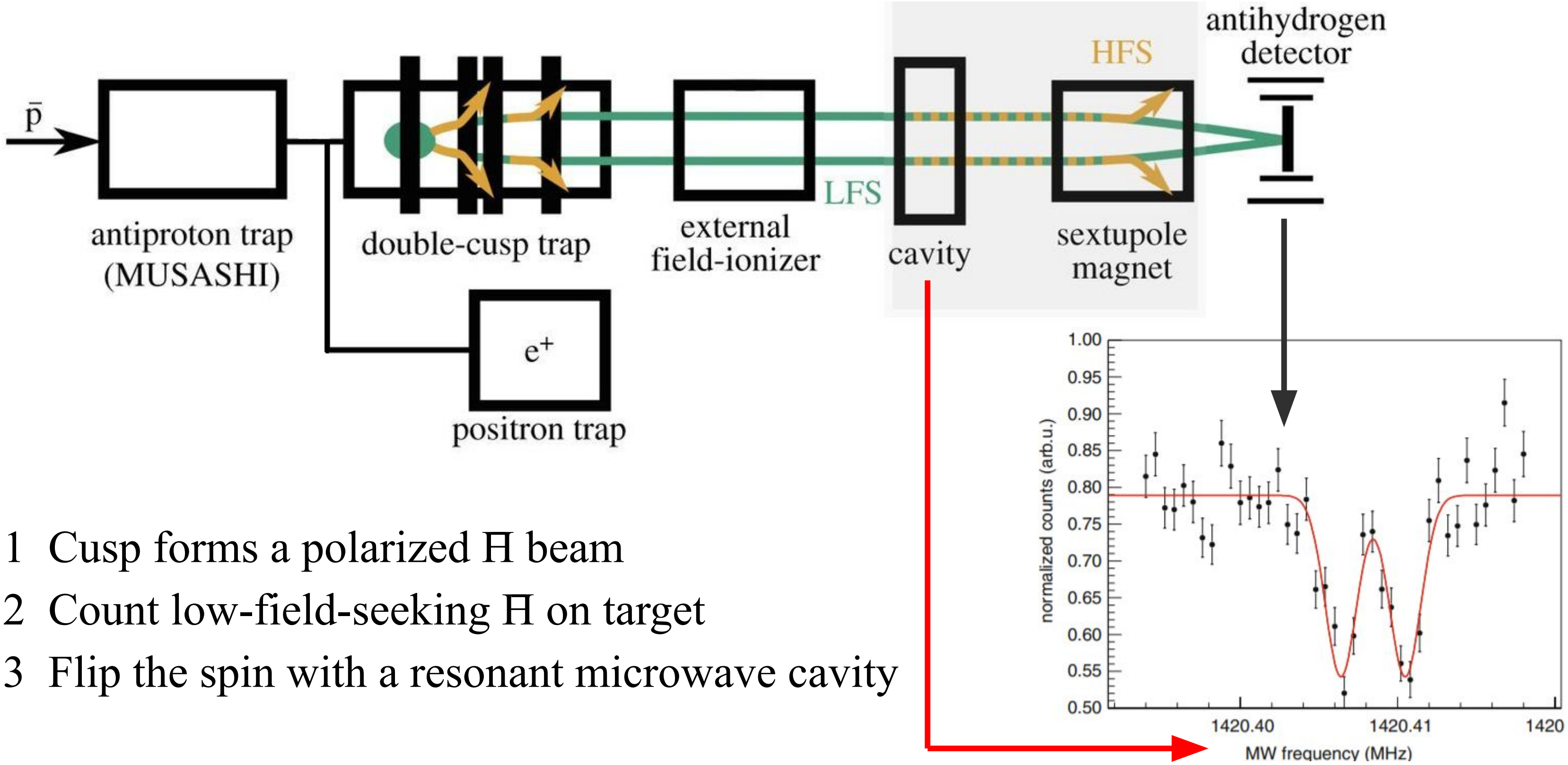
Eric Hunter
for the ASACUSA Collaboration
and the Stefan Meyer Institute

The Antiproton Decelerator (AD) at CERN





ASACUSA's spin flip proposal



1 Cusp forms a polarized H̄ beam

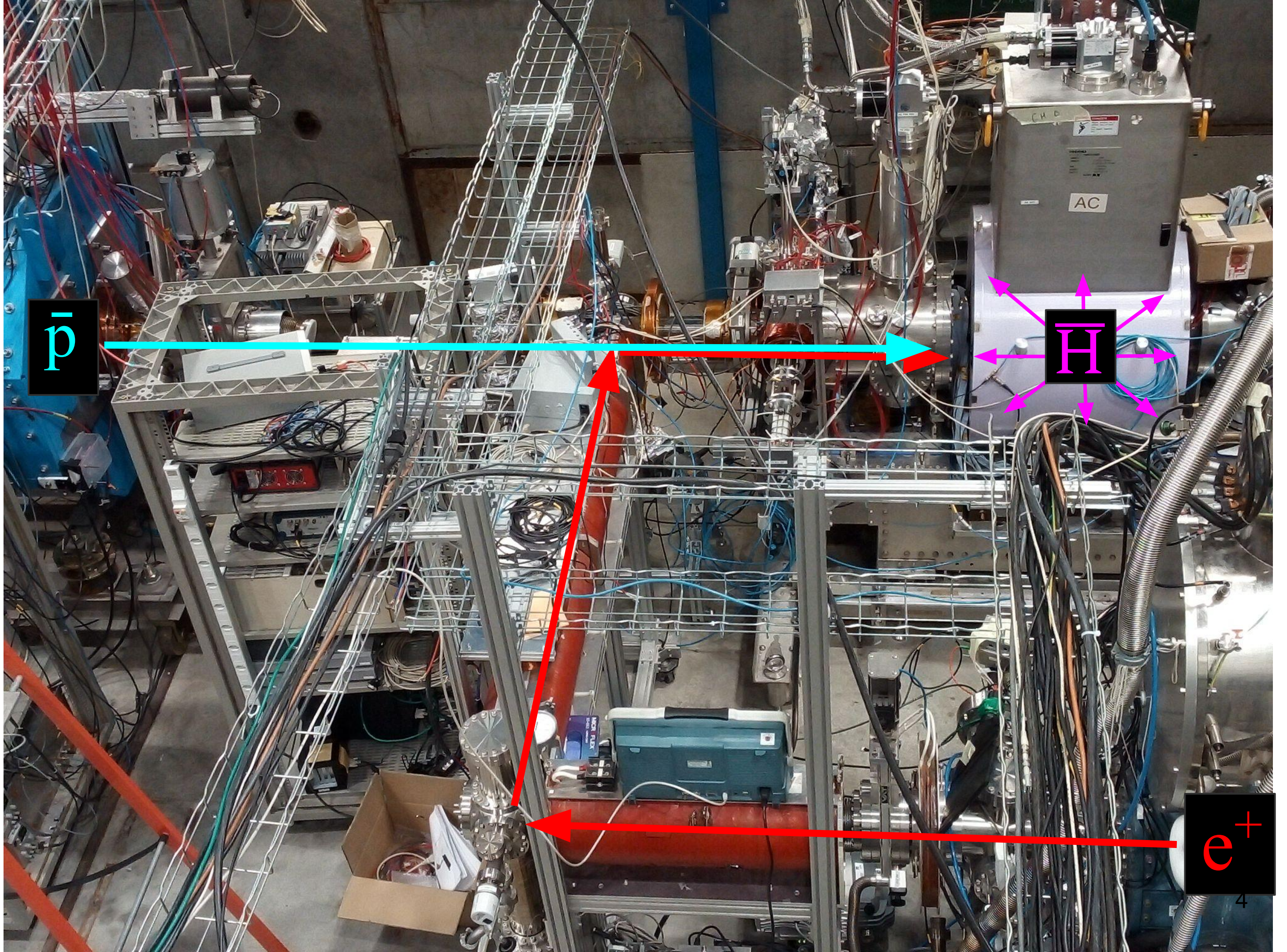
2 Count low-field-seeking H̄ on target

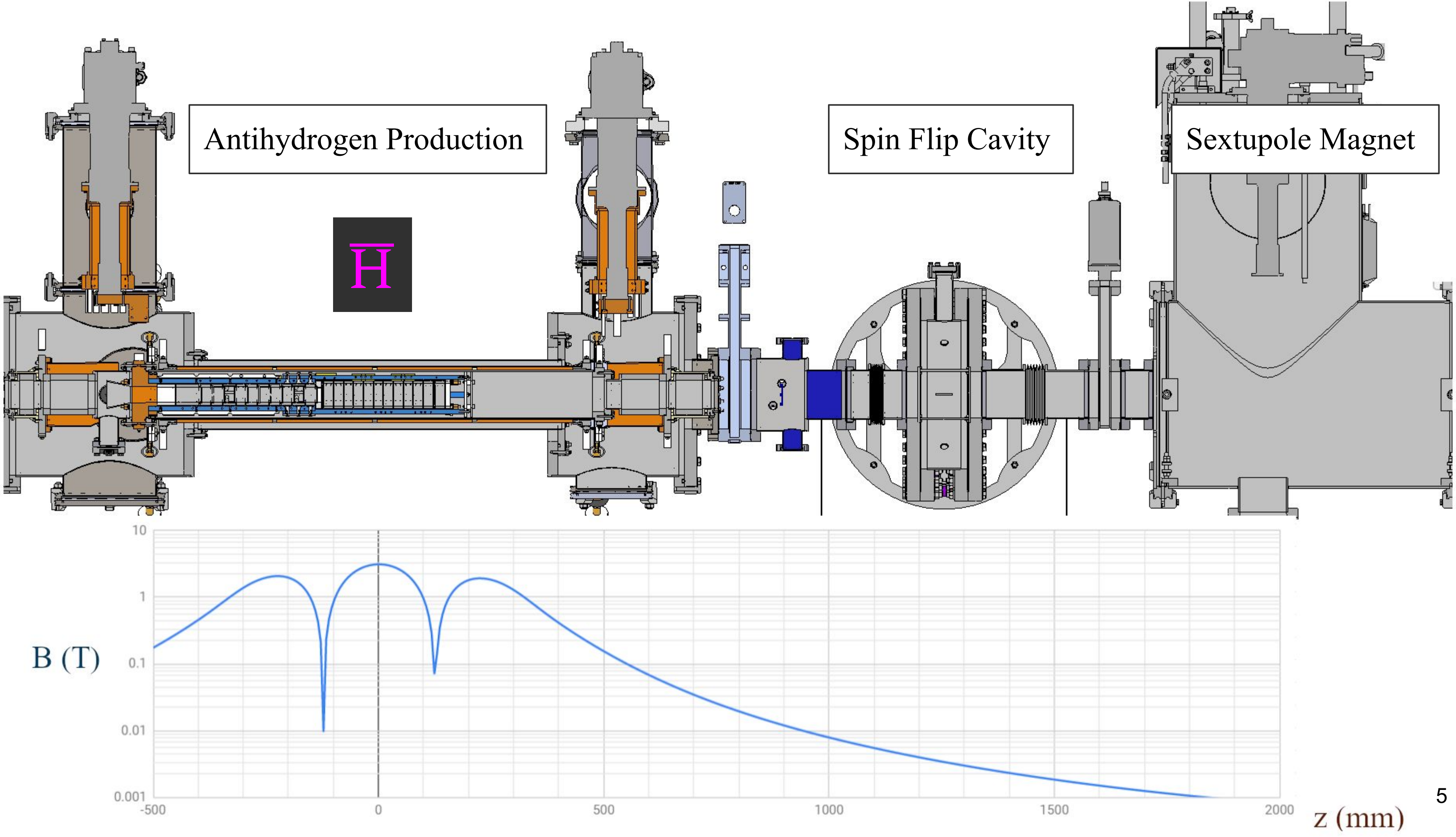
3 Flip the spin with a resonant microwave cavity

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

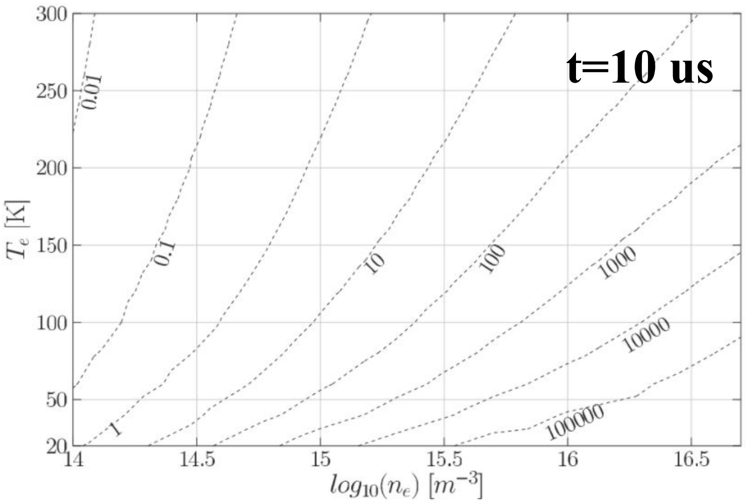



Antihydrogen Production
H
Spin Flip Cavity
Sextupole Magnet
B (T)
10
1
0.1
0.01
0.001
-500
0
500
1000
1500
2000
z (mm)

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

Simulations of antihydrogen formation suggest:

1. maximize interaction of H̄ with e^+
2. minimize plasma temperature



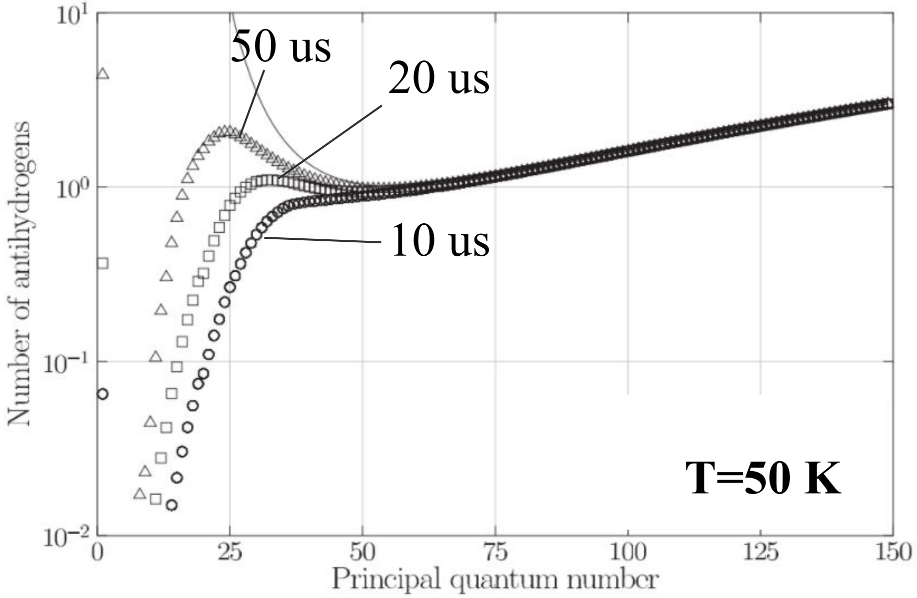


FIG. 1. Antihydrogen bound-state level population distribution after evolution of 10 μs (circle), 20 μs (square), and 50 μs (triangle) and the thermal equilibrium level population distribution (solid line) for positron temperature of $T_e = 50$ K and positron density $n_e = 10^{14}$ m^{-3}(with 10^6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

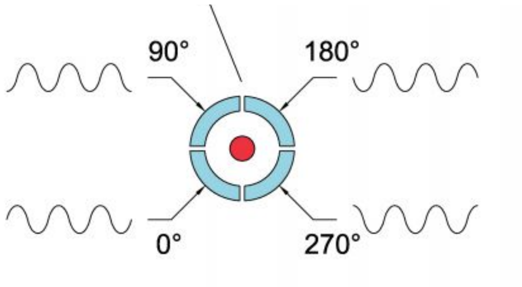
Radics, B., Murtagh, D. J., Yamazaki, Y., & Robicheaux, F. (2014). Scaling behavior of the ground-state antihydrogen yield as a function of positron density and temperature from classical-trajectory Monte Carlo simulations

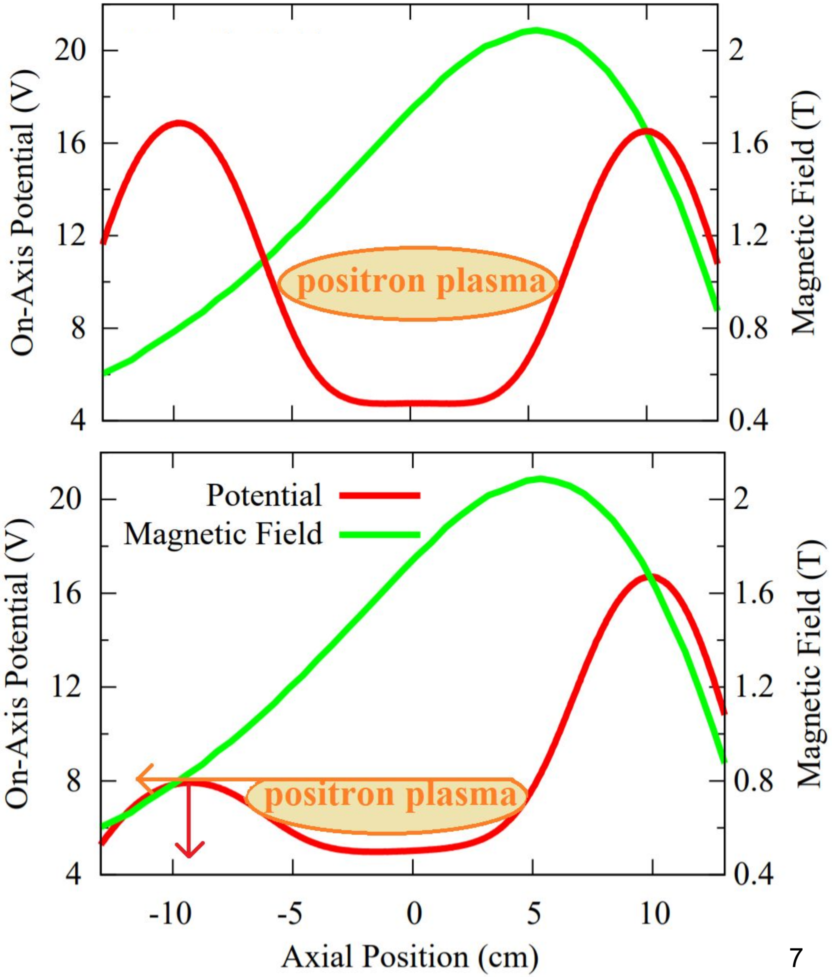
Control of plasma parameters

length
= electrode potentials

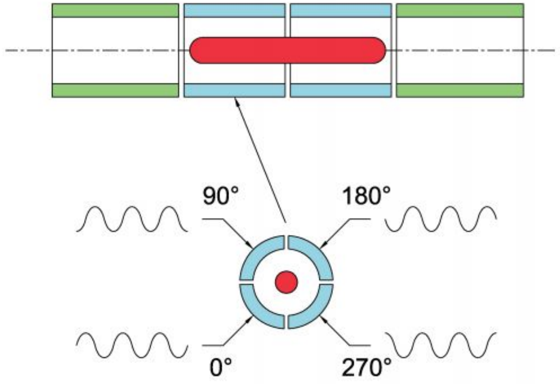
number of particles, temperature
= forced evaporation

density, radius
= rotating wall (next slide)





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

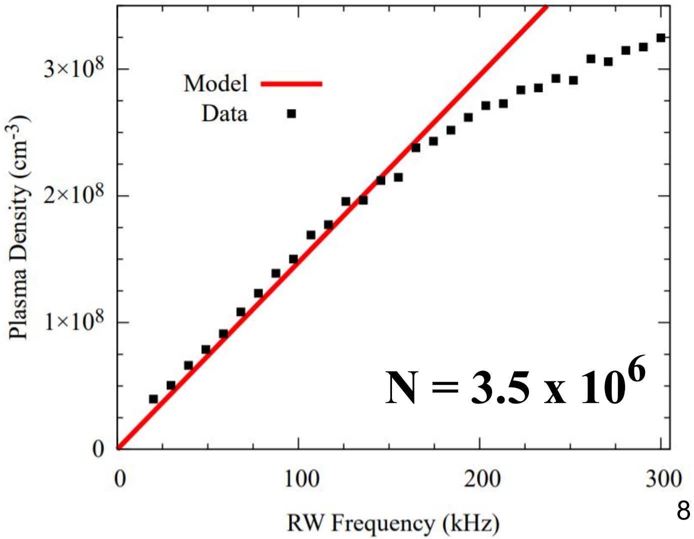


'Rotating' electrostatic field creates a torque, when the plasma rotation is slower than the field rotation frequency
→ Plasma rotation frequency asymptotes to RW frequency

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
→ Plasma density proportional to RW frequency

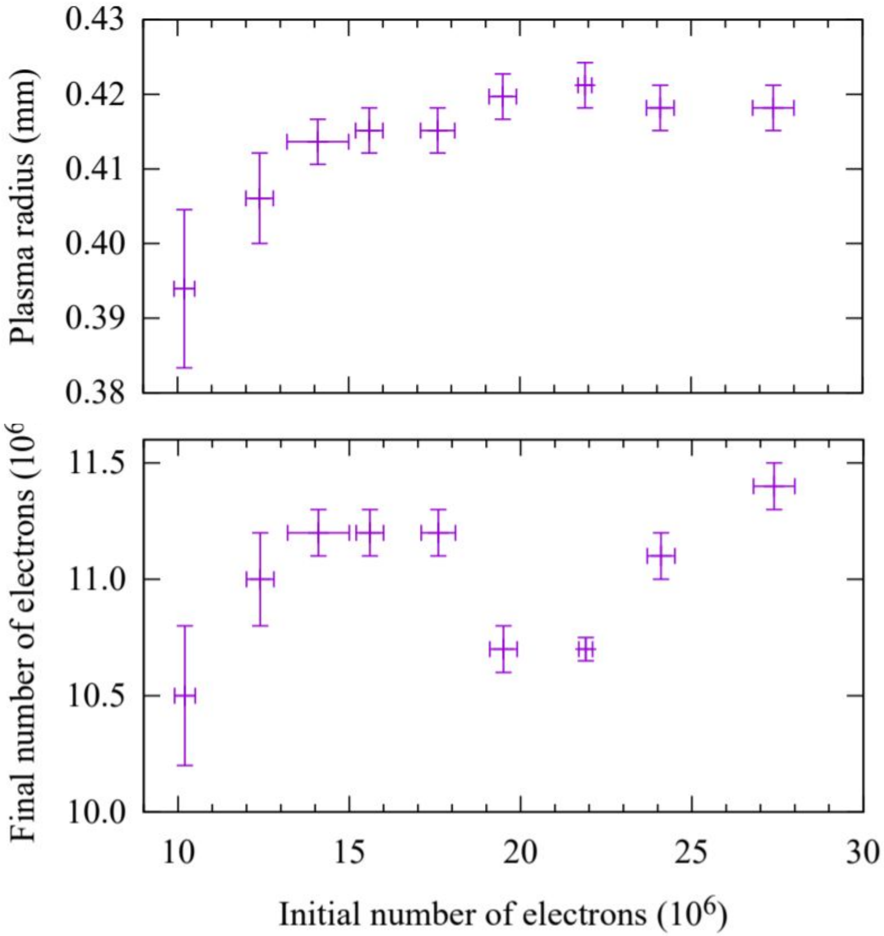


SDR + **EVC** = SDREVC

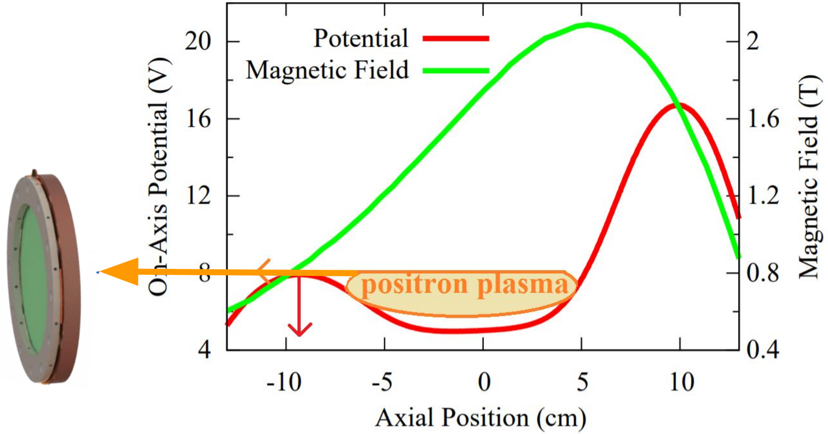
→ Simultaneous control of all plasma parameters

→ 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



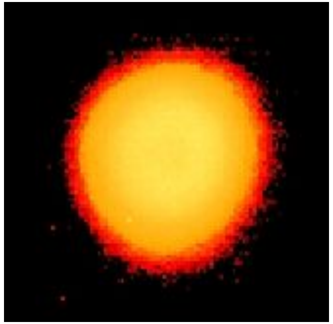
Plasma temperature diagnostic



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

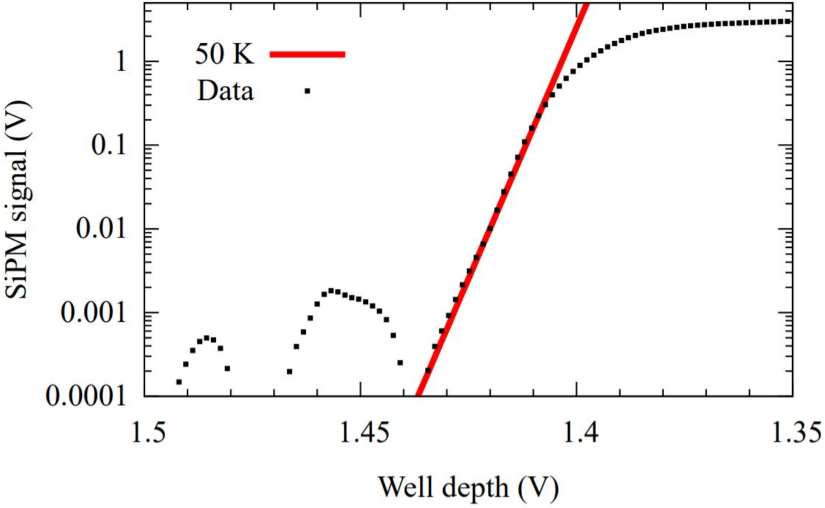
$$I(t) = G \cdot f(E(t)) \frac{dE}{dt}$$

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



$N \sim 2 \times 10^6$

$r_p \sim 1$ mm



Newton's law of cooling

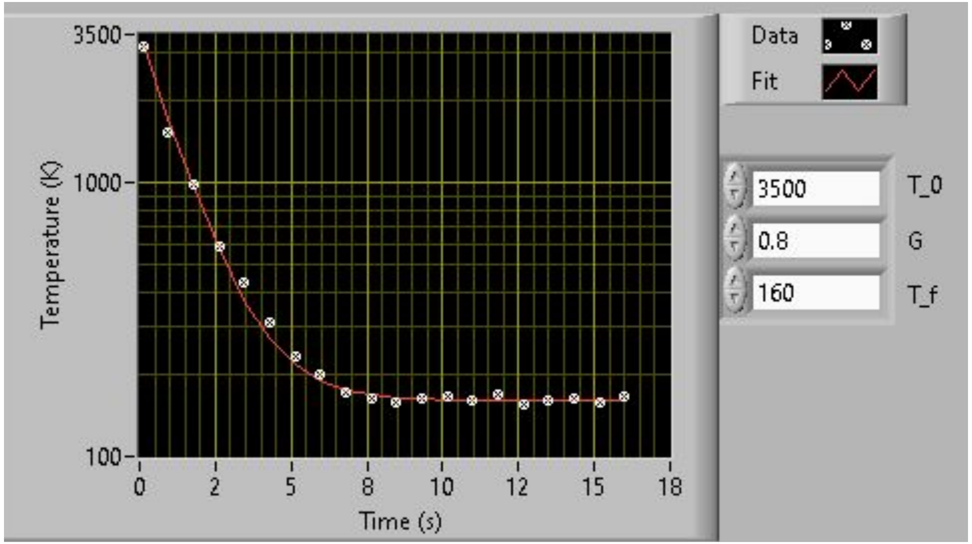
$dT/dt = -\Gamma(T - T_w) + H$

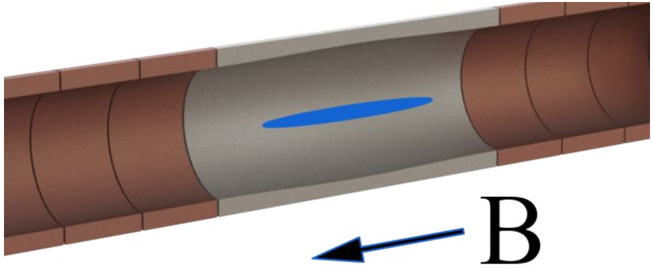
$\Rightarrow \quad T_f = T_w + H / \Gamma$

Electrode Temperature

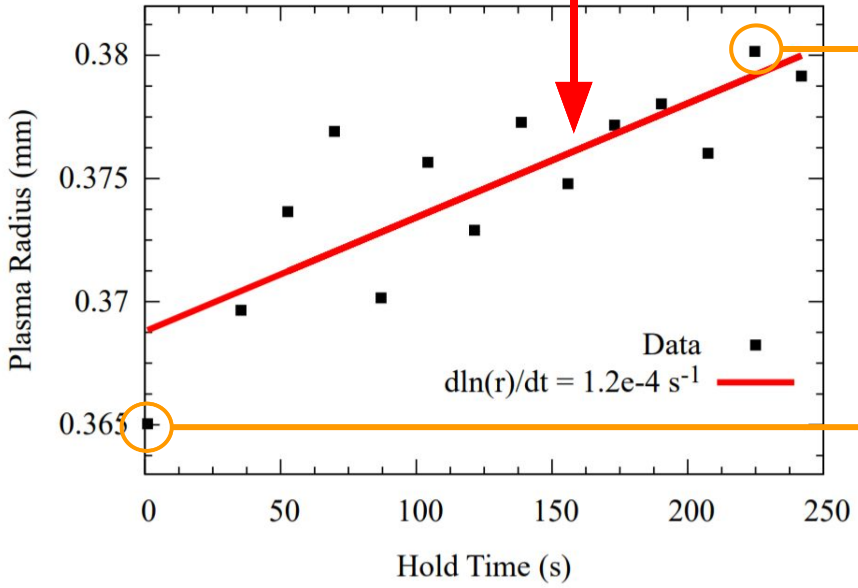
Plasma Heating Rate
(expansion and electrode noise)

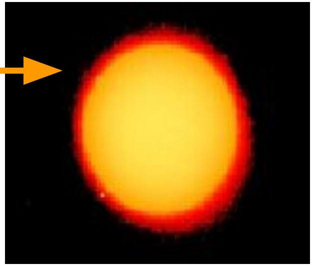
Cyclotron Cooling Rate

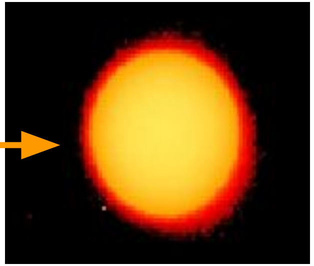


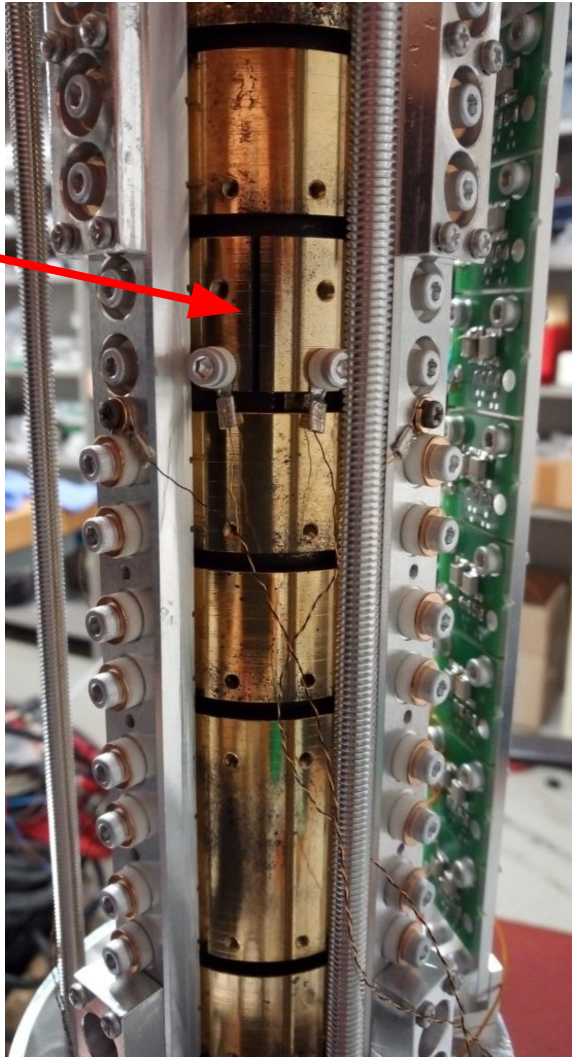


Plasma heating *H* is minimized by reducing RF noise on the electrodes and the plasma expansion rate

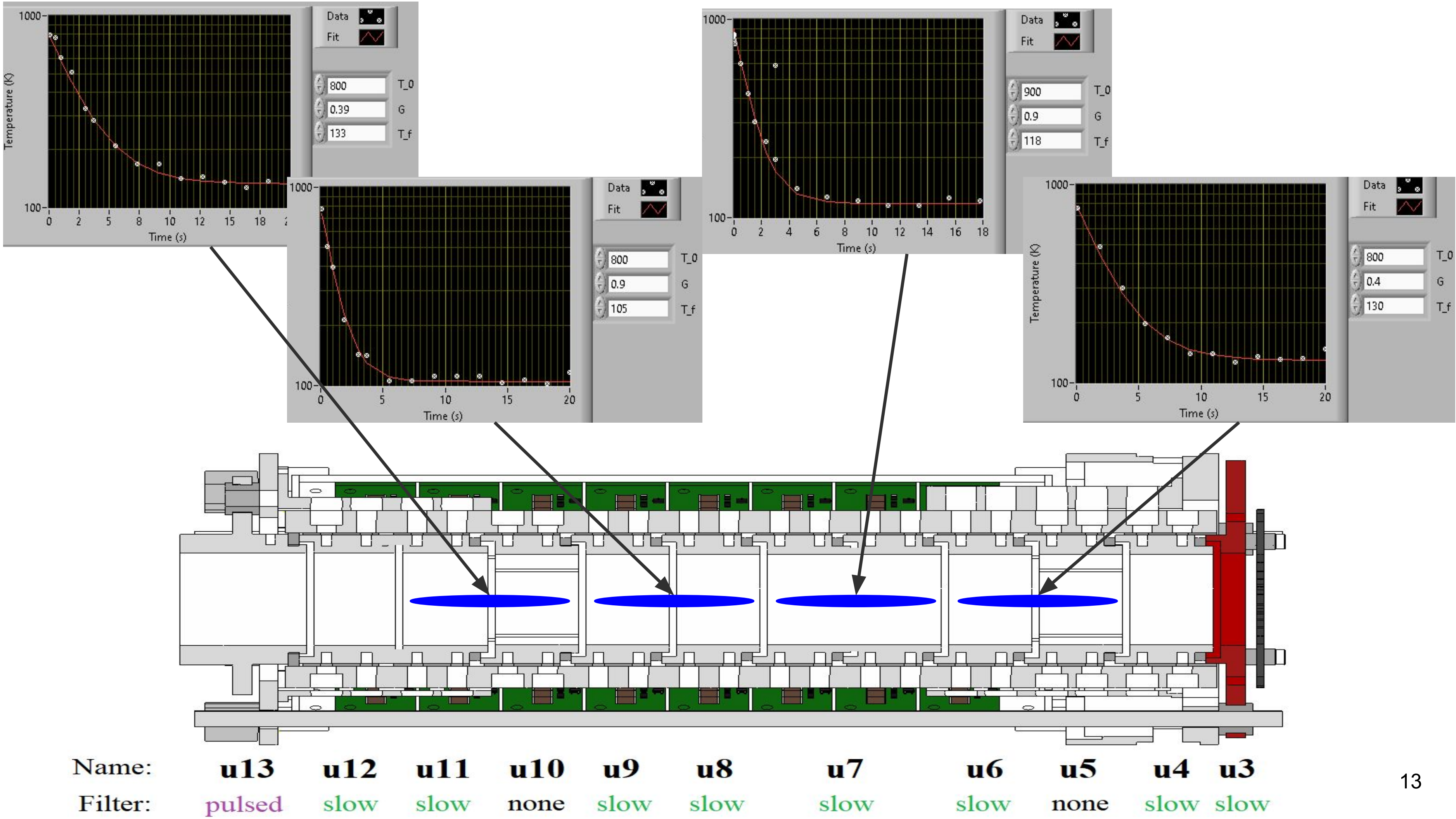








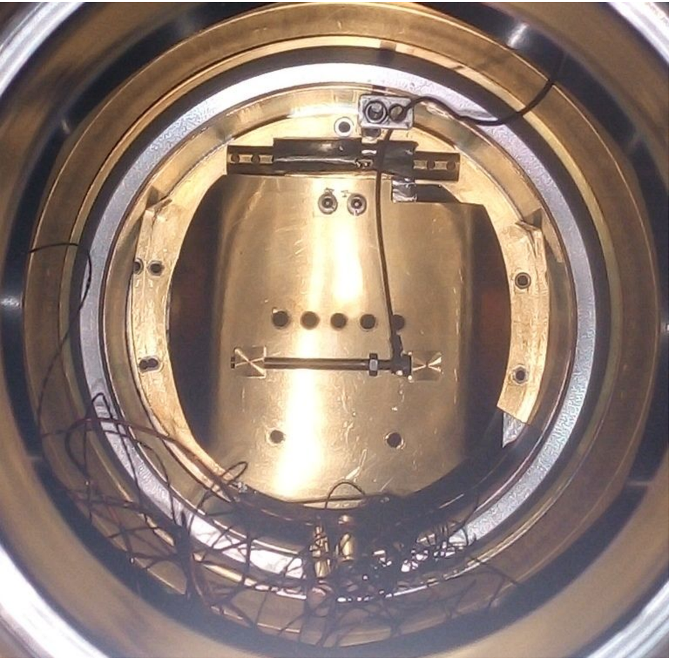
These are both very low in our trap.


Data
Fit
800 T_0
0.39 G
133 T_f
Temperature (K)
Time (s)
800 T_0
0.9 G
105 T_f
Time (s)
900 T_0
0.9 G
118 T_f
Time (s)
800 T_0
0.4 G
130 T_f
Temperature (K)
Time (s)
Name: u13 u12 u11 u10 u9 u8 u7 u6 u5 u4 u3
Filter: pulsed slow slow none slow slow slow slow none slow slow

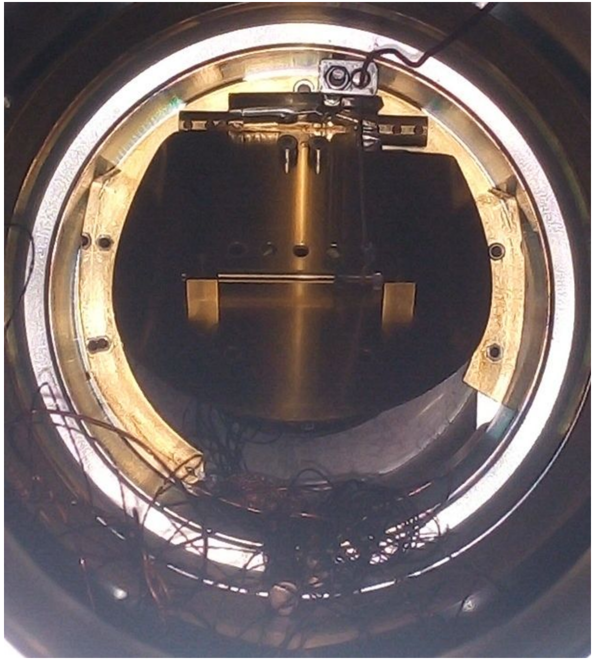
What if the radiation environment is hotter than the ~35 K electrodes?

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

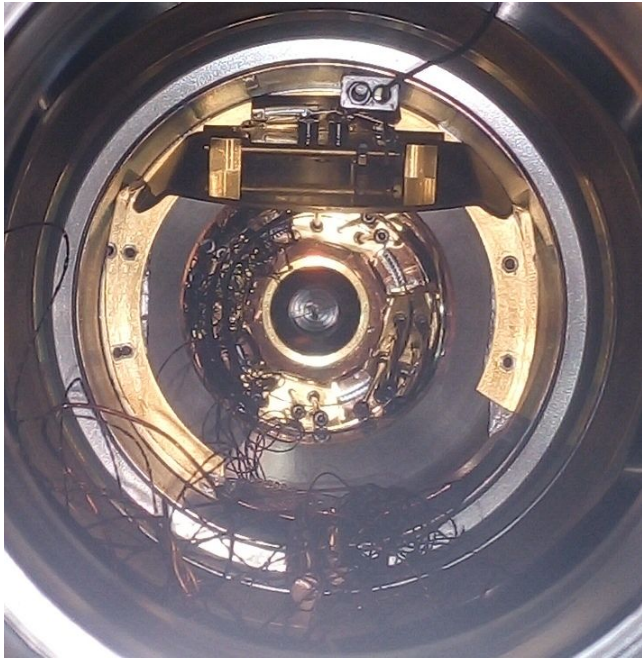
closed

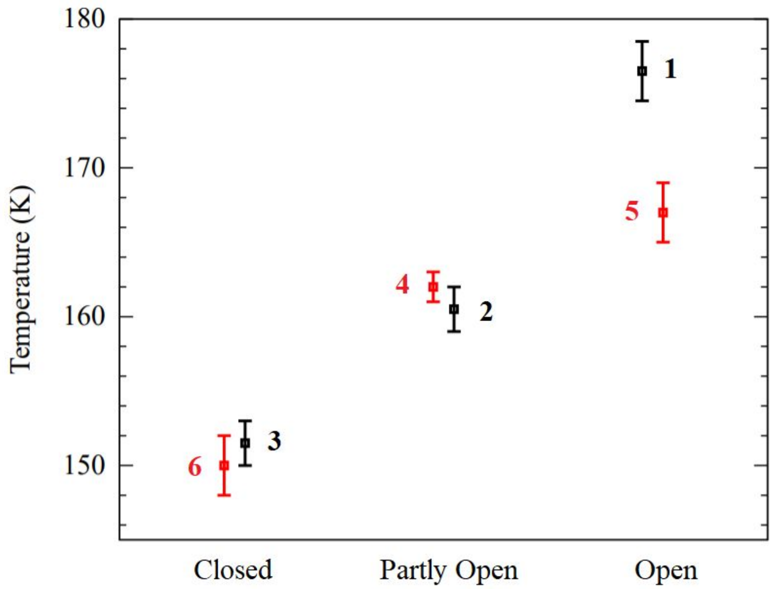


partly open

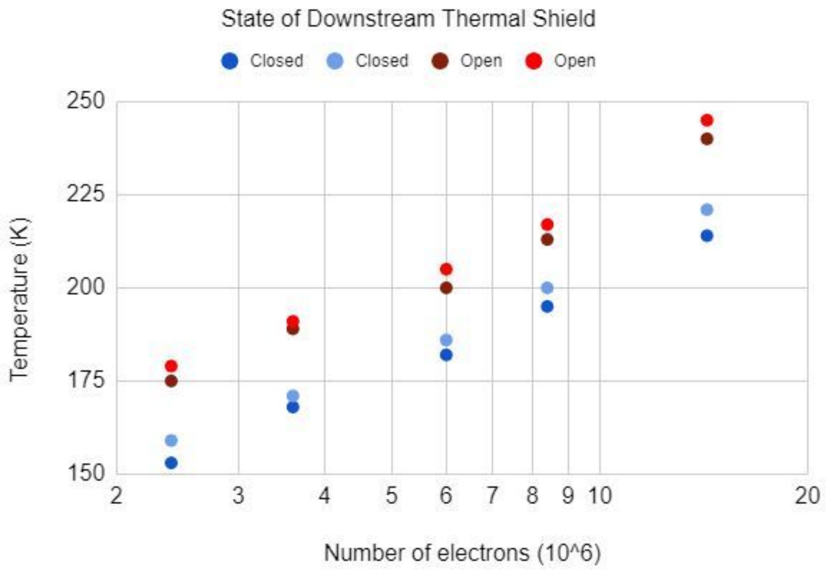


fully open

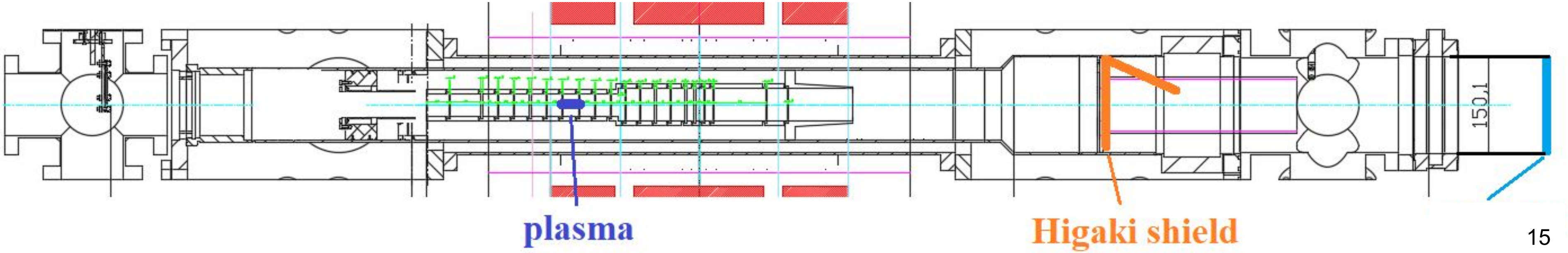




180
170
160
150
Temperature (K)
1
2
3
4
5
6
Closed
Partly Open
Open



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



150.1
plasma
Higaki shield

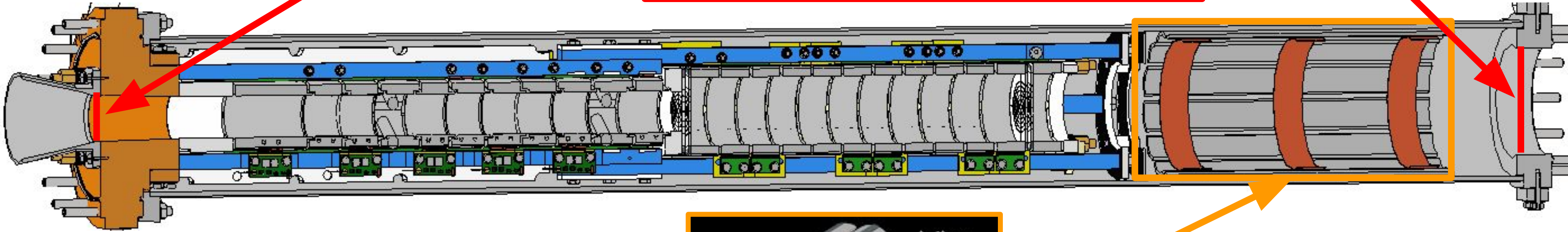
High transparency copper mesh
to reflect incoming microwaves

0.25 mm pitch

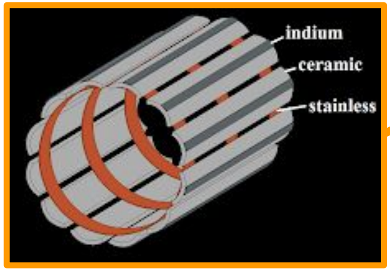
0.03 mm wire diameter

>20 dB attenuation at 60 GHz

F. Caspers



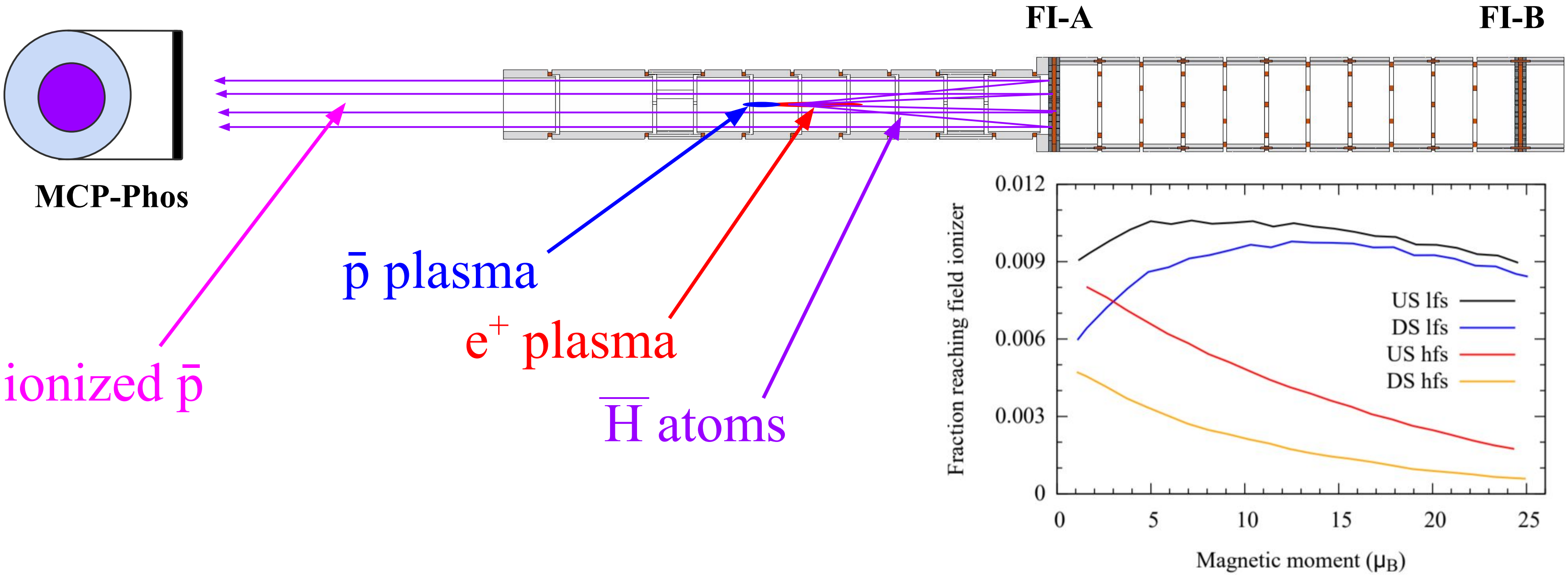
Ceramic “bracelet” to absorb
cyclotron radiation from the plasma

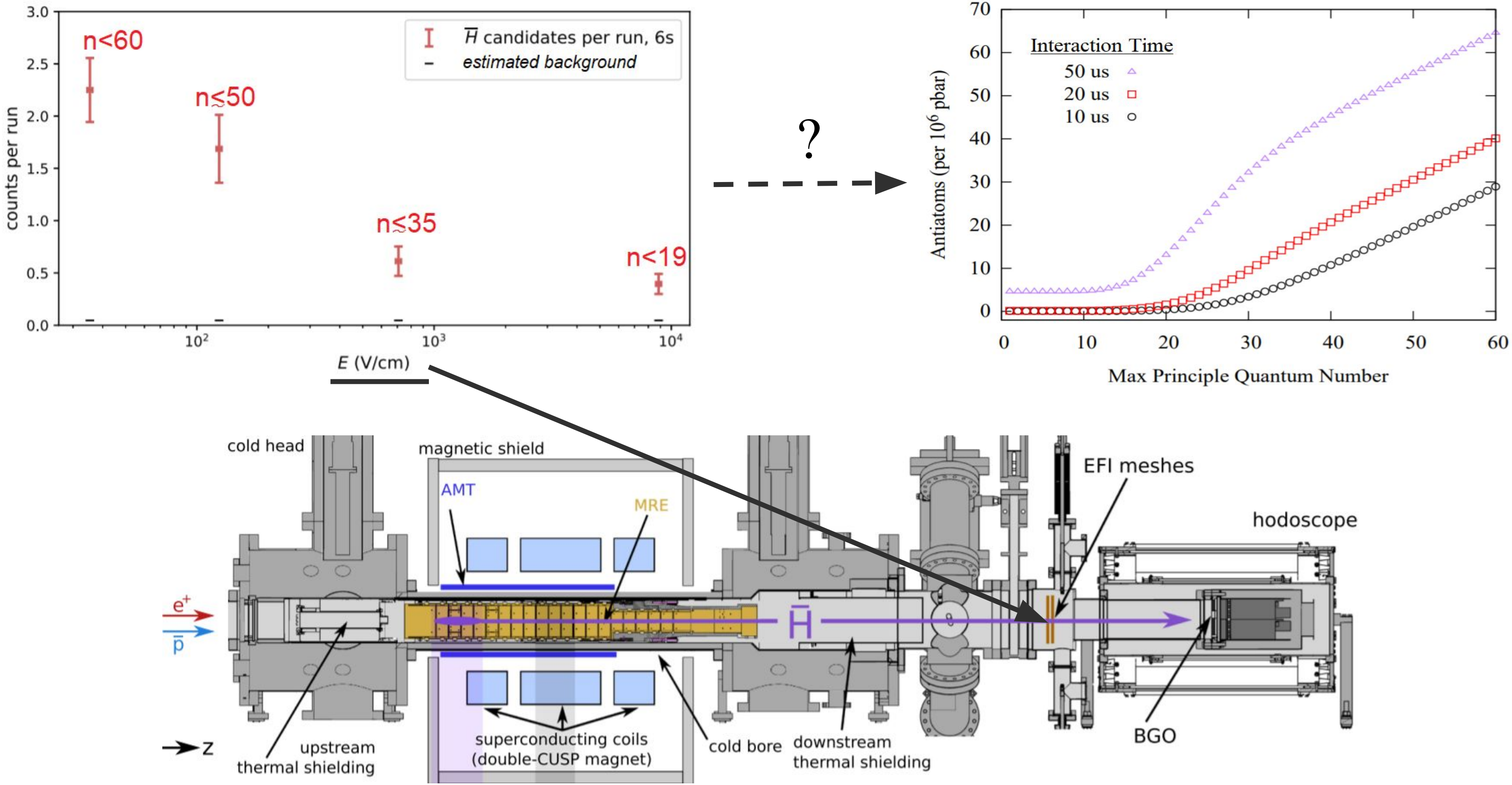


Field ionizers

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

Two ionizers: measure antihydrogen temperature (time of flight)





Measurement of the Principal Quantum Number Distribution in a Beam of Antihydrogen Atoms
B. Kolbinger et al. (ASACUSA Collaboration) Eur. Phys. J. D75 (2021) 91

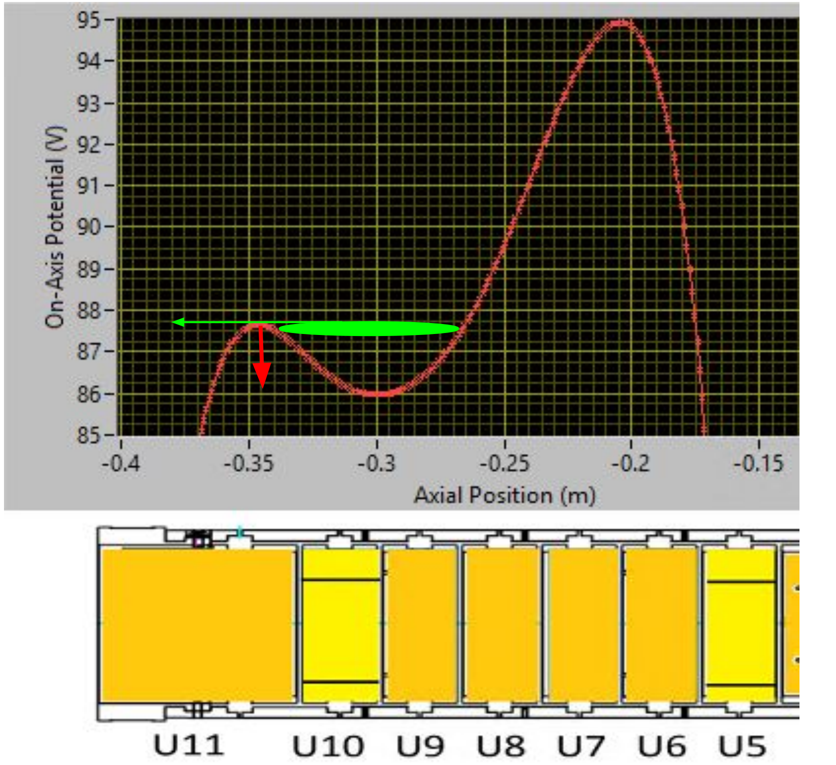
Backup slides

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

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

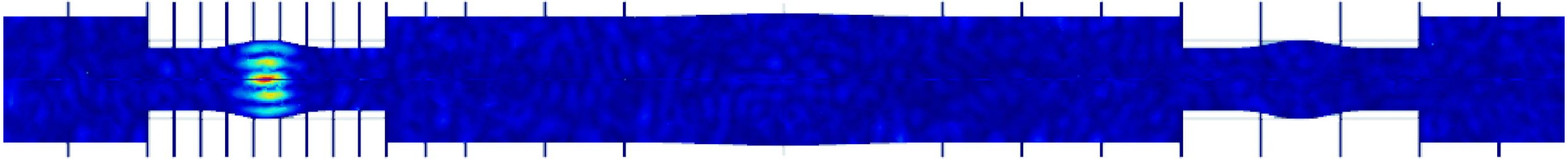
but plasma radius is not controlled



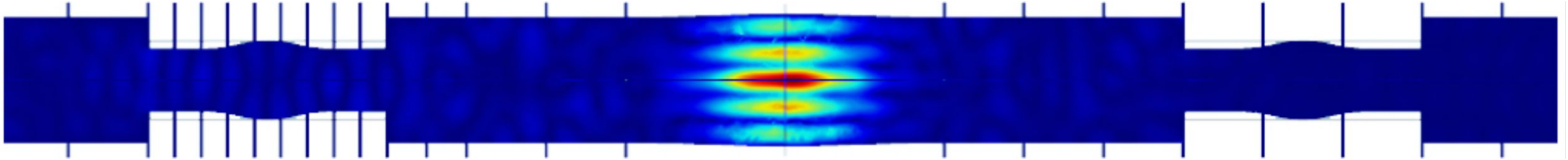
Purcell Effect

Resonant interaction with cavity modes can increase the cyclotron cooling rate

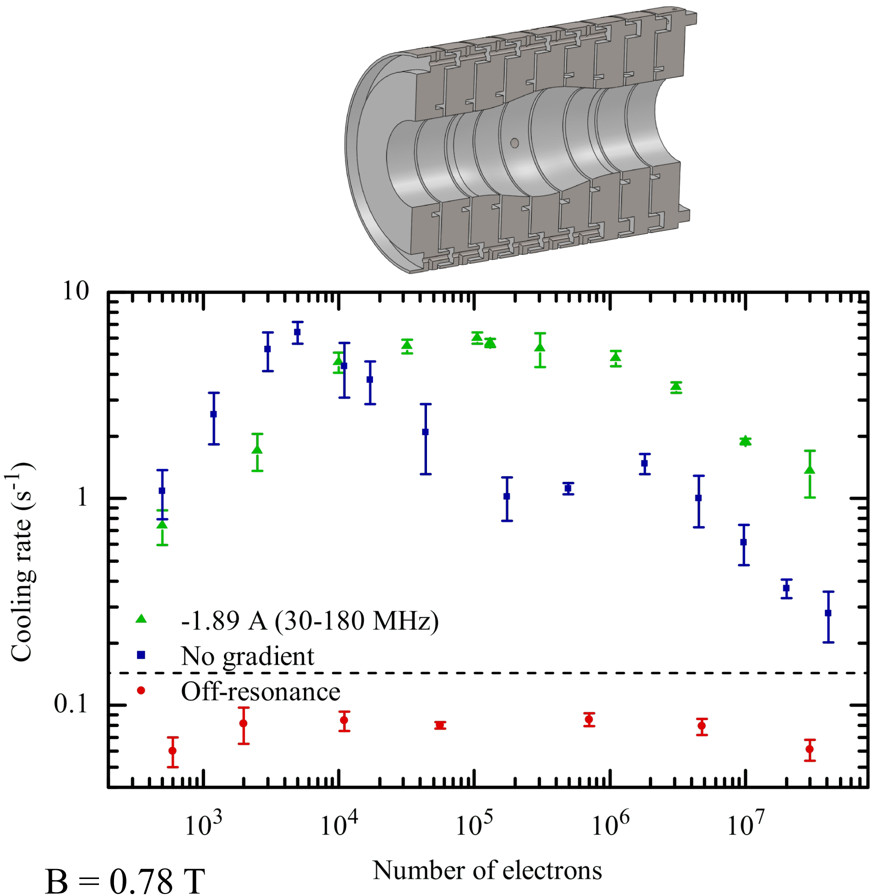
Cavity 1 -- TE_{131} -- 34.1 GHz -- qB/m at 1.22 T)



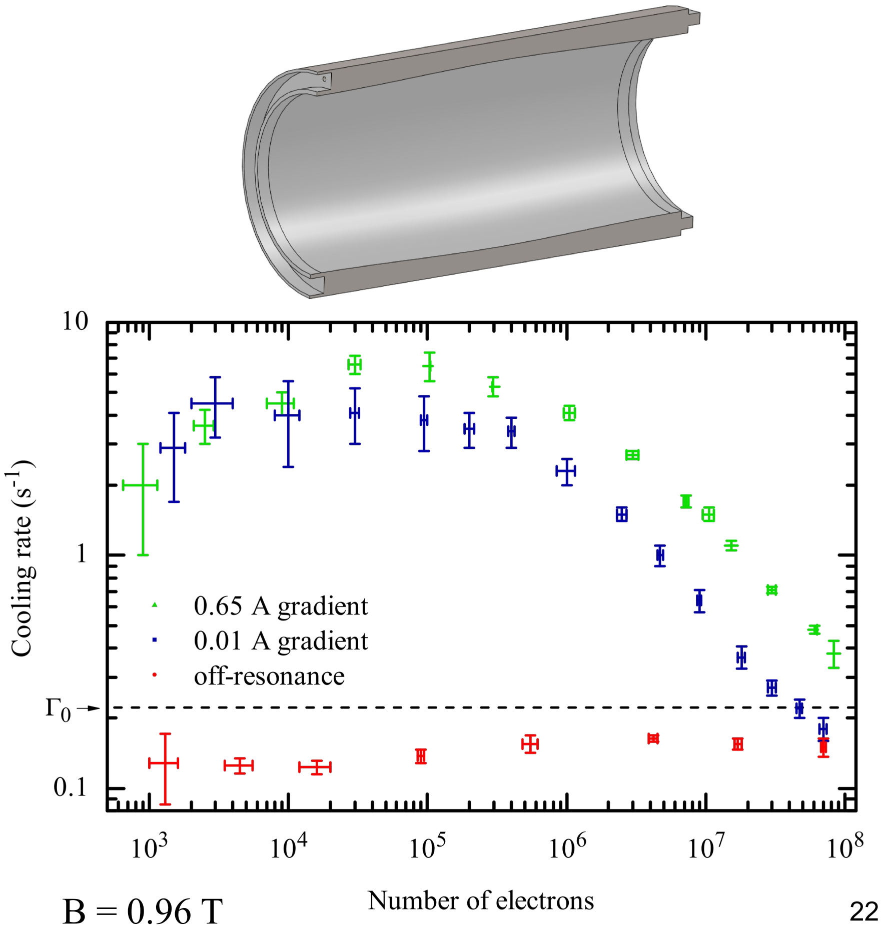
Cavity 2 -- TE_{131} -- 19.6 GHz -- qB/m at 0.70 T)



Cooling Rate

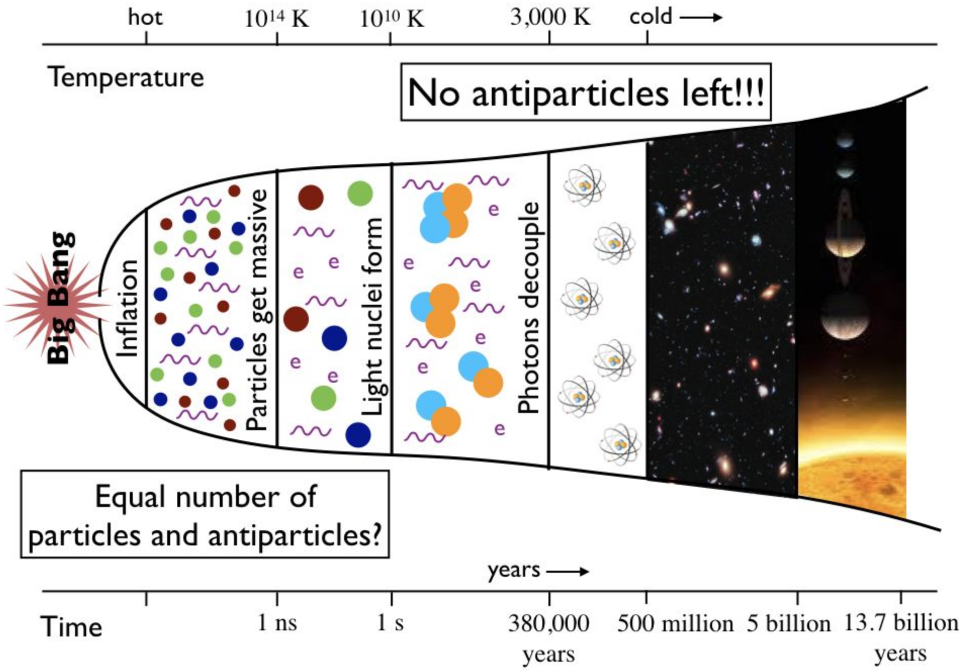


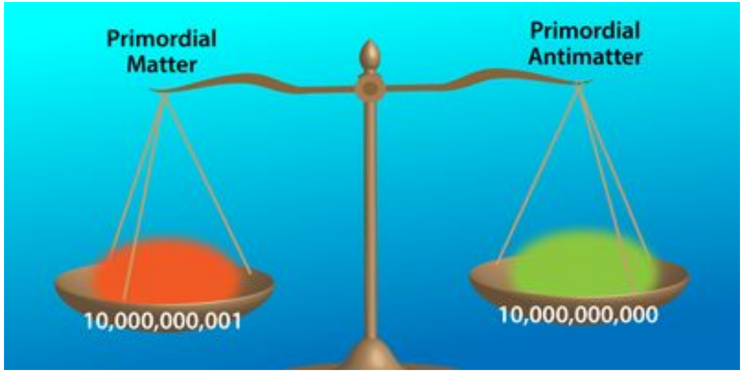
B = 0.78 T



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