An atomic beamline to measure the ground-state hyperfine splitting of antihydrogen

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on behalf of the ASACUSA collaboration

IFA (Århus), ISA (Århus), UB (Brescia), KFKI RMKI (Budapest), ATOMKI (Debrecen), CERN (Geneva), RIKEN (Saitama), UT (Tokyo), SMI (Vienna)

PST05, Tokyo, Japan, November 16, 2005

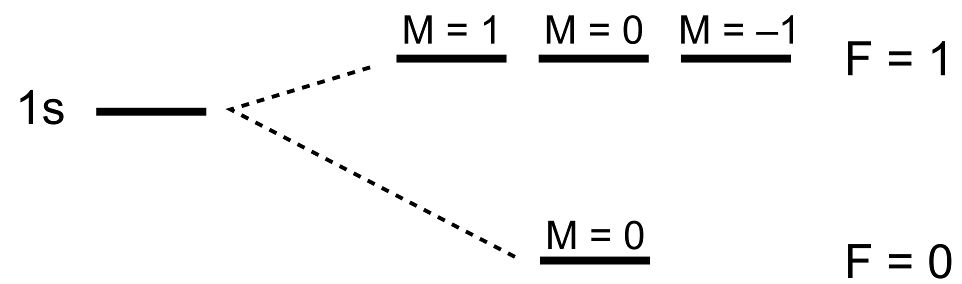
Outline

- What is ground-state hyperfine splitting
- $\overline{\text{H}}$ GS-HFS as CPT symmetry test
- How we want to measure it
  - Low-velocity $\overline{\text{H}}$ production in Paul trap or cusp trap
  - Sextupole magnets for spin selection and analysis
  - Microwave cavity
- Monte Carlo simulations
  - Beamline design
  - Expected count rate and precision

GS-HFS of (anti)hydrogen

Ground-state hyperfine splitting (GS-HFS):

- Interaction between (anti)proton and electron (positron) spin magnetic moment
- Results in triplet ($F = 1$) and singlet ($F = 0$) sublevels



- Between $F = 1$ and $F = 0$:
  $$\nu_{\mathrm{HF}} \simeq \frac{16}{3}\left(\frac{m_p}{m_p + m_e}\right)^3 \frac{m_e}{m_p}\frac{\mu_p}{\mu_N}\alpha^2 c\, Ry \simeq 1.42\ \mathrm{GHz}$$
- ν_{HF} proportional to (anti)proton magnetic moment μ_p

SME including CPTV and LIV

Kostelecky *et al.*: Standard Model extension (SME) including

- Charge-Parity-Time invariance violating (CPTV)
- Lorentz invariance violating (LIV)

terms in Lagrangian $\Rightarrow$ correction to sublevel energies:

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\begin{aligned}
\Delta E^{\mathrm{H}}(m_J, m_I) = a_0^e + a_0^p - c_{00}^e m_e - c_{00}^p m_p + \\
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Parameters a, d, and H reverse sign for antihydrogen

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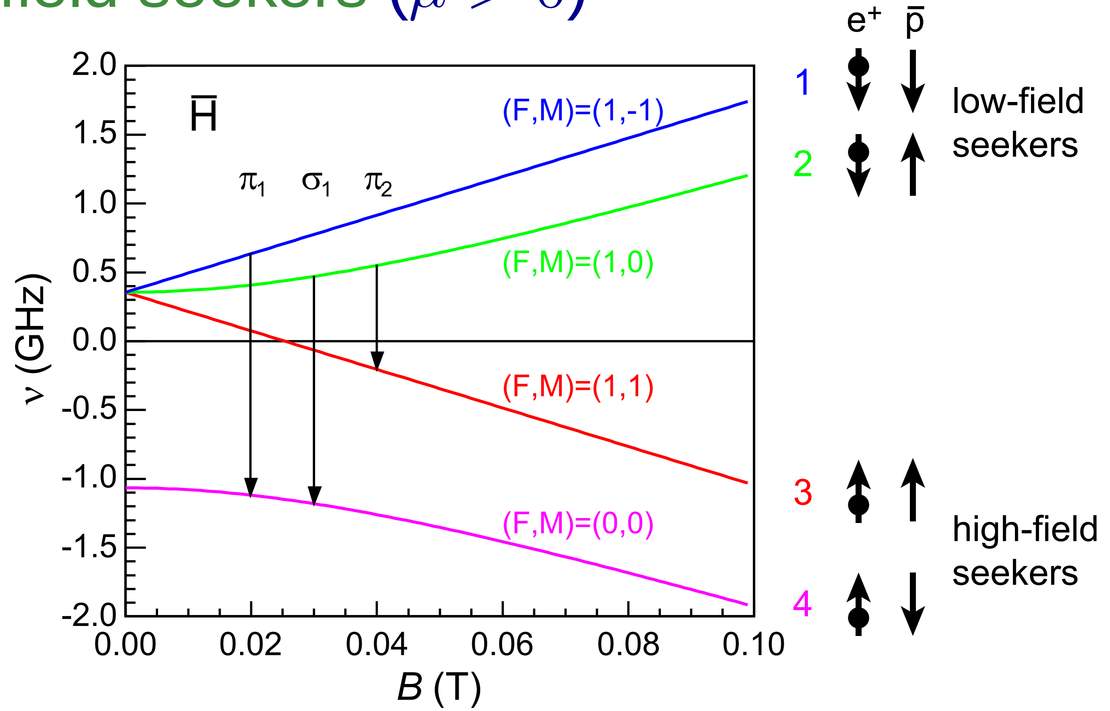
- Measurement at the Antiproton Decelerator (AD) of CERN after $\sim$2007

Ground-state H or $\overline{\text{H}}$ in magnetic field

Energies of hyperfine states change in magnetic field

- Increase for (F, M) = (1,$-$1) and (1,0)
  $\Rightarrow$ low-field seekers ($\mu < 0$)
- Decrease for (F, M) = (1,1) and (0,0)
  $\Rightarrow$ high-field seekers ($\mu > 0$)



Focusing in sextupole field

potential: $V = -\vec{\mu}\vec{B}$

force: $\vec{F} = -\text{grad}\, V = \text{grad}(\vec{\mu}\vec{B})$

If $d\theta_B/dt \ll \omega_\text{L}$ and μ constant:

$\vec{F} = \mu\, \text{grad}(B)$

Sextupole field (cylindrical coord.):

$\vec{B}(r) = (3Cr^2 \sin 3\phi, 3Cr^2 \cos 3\phi, 0)$

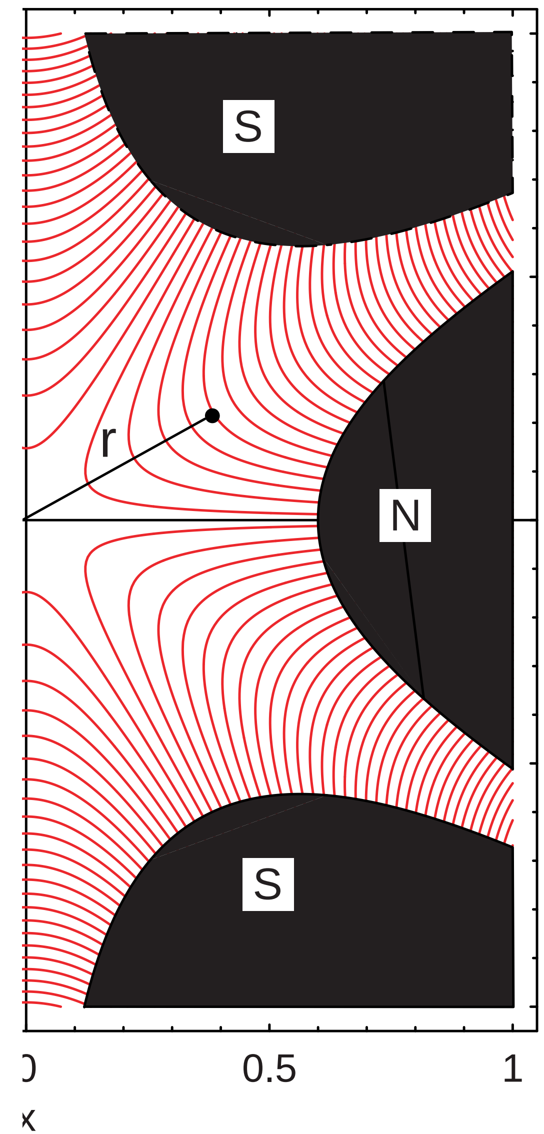
$B(r) = 3Cr^2 \Rightarrow F_r = \mu\, \partial B/\partial r = 6C\mu r$

$\Rightarrow$ harmonic oscillation:

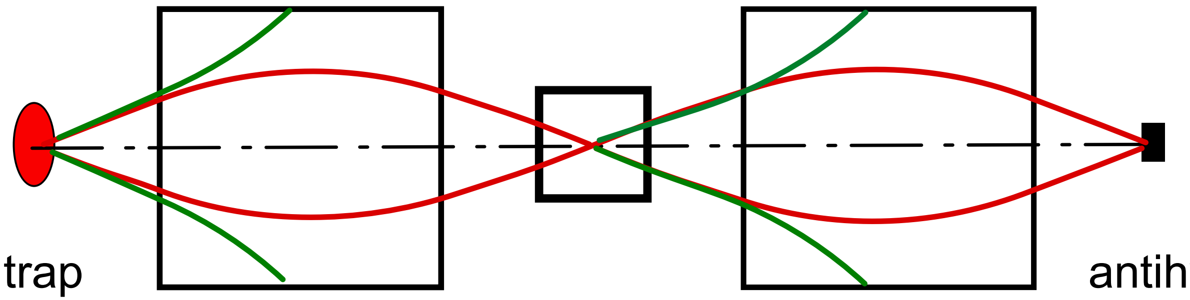
$\omega = \sqrt{6C\mu/m}$

$\Rightarrow$ point-to-point focusing for single v_z:

$l_f = \pi v_z \sqrt{m/6C\mu}$



Schematic layout



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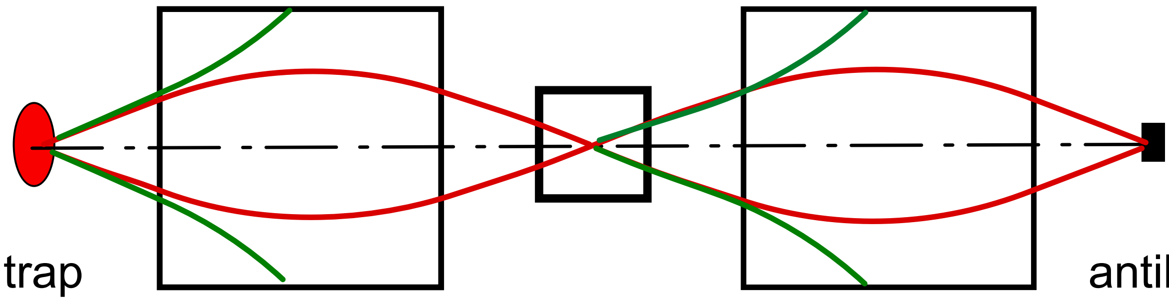

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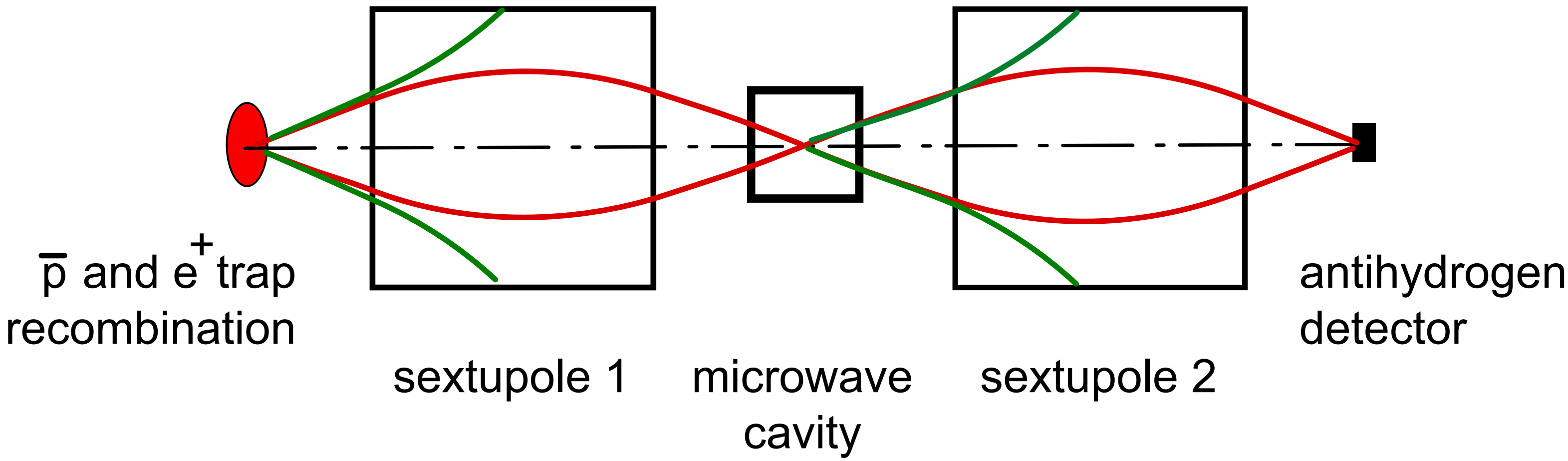

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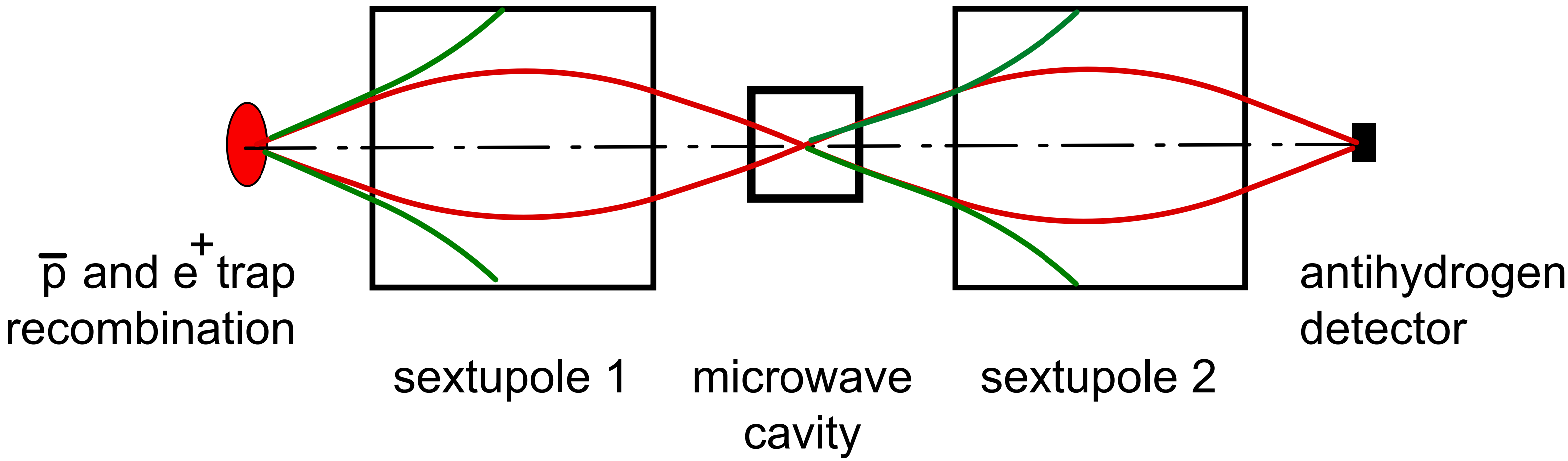

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- 2nd sextupole analyzes spin

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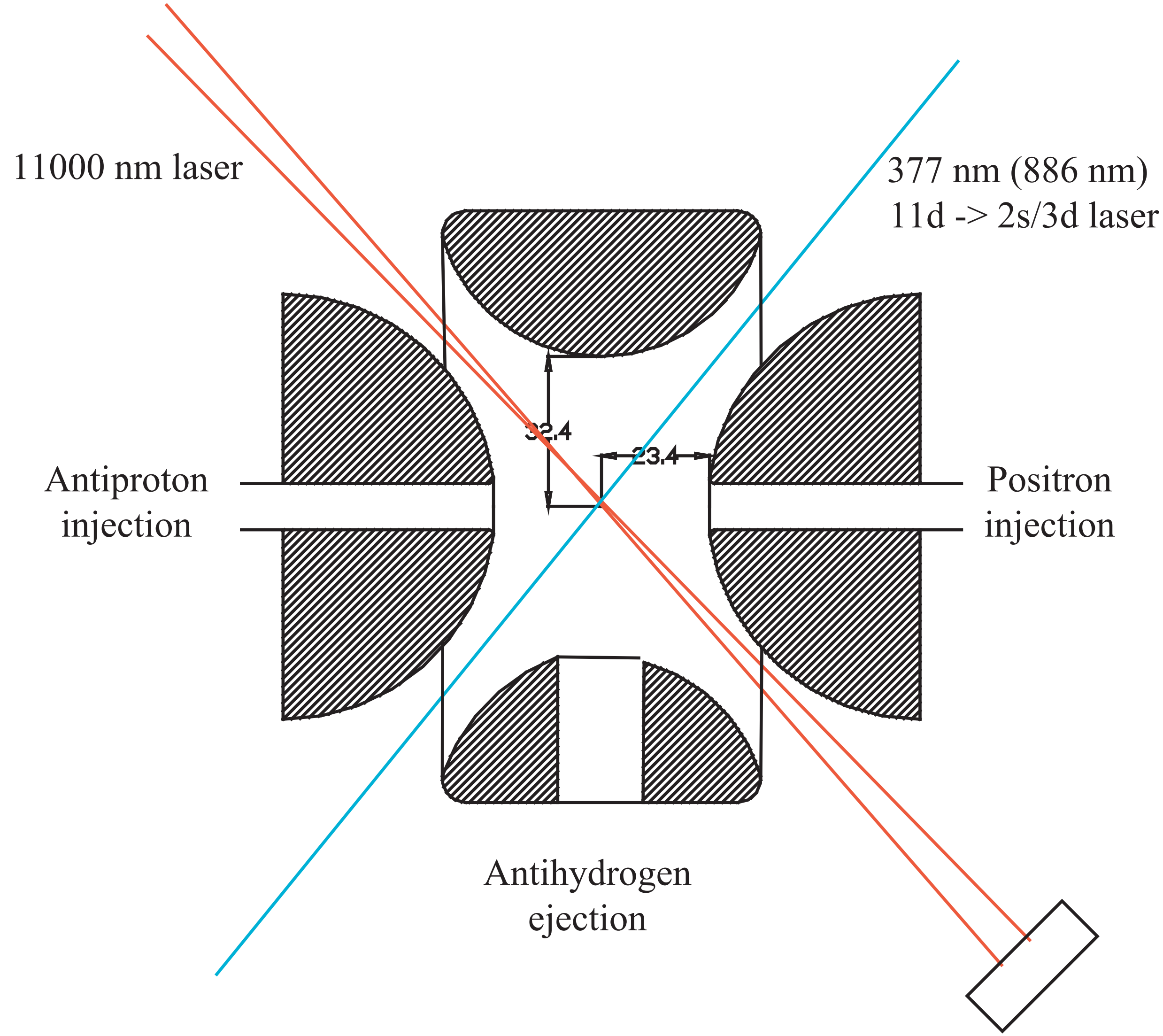

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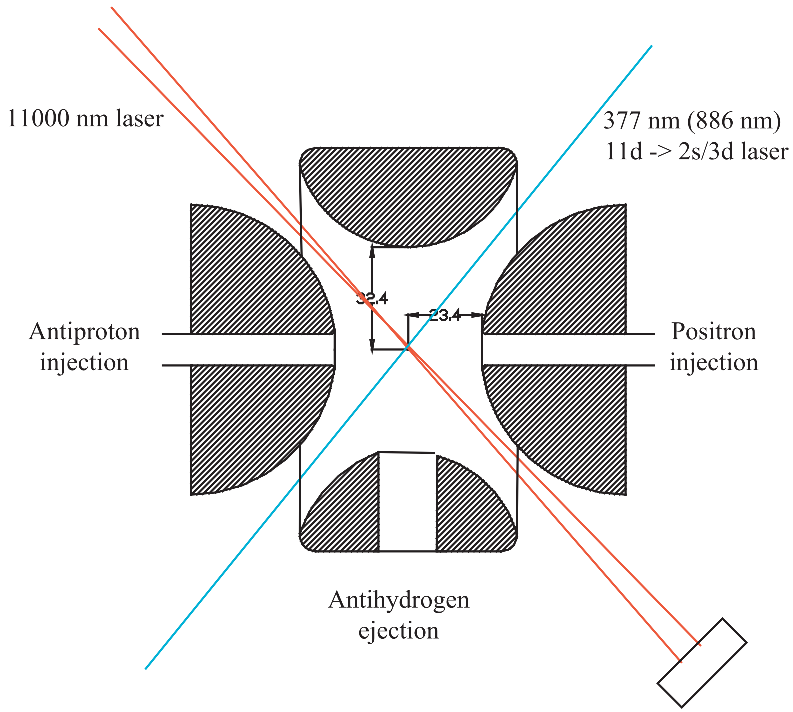

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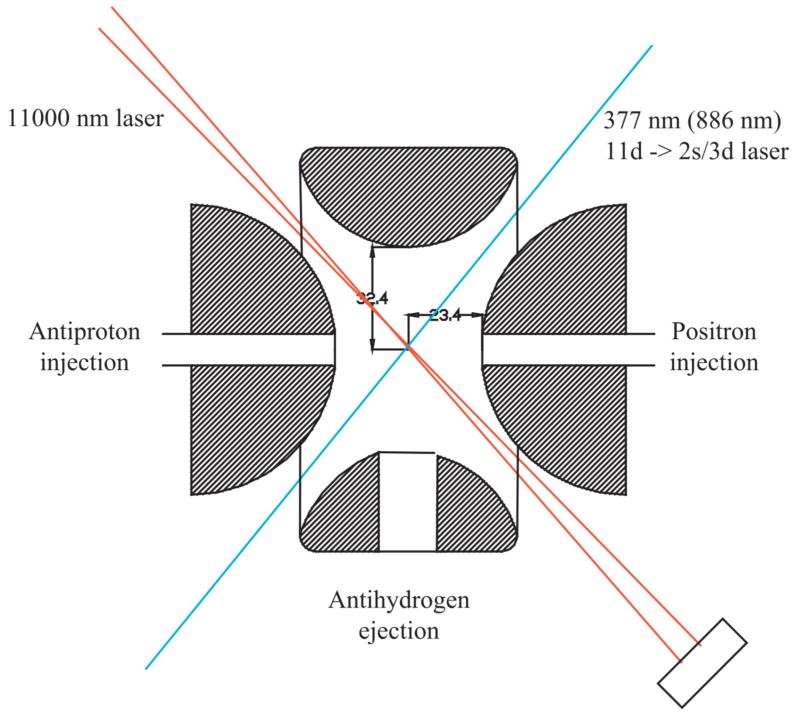

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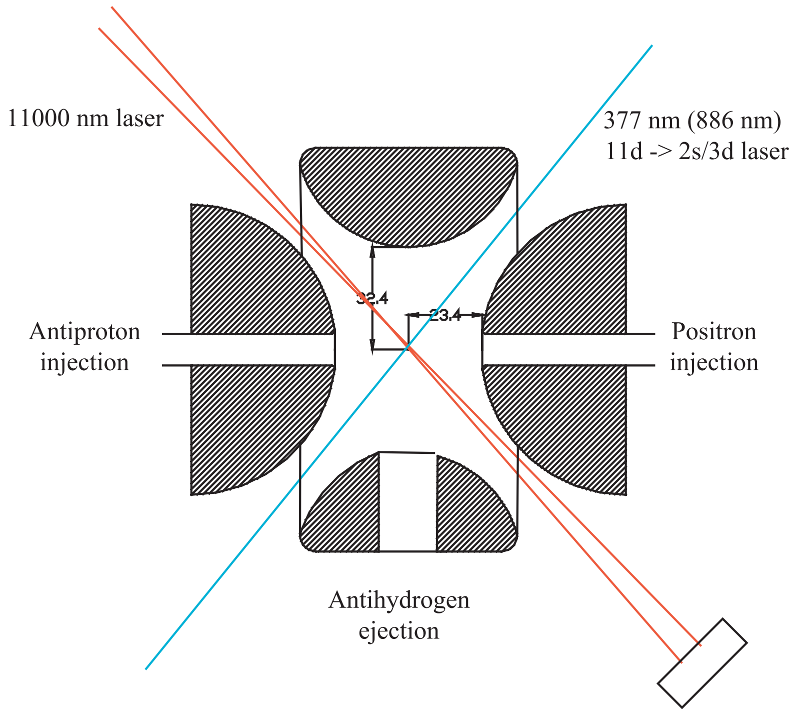

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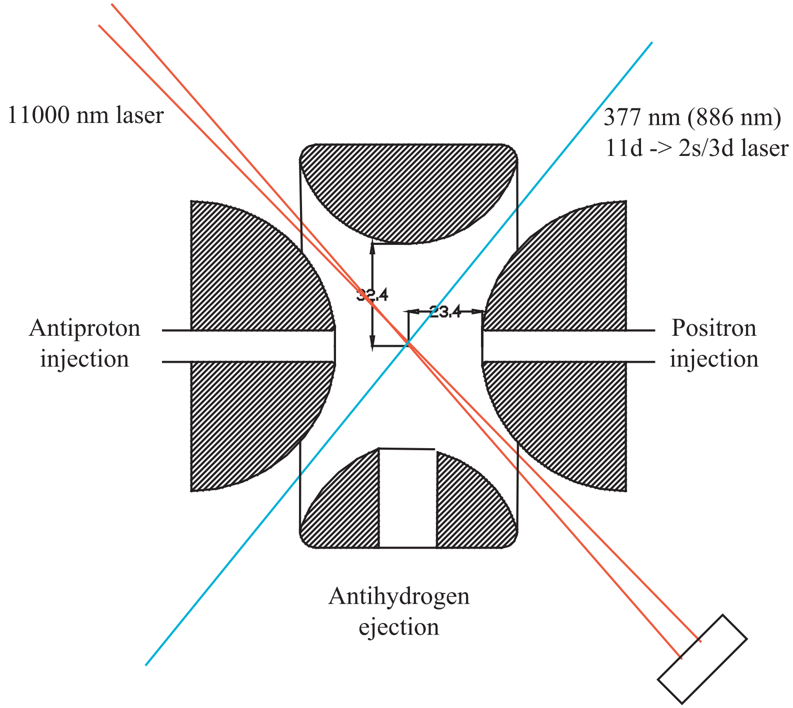

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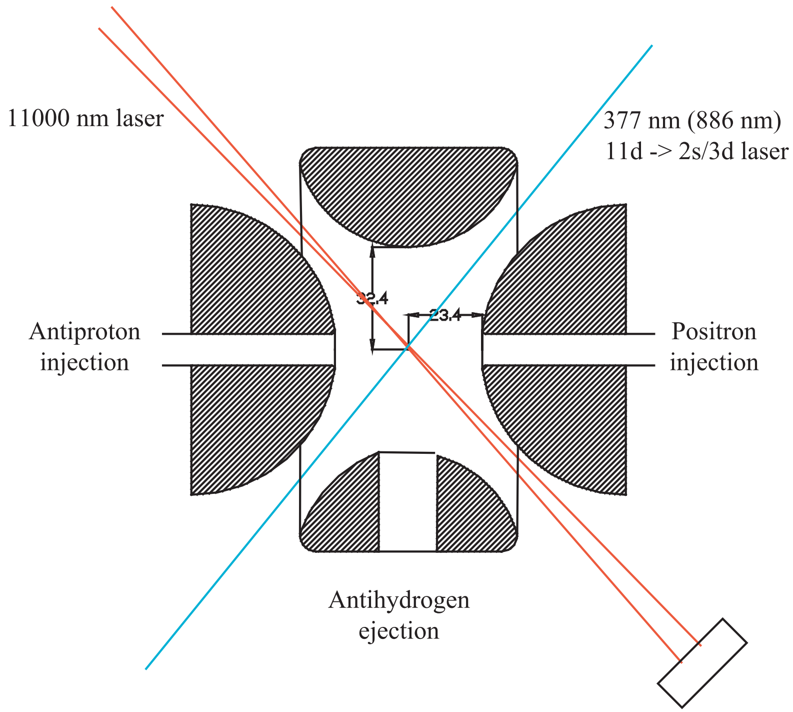

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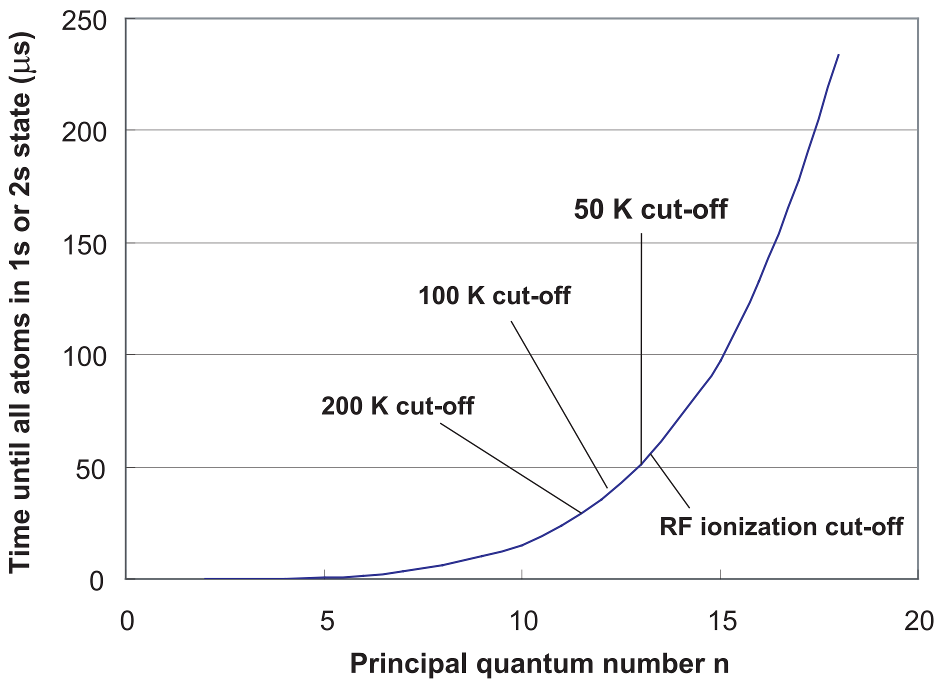

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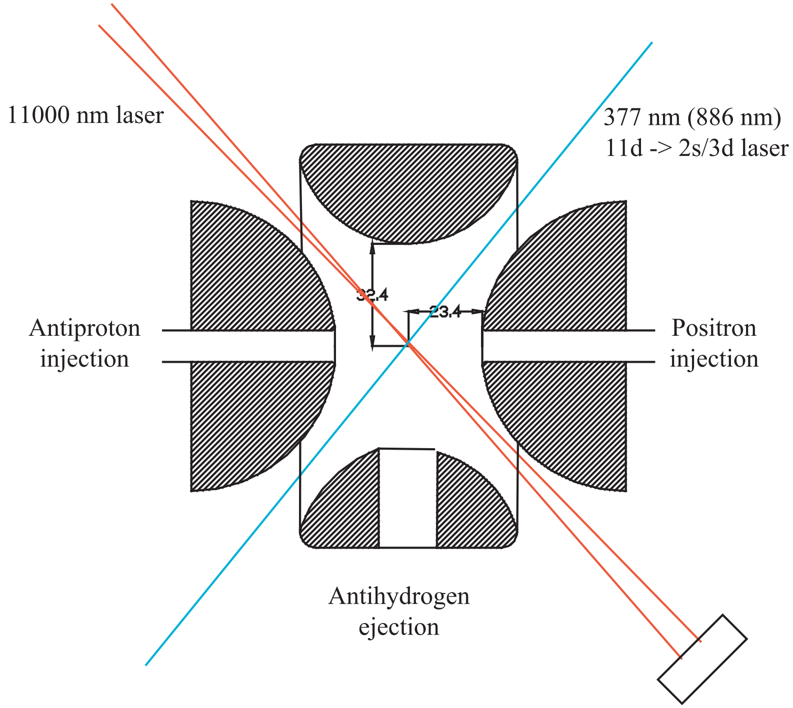

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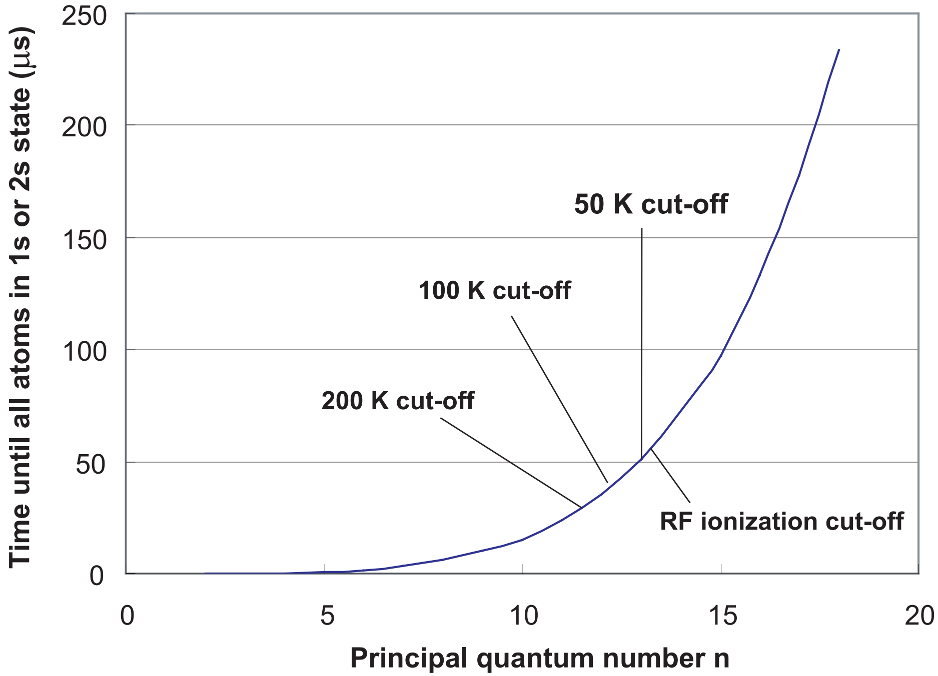
Expected production rate: 200 $\bar{H}$/sec



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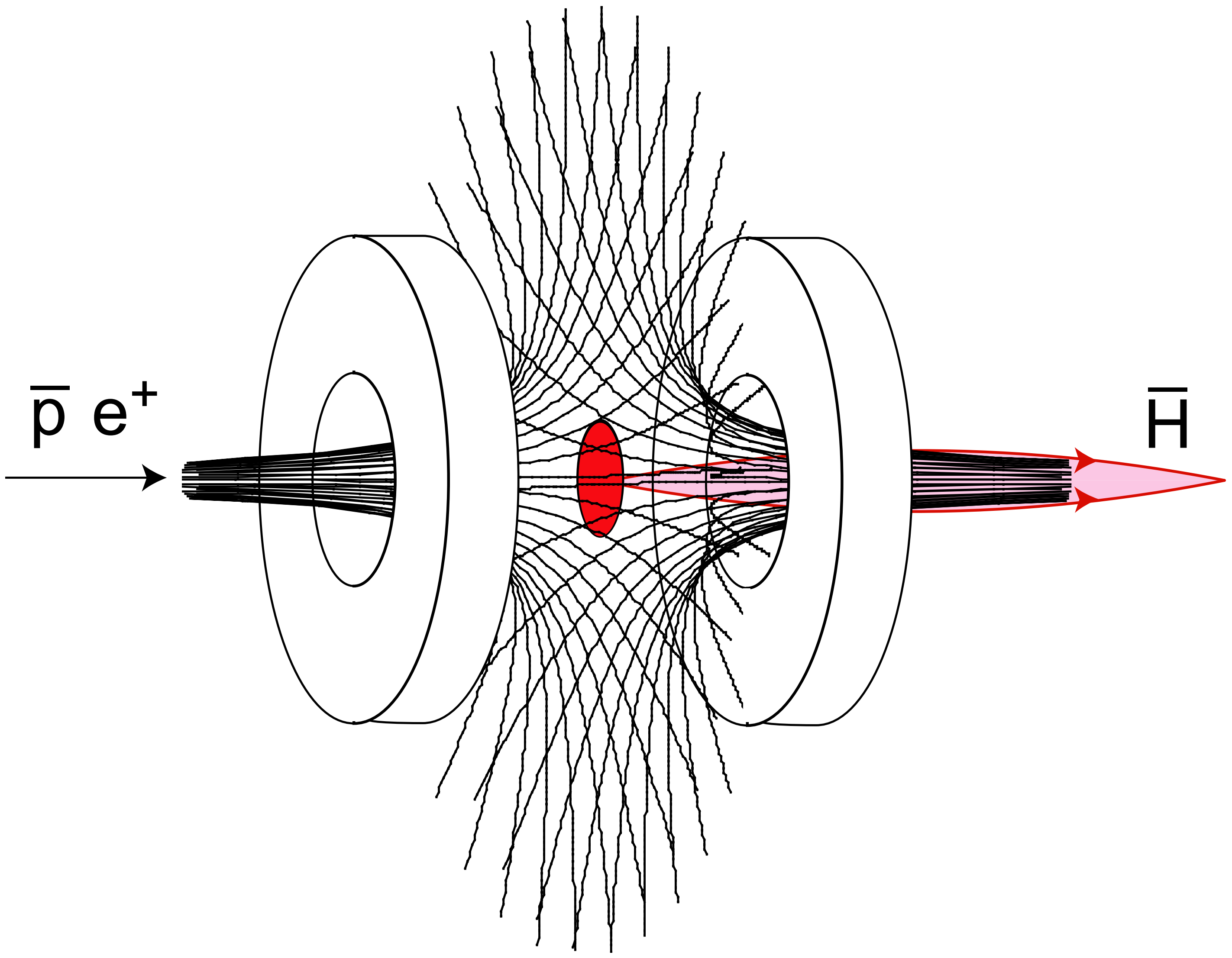

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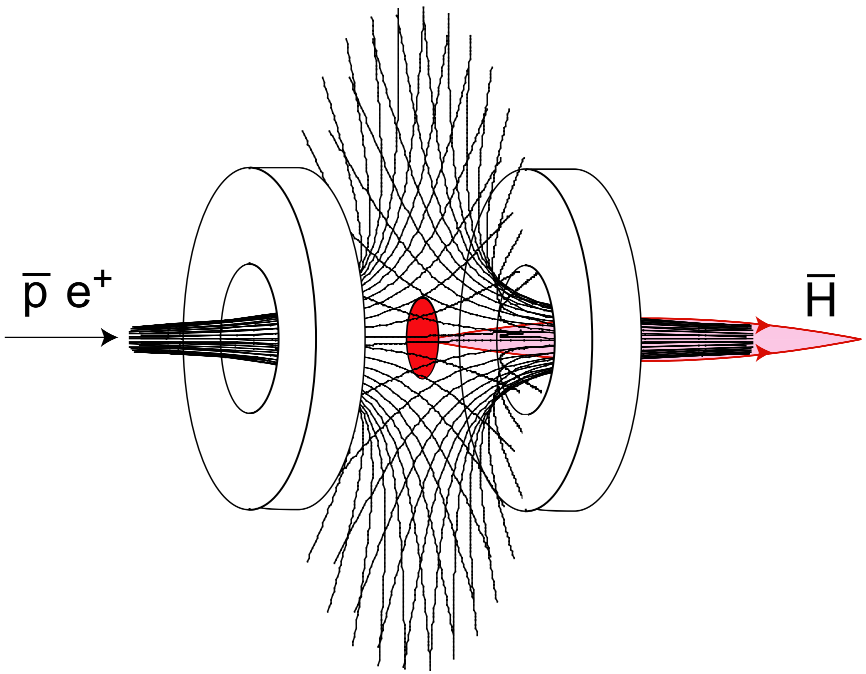

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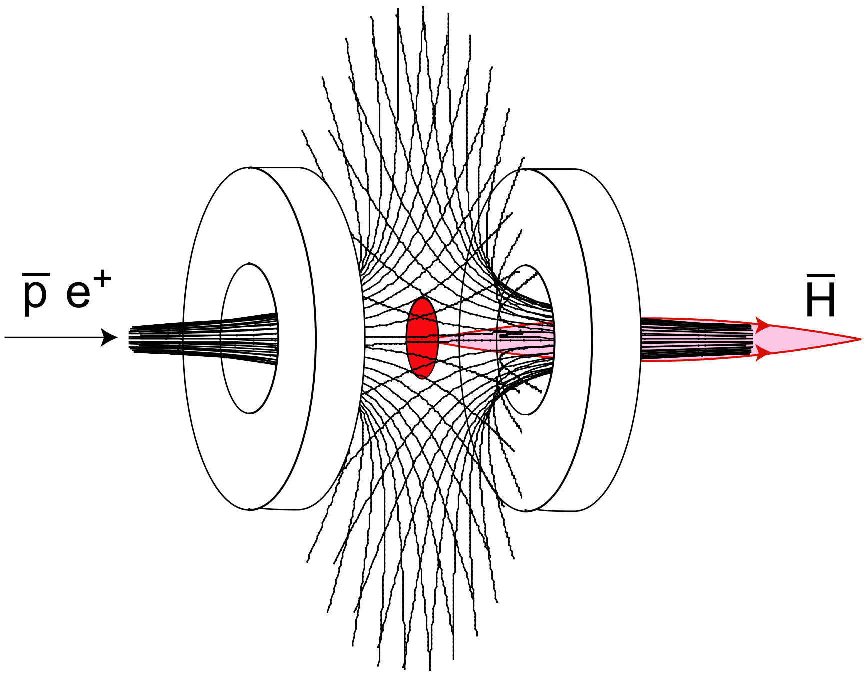

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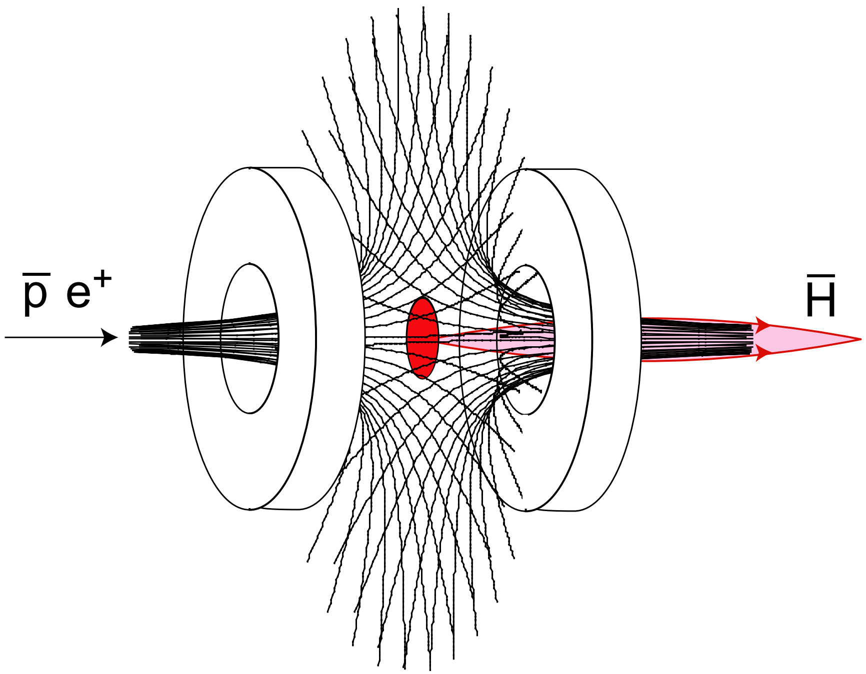

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Most probable choice: superconducting

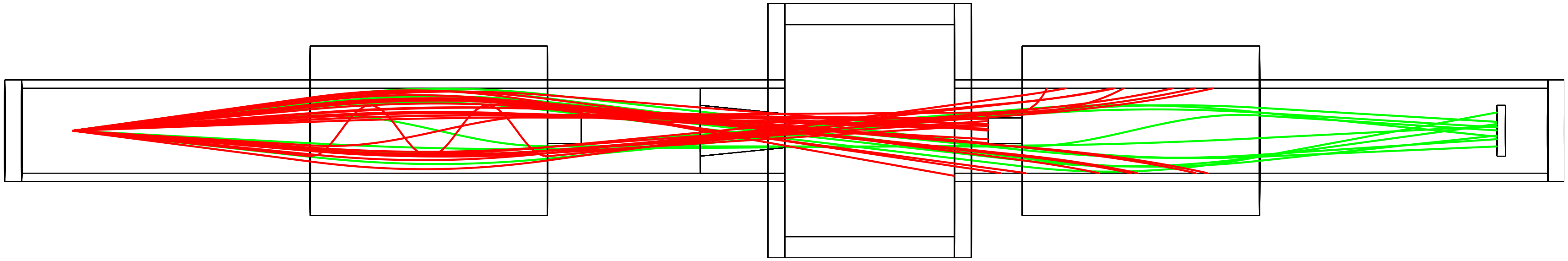
Microwave cavity

Will be an enlarged version of the 12.9 GHz MW cavity used for microwave spectroscopy of antiprotonic helium atoms

Some preliminary Monte Carlo simulations

MC – geometry

Assuming 50 K ($v_m \simeq 900$ m/s) point-like $\overline{\text{H}}$ source:



resonance on/off

Opening angle: 20°, internal diameter: 10 cm, total length: ∼170 cm, pole tip field: 4 T; $\epsilon \simeq 4 \times 10^{-4}$

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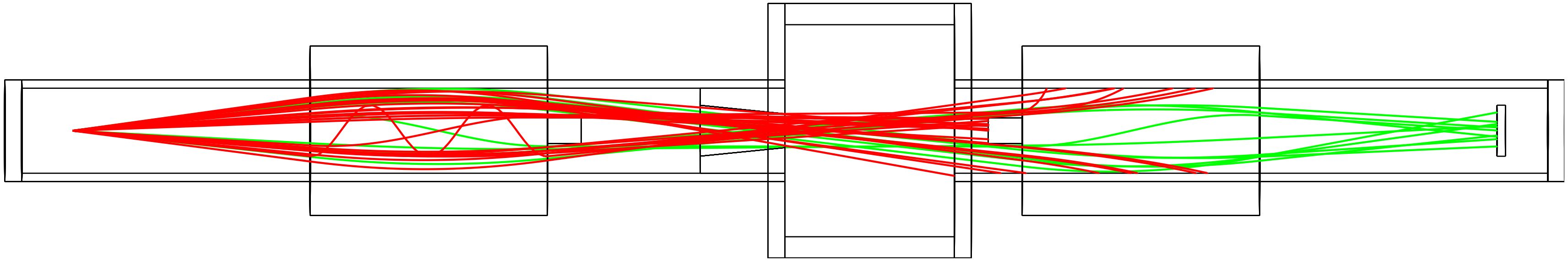

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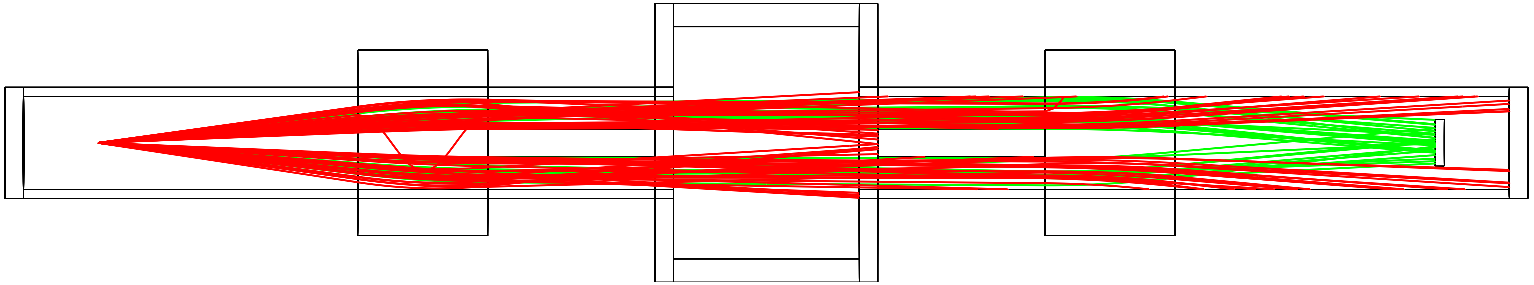

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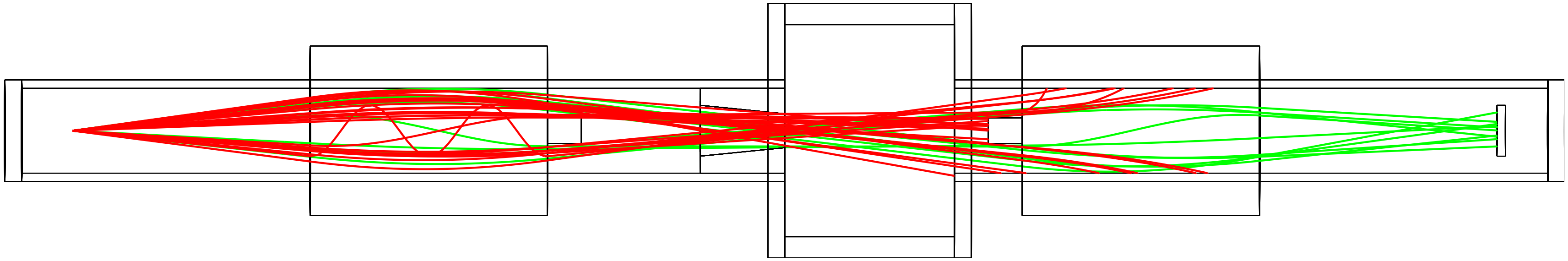

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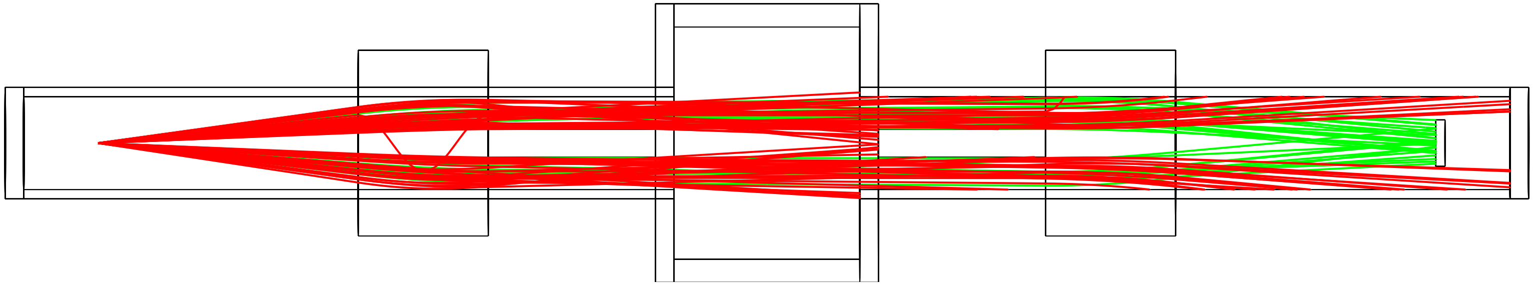

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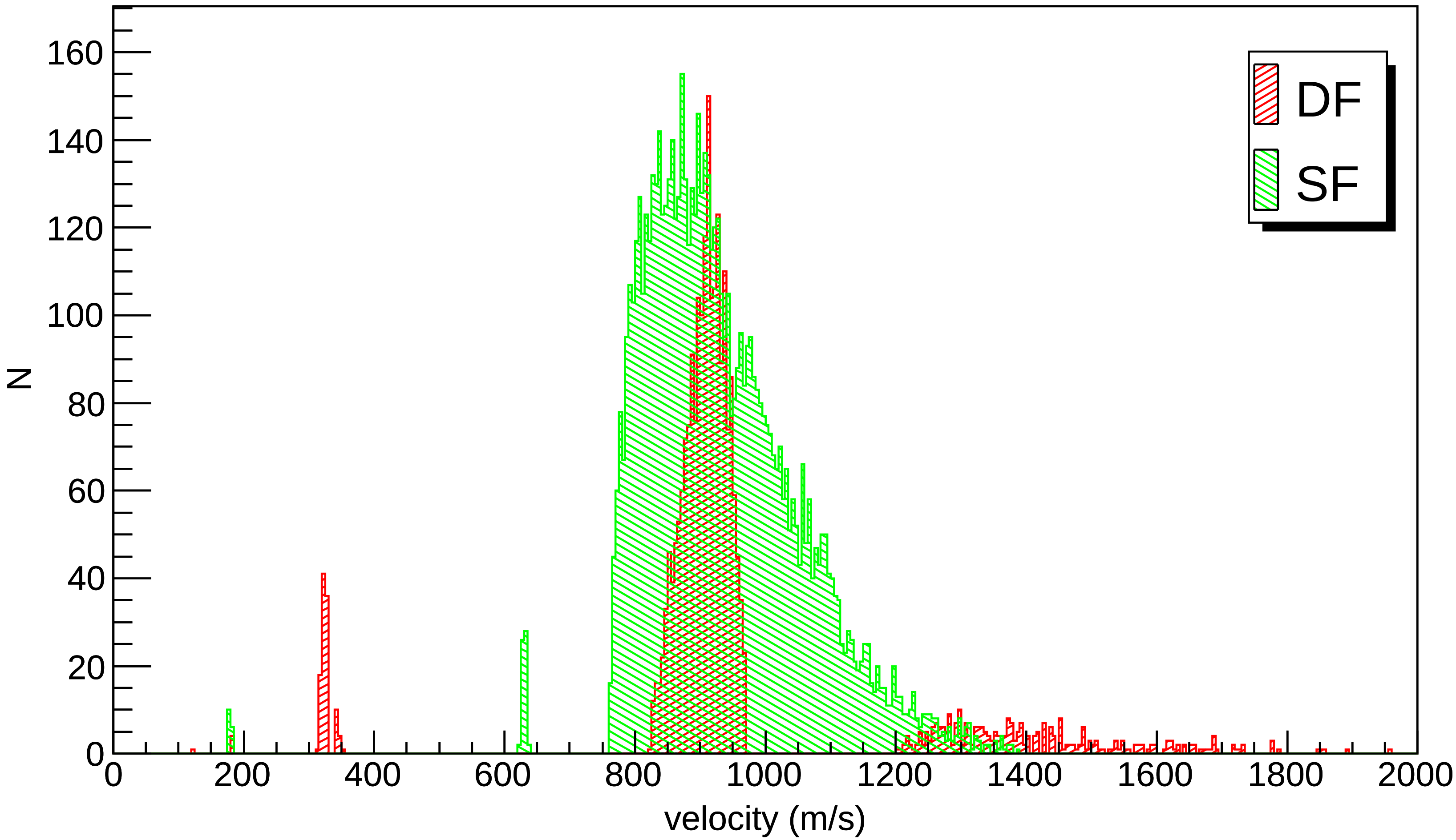
Total efficiency: 5–20 $\times$ 10^{-5} $\Rightarrow$ expected detection rate: 0.5–2 $\overline{\text{H}}$/min

MC – velocity distribution

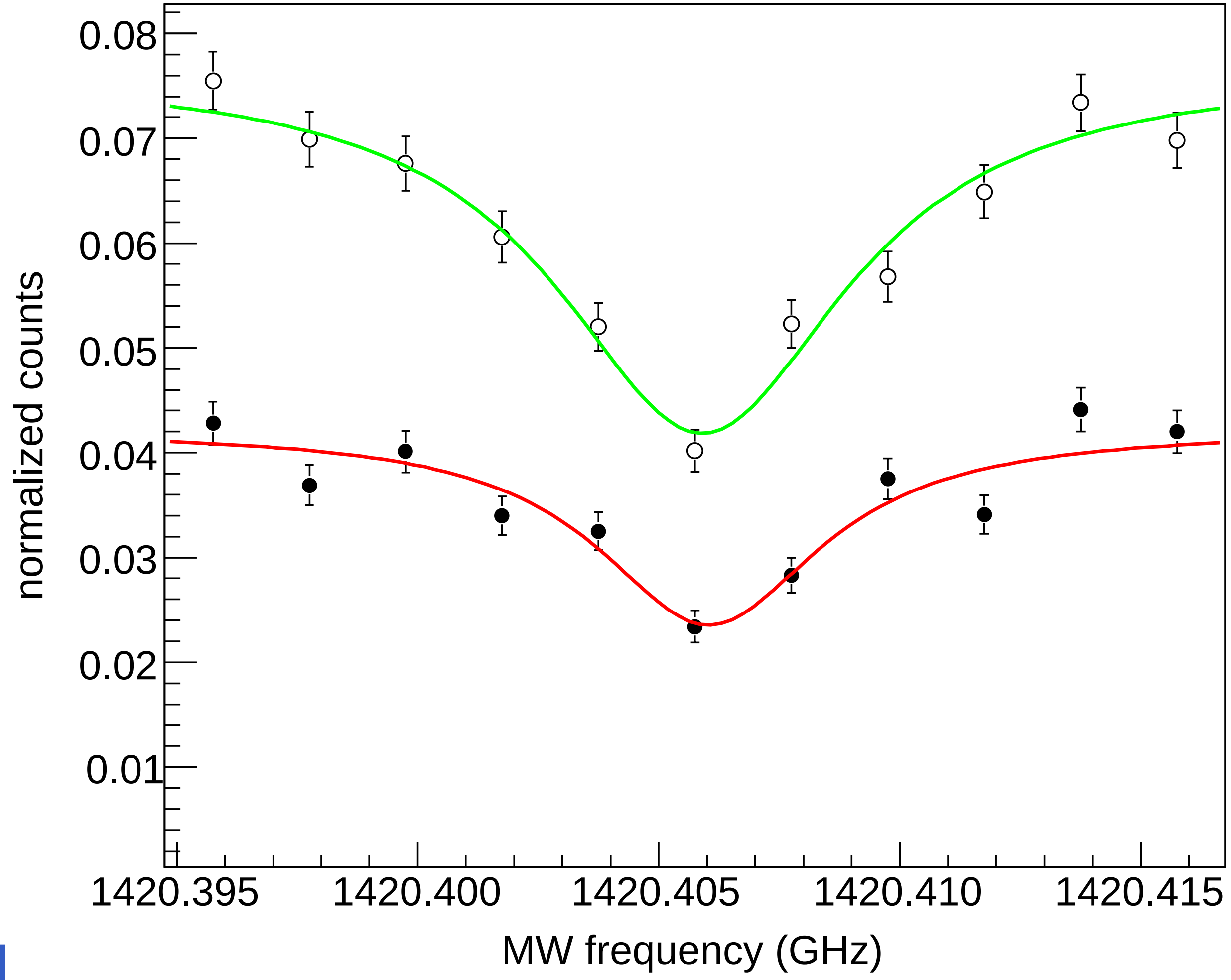


Velocity distribution in MW cavity is wider for SF

$\Rightarrow$ MW resonance is broader

MC – resonance curve

Per point: 4,000,000 50 K $\overline{\text{H}}$ from point-like source:



SF:
FWHM: 7.4 kHz
$\delta\nu$: 0.25 kHz
$\delta\nu/\nu$: 1.7×10^{-7}

DF:
narrower, but worse statistics
FWHM: 5.7 kHz
$\delta\nu$: 0.74 kHz
$\delta\nu/\nu$: 5.2×10^{-7}

Summary

- Ground-state hyperfine splitting of antihydrogen is a good candidate to test CPT violation effects
  - Kostelecky *et al.*: not relative but absolute precision matters
- Measurement: atomic beam method
  - $\overline{\mathrm{H}}$ source: two-frequency Paul trap or cusp trap
  - 2 sextupoles & 1 microwave resonance cavity
- Expected count rate: 0.5–2 $\overline{\mathrm{H}}$/min
- Expected precision: better than 10^{-6}
- Still in the early design phase – comments are welcome