New Idea in Møller Polarimetry

Møller Polarimetry with Atomic Hydrogen Targets

PAVI04, Grenoble, June 2004

E. Chudakov (JLab)
V. Luppov (Michigan)

Proposal for high precision electron polarimetry at medium energies

- Motivation
  - Demand for precision polarimetry
  - Møller and Compton polarimetry
  - Improvements in Møller polarimetry
- Polarimetry with Atomic Hydrogen Targets
  - Storage of ultra-cold polarized atomic hydrogen
  - Figure of merit and systematic errors
  - Impact of the CEBAF beam on the stored gas: possible depolarization

See `http://www.jlab.org/~gen/hyd/`

Challenges to Polarimetry

Parity violating electron scattering experiments:

- Progress in reducing the systematic errors
- Beam polarization: becomes the dominant error!

JLab planned experiments, beam current 50-100μA:

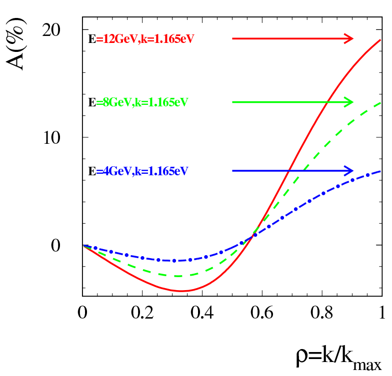
Experiment	Syst. err without pol	Polar. error	Stat. error	Energy GeV	Comments
$^4He\ \rho_s$	0.6%	2.0%	2.2%	3.2	soon
^{208}Pb n-skin	0.5%	1.0%	3.0%	0.85	soon
eP $sin^2\theta_W$	2.4%	$<$1.4%	2.8%	1.16	?
DIS $sin^2\theta_W$	0.3%	$<$1.0%	0.8%	10.0	distant

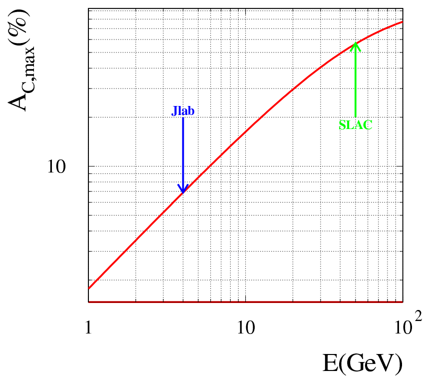
A 1%, polarimetry accuracy is needed A 0.5% accuracy would be even better...

New Idea on Møller Polarimetry

Compton Polarimetry

$\vec{e}^{\,-} + (h\nu)_\sigma \rightarrow e^- + \gamma$ QED.





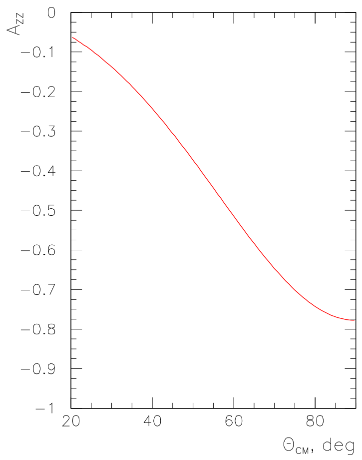
- Detecting the γ at 0 angle
- Detecting the e^- with an energy loss
- Strong $\frac{dA}{dk'}$ - good $\sigma E_\gamma / E_\gamma$ needed
- $A \propto kE$ at $E < 20$ GeV
- $T \propto 1/(\sigma \cdot A^2) \propto 1/k^2 \;\times\; 1/E^2$
- $\mathcal{P}_{laser} \sim 100\%$
- Non-invasive measurement

Syst. error 3→50 GeV: $\sim 1. \rightarrow 0.5\%$

Hard at <1 GeV: a project (JLab) ~0.8%

Møller Polarimetry

$\vec{e}^{\,-} + \vec{e}^{\,-} \rightarrow e^- + e^-$ QED.



A(E)=const=-7/9

- Detecting the e^- at $\theta_{CM} \sim 90^\circ$
- $\frac{dA}{d\theta_{CM}}|_{90^\circ} \sim 0$ - good systematics
- Beam energy independent
- Ferromagnetic target $\mathcal{P}_T \sim 8\%$
  - $> 4\ \mu$m: invasive measurement
  - Beam $I_B < 2 - 4\ \mu A$ (heating)
  - Levchuk effect
  - Low $\mathcal{P}_T \Rightarrow$ dead time
  - Syst. error $\sigma(\mathcal{P}_T) \sim 3\%$ (0.3%)

Syst. error $\sim 3\%$ typically, (0.5%)

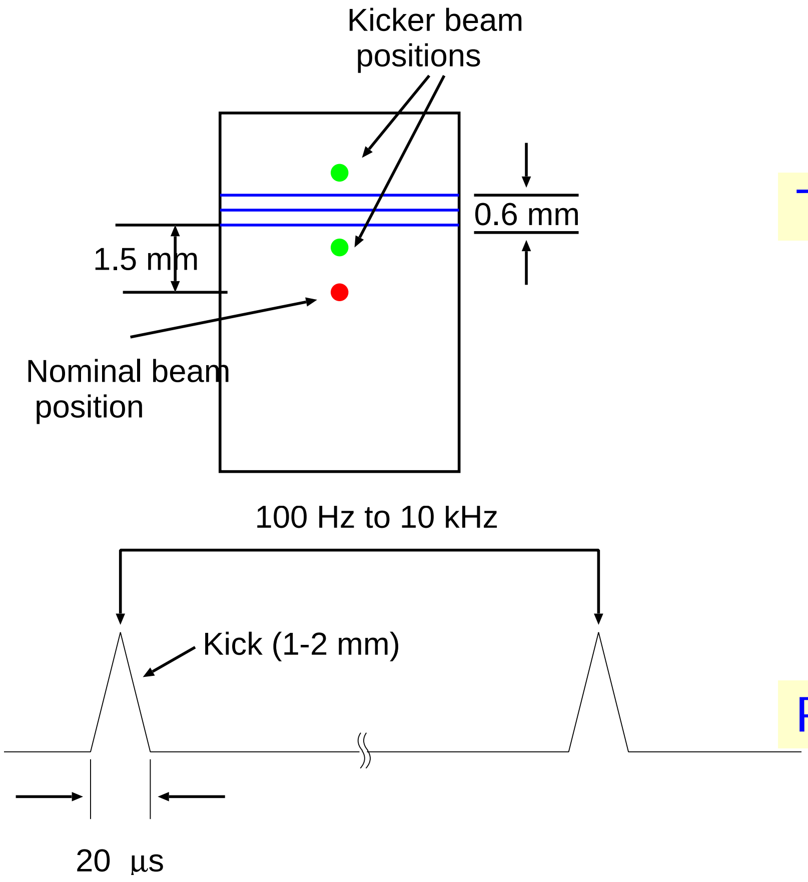
Møller JLab Halls A,C: Systematic Errors

source	Hall C		Hall A		$\vec{H}$
	uncertainty	A error	uncertainty	A error	
target	4 T,	0°	0.03 T,	20°	
beam optics		0.20%	-	-	
analyzing power		0.21%		0.3%	↓
radiat. corrections		?		?	
multiple scattering	10 %	0.12%	-	-	×
target temperature	50 %	0.05%	50 %	0.1 %	
direction of B-field	2°	0.06%	-	-	
value of B-field	5%	0.03%	-	-	
target polarization		0.25%		3.0%	×
Levchuk effect	10 %	0.30%	30%	0.2%	×
target angle	-	-		0.5%	×
Background		?		<1%	↓
dead time		?		0.3%	×
beam current		?		1%	×
total		0.50%		3.4%	

Attempts to Run Møller Polarimeter at High Current

JLab Hall C (thanks to David Gaskell)

- Ferromagnetic foils (1-4μm), wires (25μm) normal to ∼4 T magnetic field
- Low duty cycle in order to reduce the average beam current



Tests with wires

- Beam $\sigma_X \approx 50\mu\text{m} > r = 12\mu\text{m}$
- At 20μA - accidentals/real≈0.4 ⇒ dead time
- Statistical accuracy ≈ 2h for 1% measurement

Plans

- Use a 1μA thick half-foil
- Higher duty factor

Possible Breakthrough in Accuracy

Møller polarimetry with 100% polarized atomic hydrogen gas, stored in a ultra-cold magnetic trap.

Advantages:

- 100% electron polarization
  - very small error on polarization
  - sufficient rates $\sim\ \times 0.005$ - no dead time
  - false asymmetries reduced $\sim\ \times 0.1$
- Hydrogen gas target
  - high beam currents allowed
  - no Levchuk effect
  - low single arm BG from radiative Mott (×0.1 of the BG from Fe)

Goal:

$\sim$0.5% systematic error

Hydrogen Atom in Magnetic Field

H_1: $\vec{\mu} \approx \vec{\mu_e}$;

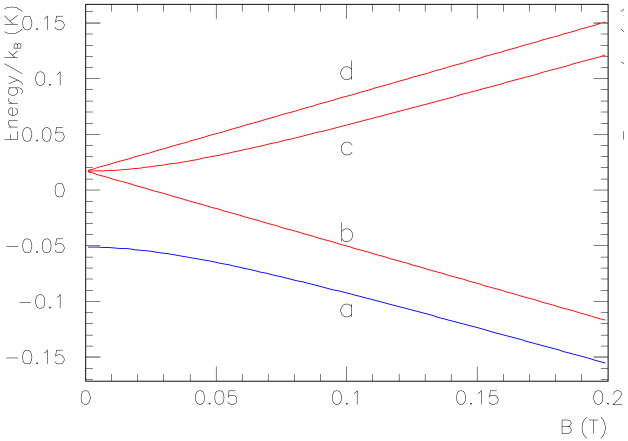
H_2: opposite electron spins

Consider H_1 in $B = 7\ T$ at $T = 300\ mK$

At thermodynamical equilibrium:

$n_+/n_- = exp(-2\mu B/kT) \approx 10^{-14}$

Complication from hyperfine splitting:



Low energy

$|b\rangle = |\downarrow ⇟\rangle$

$|a\rangle = |\downarrow ⇞\rangle \cdot \cos\theta - |\uparrow ⇟\rangle \cdot \sin\theta$

High energy

$|d\rangle = |\uparrow ⇞\rangle$

$|c\rangle = |\uparrow ⇟\rangle \cdot \cos\theta + |\downarrow ⇞\rangle \cdot \sin\theta$

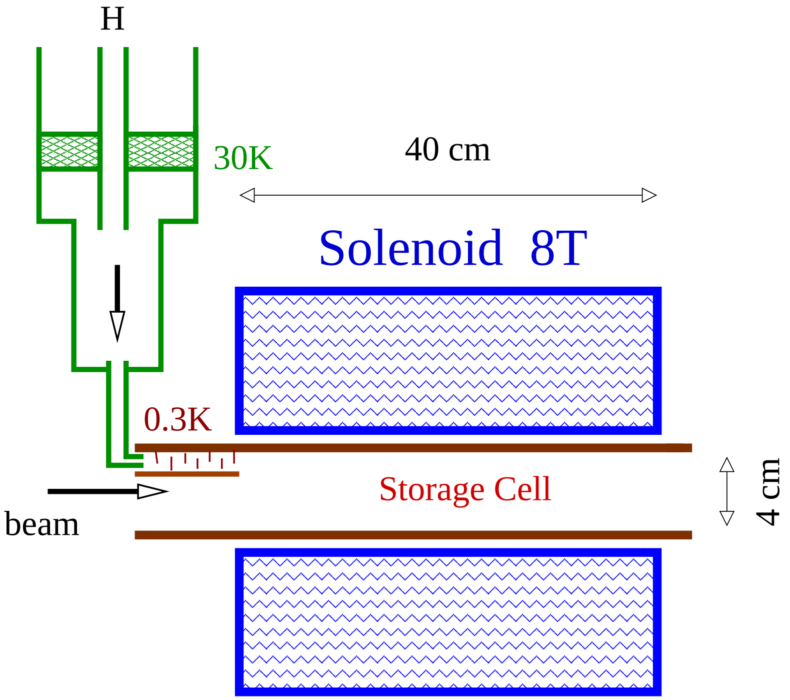
---

where $\tan 2\theta \approx 0.05/B(T)$, at 7 T $\sin\theta \approx 0.0035$

Mixture ~53% of $|a>$ and ~47% of $|b>$:

$\mathcal{P}_e \sim 1 - 10^{-5}$,

Storage Cell



First: 1980 (I.Silvera,J.Walraven)

$\vec{p}$ jet (Michigan)

Never put in high power beam

- $-\vec{\nabla}(\vec{\mu_H}\vec{B})$ force in the field gradient
  - pulls $|a\rangle$, $|b\rangle$ into the strong field
  - repels $|c\rangle$, $|d\rangle$ out of the field
- $H+H \rightarrow H_2$ recombination (+4.5 eV) high rate at low T
  - parallel electron spins: suppressed
  - gas: 2-body kinematic suppression
  - gas: 3-body density suppression
  - surface: strong unless coated ~50 nm of superfluid ^{4}He
- Density $3 \cdot 10^{15} - 3 \cdot 10^{17}$ cm^{-3}.
- Gas lifetime > 1 h.

Dynamic Equilibrium and Proton Polarization

Proton polarization builds up, because of recombination of states with opposite electron spins:

$|a\rangle = |\downarrow\text{⤉}\rangle\alpha + |\uparrow\text{⤈}\rangle\beta$ and

$|b\rangle = |\downarrow\text{⤈}\rangle$

As a result, $|a\rangle$ dies out and only $|b\rangle = \downarrow\text{⤈}$ is left!

$\mathcal{P} \rightarrow 0.8$

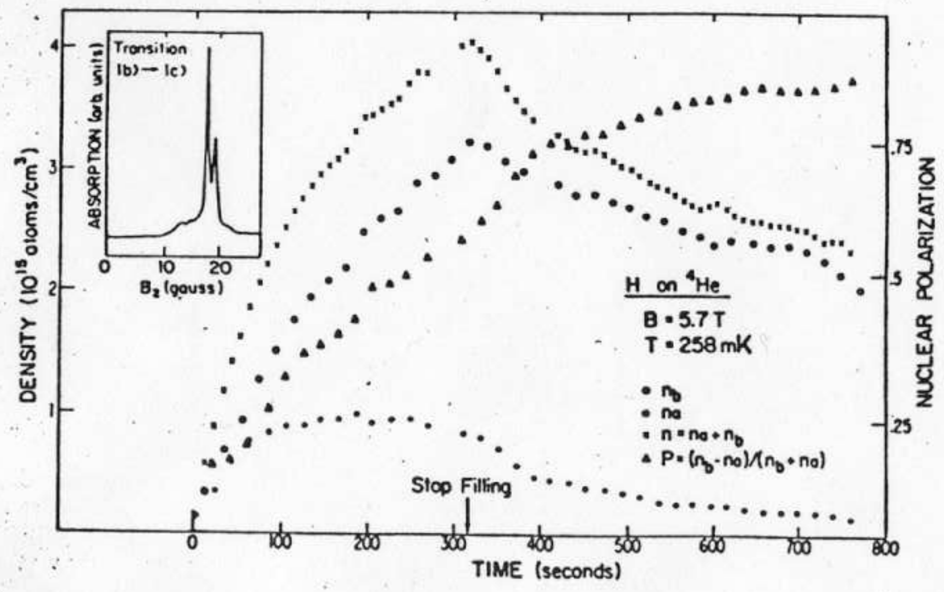


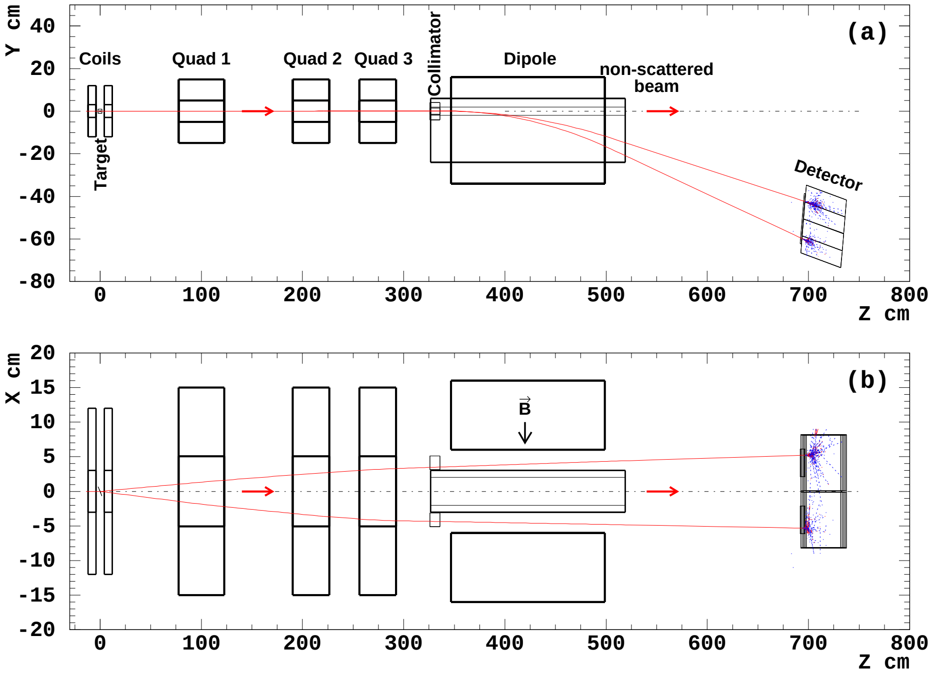
Fig. 5.11. Development of the densities of the hyperfine states and polarization as a function of time as measured by ESR. The inset shows the ESR line shape for one of the transitions (after van Yperen et al. 1983).

Polarimeter with Atomic Hydrogen

Modification of JLab Hall A Møller polarimeter - target replacement only.

Hall A polarimeter, Fe target

- stat. 1% in 2 min on 30μm Fe at 0.3μA



Hall A polarimeter, H target

- Solenoid $B_{max} \sim 7\ T \sim\ 300\ mK$
- Gas density $\sim 3 \cdot 10^{15}$ e$^-$/cm^3
- Target length 10 cm (0.85 GeV)
- 30μA

Stat. accuracy 1% in $\sim$ 30 min

Syst. accuracy $< 0.5\%$

Contaminations and Depolarization of the Target Gas

Ideally, the trapped gas polarization is nearly 100% ($\sim 10^{-5}$ contamination).
Good understanding of the gas properties (without beam).

Gas Properties

- Atom velocity ≈ 80 m/s
- Atomic collisions $\approx 1.4 \cdot 10^5$ s^{-1}
- Mean free path $\lambda \approx 0.6$ mm
- Wall collision time $t_R \approx 2$ ms
- Escape (10cm drift) $t_{es} \approx 1.4$ s

CEBAF Beam

- Bunch length σ=0.5 ps
- Repetition rate 497 MHz
- Beam spot diameter $\sim$0.2 mm

Contamination and Depolarization

No Beam

- Hydrogen molecules $\sim 10^{-5}$
- Upper states $|c\rangle$ and $|d\rangle$ $< 10^{-5}$
- Excited states $< 10^{-5}$
- Helium and residual gas <0.1%
  - measurable with the beam

100 μA Beam

- Depolarization by beam RF $< 2 \cdot 10^{-4}$
- Ion, electron contamination $< 10^{-5}$
- Excited states $< 10^{-5}$
- Ionization heating $< 10^{-10}$

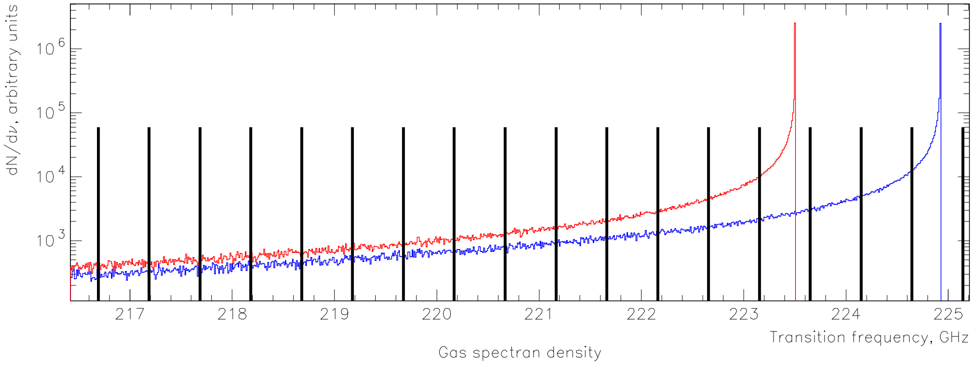
Expected depolarization $< 2 \cdot 10^{-4}$

The Most Important Beam Impacts on the Target Gas

$100\ \mu$A CEBAF beam:

Beam RF influence

- $|a\rangle \rightarrow |d\rangle$ and $|b\rangle \rightarrow |c\rangle$ $\sim$200 GHz
- RF spectrum: flat at $<$300 GHz

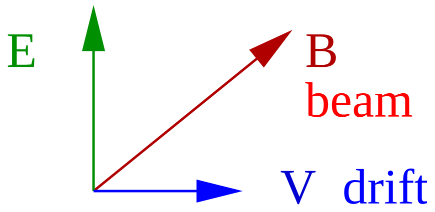


- $\sim 10^{-4}$ s^{-1} conversions (all atoms)
- $\sim 6\%$ s^{-1} conversions (beam area)
- Diffusion: contamination

  $\sim 1.5 \cdot 10^{-4}$ in the beam area
- Solenoid tune to avoid resonances

Gas Ionization

- 10^{-5} s^{-1} of all atoms
- 20% s^{-1} in the beam area
- Problems:
  - No transverse diffusion (charged)
  - Recombination suppressed
  - Contamination $\sim$40% in beam
- Solution: electric field $\sim$1 V/cm
  - Drift $v = \vec{E} \times \vec{B}/B^2 \sim 12$ m/s
  - Cleaning time $\sim 20\ \mu$s
  - Contamination $< 10^{-5}$
  - Ions, electrons: same direction
  - Beam $\overline{E_r}(160\mu\text{m}) \approx 0.2$ V/cm



Conclusion and Outlook

Polarimetry with 100% polarized ultra-cold atomic hydrogen in a magnetic trap:

- Systematic error $<$1.%, potentially $\sim$0.5%
- Good reason to expect no serious problem with beam ($\sim 10^{-4}$ depolarization)
- Working parallel with the experiment
- Competition/complementarity with Compton:
    - Compton: less influence on the beam, no upper limit on the beam current, any duty cycle
    - Moller: better systematics on the analyzing power, good at all energies

Appendix: Gas Properties

- $n = 2 \cdot 10^{15}$ cm^{-3} - density
- $T = 0.3$ K - temperature

- Diffusion speed ⇒ cleaning time
- Heat conductance
- Depend on the atomic cross-section σ

Ref., date	conditions	H polarized σ, cm^2 10^{-16}	H polarized d, cm 10^{-8}	H unpolarized σ, cm^2 10^{-16}	H unpolarized d, cm 10^{-8}
Allison,71	T>1 K	87.0	5.26	68.0	4.65
Miller,77	T∼0 K	42.3	3.69	-	-
Friend,80	T∼0 K	6.5	1.44	4.9	1.25
Lhuillier,83	T=2.5 K	∼30.0	3.10	-	-

Using Miller,77:

- $\overline{v} = \sqrt{8kT/\pi m} = 80\ \mathrm{m/s}$ - atom speed
- $\frac{dn_{col}}{dt} = \sigma \cdot 4n\sqrt{\frac{kT}{\pi m}} \approx 1.4 \cdot 10^5$ s^{-1} - atomic collisions
- $\ell = (\sigma n \sqrt{2})^{-1} \approx 0.57$ mm - mean free path
- $\tau_{es} \approx 1.4$ s - mean drift time to $|Z| = 10$ cm
- $\tau_R \approx 2$ ms - mean drift time R=0 → R=2 cm

Appendix: CEBAF Beam Parameters

General

- $\tau \ = 0.5$ ps - bunch time width (RMS) in LAB frame
- $\sigma_{Bx/y} \ = 100\ \mu$m - bunch transverse width (RMS)
- $\mathcal{F} \ = 497$ MHz - bunch repetition rate
- $\gamma \geq \ \sim 10^4$ - beam γ-factor
- $\mathcal{I}_b \ = 100\ \mu$A - average beam current

Electromagnetic Field of the Bunch

In CM of the bunch: $\sigma_Z > 15$ cm $\gg R_{pipe} \Rightarrow E_B \propto r^{-1}$. Boost to Lab.

- The field is located in a thin disk around the bunch
- $\vec{E}(z,r,t)$ - radial
- $\vec{B}(z,r,t)$ - azimuthal, $B(z,r,t) = E(z,r,t)/c$
- $B(0,r,t) = \frac{\mathcal{I}_b}{\mathcal{F}\cdot\tau} \cdot e^{-0.5(t/\tau)^2} \cdot (1 - e^{-0.5(r/\sigma_{Bx})^2})\frac{1}{r} \cdot \frac{\mu_\circ}{(2\pi)^{3/2}}$
  $B(0,r,t)_{max} = B(0, 160\mu\text{m}, 0) = 0.144$ mT
- $W = \mathcal{F} \cdot |B|^2 c/\mu_\circ/2 \approx 2$ mW - energy flux $\ll 20$ mW of the refrigerator.

Appendix: Beam Spectral Density

One Bunch

$B(t) = B_\circ \cdot exp(-\frac{t^2}{2\tau^2}) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega \cdot \hat{B}(\omega) e^{i\omega t}$, where
$\hat{B}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt \cdot f(t) e^{-i\omega t} = B_\circ \cdot \tau \cdot exp(-\frac{\omega^2\tau^2}{2})$

$\tau \cdot 200$ Ghz$\cdot 2\pi = 0.62$ - no spectral suppression!

RF

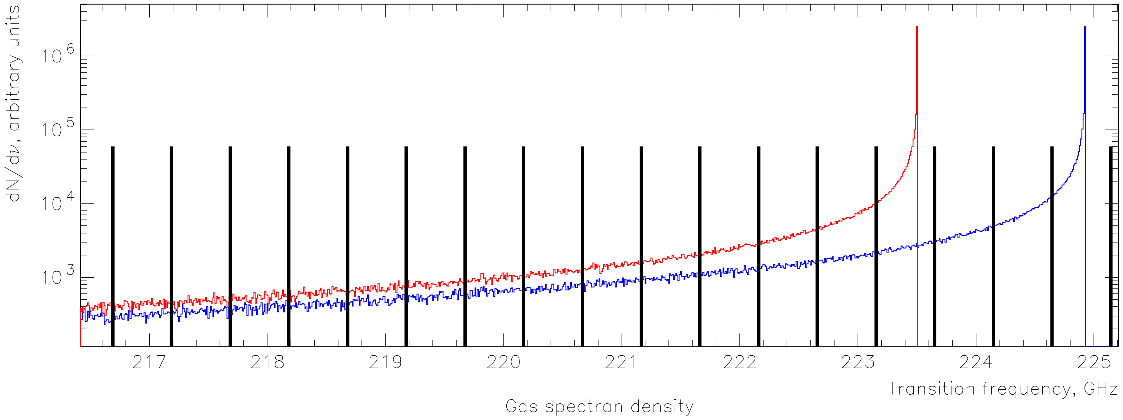
$B(t) = \sum_{n=-\infty}^{\infty} \hat{B}_n \cdot e^{i\omega_\circ n t}$, where $\omega_\circ = 2\pi\mathcal{F}$.
$\hat{B}_n \approx B_\circ \sqrt{2\pi} \cdot \tau\mathcal{F} \cdot exp(-\frac{\omega_\circ^2 n^2 \tau^2}{2})$,

Appendix: Depolarization by Beam RF

$|a\rangle \!\rightarrow |d\rangle$ and $|b\rangle \!\rightarrow |c\rangle$ transitions ∼200 GHz.

B_r coupling: harmonic perturbation $\mu_e \cdot B \cdot e^{i\omega t} \Rightarrow \frac{dV_{a\rightarrow d}}{dt} = \frac{2\pi}{\hbar^2}\left|\mu_e \cdot B\right|^2 \delta(\omega - \omega_{ad})$

One bunch: $V^B_{a\rightarrow d} = \left(\frac{\mathcal{I}_b}{\mathcal{F}}\right)^2 \left(\frac{\mu_\circ \mu_e}{2\pi\hbar r_\circ}\right)^2 \cdot exp(-\omega_{ad}^2\tau^2)G^2(r)$



Gas spectran density

100 μA inflicts:

- $\sim 10^{-4}$ s^{-1} conversions (all atoms)
- $\sim 6\%$ s^{-1} conversions (beam area)

Diffusion:

- Lifetime $\tau_d \approx 1.4$ s, lateral diffusion ~ 2 ms
- Contamination (beam area) $\sim 1.5 \cdot 10^{-4}$
- Solenoid uniformity $< 10^{-3}$
- Magnetic field tune to avoid resonances
- Magnetic field tune to destroy $|a\rangle$?

Appendix: Beam Ionization

Energy Loss

- 6.3 MeV/g·cm^2 full loss per beam particle
- 1.8 MeV/g·cm^2 carried out of the cell by δ-electrons
- 4.5 MeV/g·cm^2 absorbed in the cell
- 100 μA, $3 \cdot 10^{15}$ cm^{-3}:
  $1.4 \cdot 10^{13}$ eV/s/cm loss ⇒ 0.04 mW in the cell

Gas Heating

- $\Delta T \propto \mathcal{I}_b \cdot n\sigma/\sqrt{T}$,
- $\Delta T(0) \approx 0.03K \cdot \ln\left(\frac{R}{r_B} + 0.5\right)$,
  - $r_B = 0.2$ mm (no raster) $\Delta T(0) \approx 0.140$ K
  - $r_B = 2.0$ mm (raster) $\Delta T(0) \approx 0.075$ K
- Density $n \cdot \sqrt{T}$ =const : 10% drop at the center
- Depolarization: $10^{-16} \rightarrow 10^{-11}$ - OK
- Is raster needed?

Appendix: Beam Ionization

Ions and Free Electrons

- Primary and secondary ionization in hydrogen: 40 eV/pair
- 100 μA, $3 \cdot 10^{15}$ cm^{-3}: $3.5 \cdot 10^{11}$ pairs/s/cm : 10^{-5} s^{-1} - all atoms, ~20% s^{-1} - beam area
- Problems:
  - No transverse diffusion of charged particles
  - Recombination kinematically suppressed
  - For $\tau_{ch} = 1.4$ s contamination ~40% in the beam
- Solution: electric field ~1 V/cm normal to the axis
  - Larmore $\omega_L = q_e B/m = 1.4 \cdot 10^{12}\ \mathrm{s}^{-1}$ for e$^-$, $0.8 \cdot 10^{9}\ \mathrm{s}^{-1}$ for p $\Rightarrow \omega_L \tau_{coll} \gg 1$
  - Drift with $v = \vec{E} \times \vec{B}/B^2 \sim 12$ m/s
  - Cleaning time $\sim 20\ \mu$s : contamination $< 10^{-5}$
  - Positive and negative - the same direction
  - Average field of the beam $E_{max}(160\mu\mathrm{m}) \approx 0.2$ V/cm - not important
  - Design for electrodes?

Appendix: Excitations by the Beam Particles

Neutral atoms n>1

- Total energy release: $1.4 \cdot 10^{13}$ eV/s/cm
- Excitation energy > 10 eV
- Excited atoms $< 1.4 \cdot 10^{12}$ eV/s/cm -
  $< 4 \cdot 10^{-5}$ s^{-1} of all, 50% - wrong polarization
- For $\tau_{es} = 1.4$ s contamination $< 3 \cdot 10^{-5}$

$|a\rangle \longrightarrow |d\rangle$ transitions

- Single beam particle - similar to the beam RF calculation
- Integrating for $r > 10^{-8}$ cm $V^B_{a\rightarrow d} \sim 10^{-12}$ s^{-1} : negligible