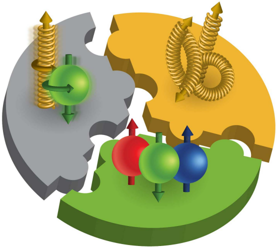


Beam-induced target depolarization at RHIC and EIC

Frank Rathmann

July 3, 2024

Contents

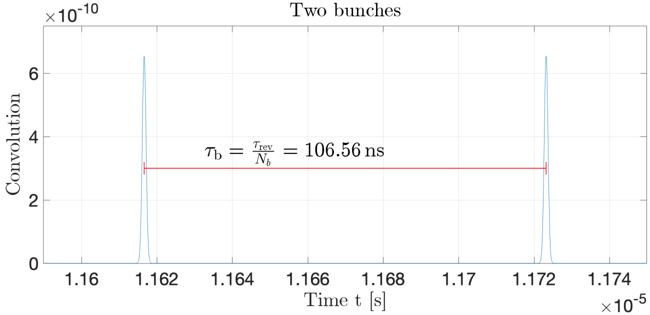
Introduction

- Development of polarized hydrogen jet (HJET) for RHIC finished 20 yrs ago.
- Many details on the technical structure and operation cannot be found in the literature, and there is also no comprehensive publication.
- Hardly anyone around to ask:
  - Tom Wise send me some unfinished paper drafts and other material.
  - I am in touch with Alexander Nass about BRP operation and most recent BRP measurement (from 2004).
- **Today's item:**
  1. **Beam-induced depolarization of target atoms**
     - Bunch repetition frequency will be much larger at EIC than at RHIC
     - Goal: Understand corresponding situation at EIC

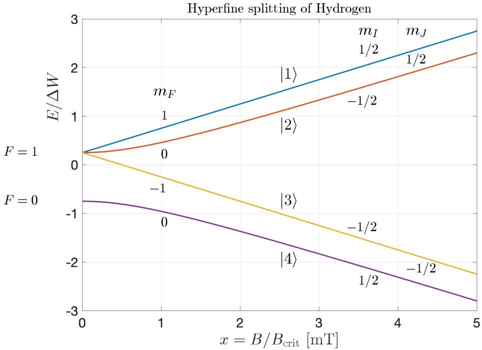
Bunch structure

RHIC situation:

- Time period between two adjacent bunches: $\tau_\text{b} = \frac{\tau_\text{rev}}{N_b} = 106.57\,\text{ns}$
- Number of stored bunches $N_b = 120$
- Bunch frequency $f_\text{b} = \frac{1}{\tau_\text{b}} = 9.3831\,\text{MHz}$
- Large number of harmonics contribute to induced magnetic high-frequency field close to RHIC beam, as bunches are short ($\sigma_t = 0.5\,\text{ns}$)



Hyperfine states of hydrogen



Critical field B_c (slide 23)

- Zeeman energy $g_J \mu_B B$ comparable to $E_{\rm hfs}$
- $E_{\rm hfs} \approx 5.874 \times 10^{-6}$ eV ($\approx$1420 MHz [1]):
- $B_c = 50.7$ mT

Transition frequencies

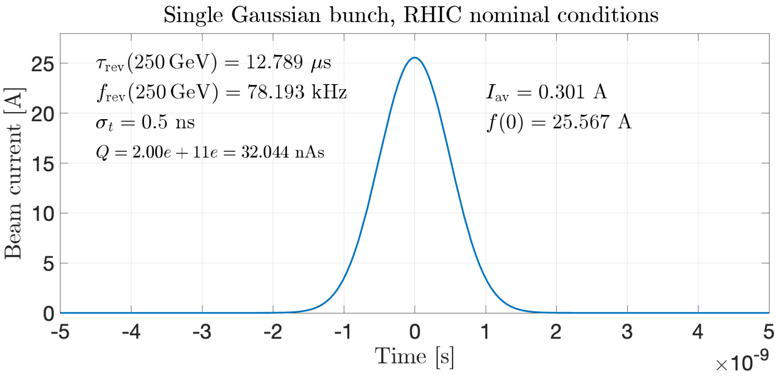
- Transition frequency between two hyperfine states $|i\rangle$ and $|j\rangle$ given by:

$$f_{ij} = \frac{E_{|i\rangle}(B) - E_{|j\rangle}(B)}{h} \qquad (1)$$

- When f_{ij} matches one of the beam harmonics at a certain holding field B, resonant depolarization occurs [2].

Single bunch distribution

- (Gaussian) bunch in RHIC



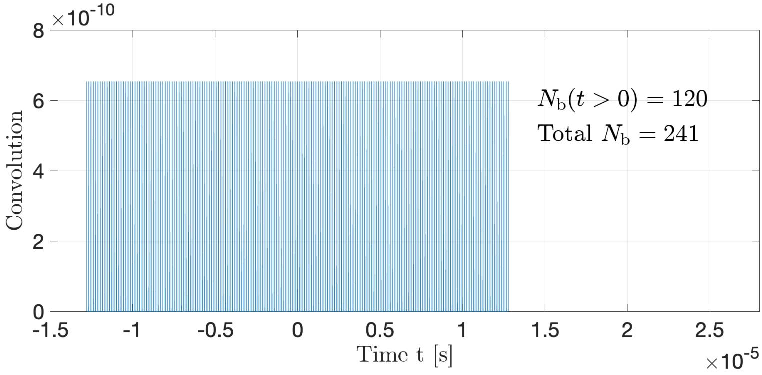
Pulse shape described by

$$f(t) = \frac{Q}{\sqrt{2\pi}\sigma_t} \exp\left(-\frac{t^2}{2\sigma_t^2}\right) \tag{2}$$

Gaussian convoluted with (finite) series of delta functions

Total beam current as function of time t given by

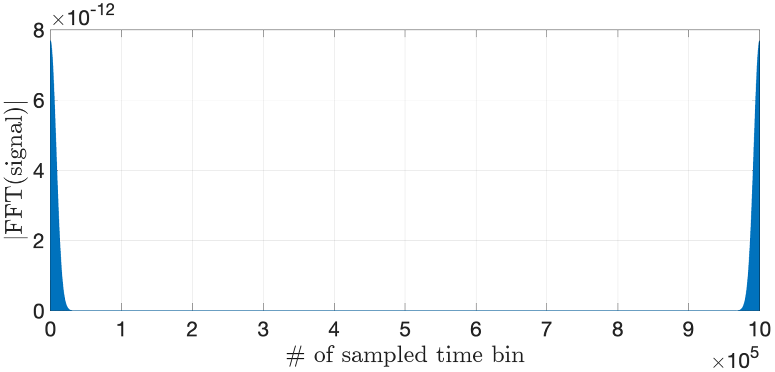
$$I(t) = \int_{-\infty}^{\infty} f(t-\xi) \sum_{k=-\infty}^{\infty} \delta\left(\xi - k\frac{T_{\text{rev}}}{N_\text{b}}\right) \mathrm{d}\xi \qquad (3)$$



Radiofrequency-fields

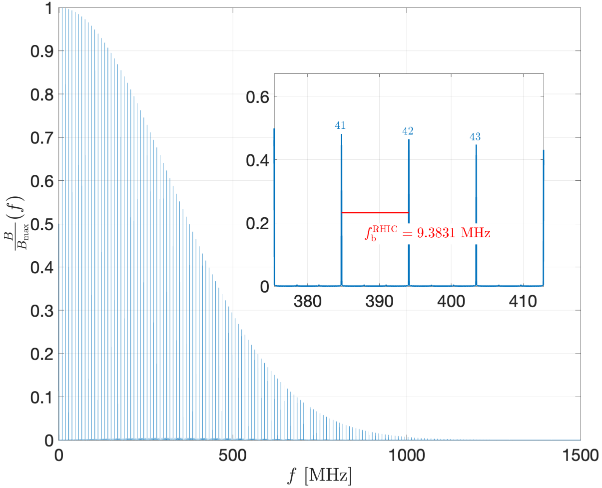
FFT of convolution

- Two-sided amplitude spectrum of FFT of the convolution



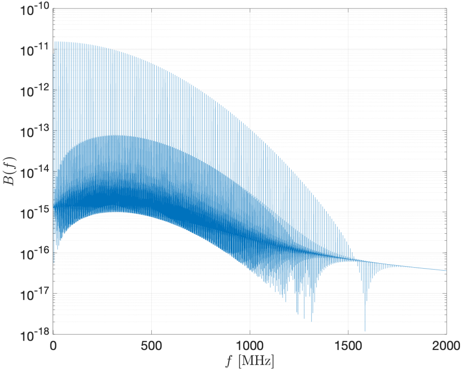
Produced radio-frequency fields

- Single-sided amplitude spectrum of FFT
- *x*-axis converted to frequency



Amplitudes of magnetic RF fields

- Same, but logy
- FFT background $\leq 1\%$
  - not at f_{rev}
  - not from finite set of δ fcts
  - $\rightarrow$ probably numerical from FFT



Transition frequencies between hyperfine states of H

Based on Zeeman splitting, shown on slide 5, using Eq. (1)

- Determine transition frequencies f_{ij} between hyperfine states $|i\rangle$ and $|j\rangle$.
- Cclassification refers to change of quantum numbers (see Ramsey [3]):
  - B_0 is static field, B_1 is RF field that exerts torque on magnetic moment μ:
  - π ($B_1 \perp B_0$) transitions *within one* F multiplet:

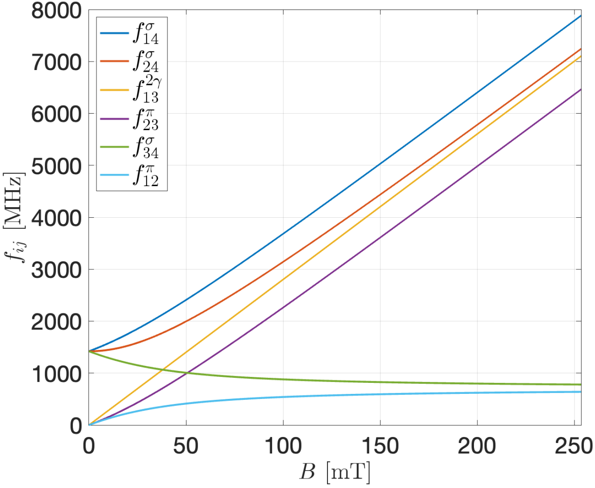
$$\Delta F = 0, \quad \Delta m_F = \pm 1. \tag{4}$$

  - σ ($B_1 \parallel B_0$) transitions *between different* F multiplets:

$$\Delta F = \pm 1, \quad \Delta m_F = 0, \pm 1. \tag{5}$$

  - Single photon transitions in H: f_{12}^{π}, f_{23}^{π}, f_{14}^{σ}, f_{24}^{σ}, and f_{34}^{σ}.
  - Transition $f_{13}^{2\gamma}$ with $\Delta m_F = 2$ requires two photons.

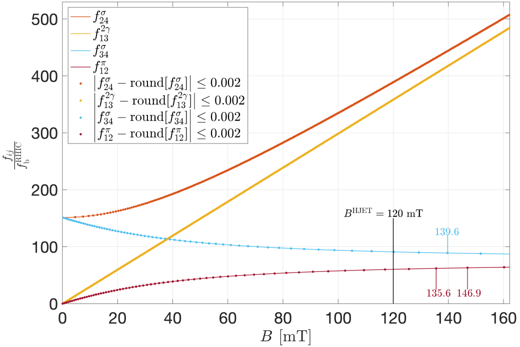
Transition frequencies between hyperfine states of H



Hydrogen hyperfine transitions from bunch fields

Depolarization when f_{ij} multiple of bunch frequency f_b^{RHIC}

- HJET injects states $|1\rangle + |4\rangle$ ($p^\uparrow$) and $|2\rangle + |3\rangle$ ($p^\downarrow$).
  - What is actual orientation of B^{HJET}?

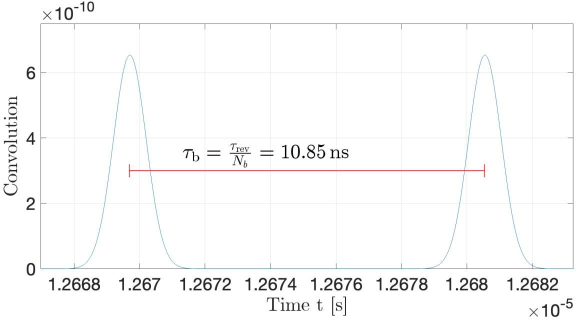


- $\left|\frac{f_{ij}}{f_b^{\mathrm{RHIC}}} - n\right| \leq 0.002\,,\ n \in \mathbb{N}$
- Same $m_I \Rightarrow f^\sigma_{14},\ f^\pi_{23}$ omitted

Bunch structure

EIC situation:

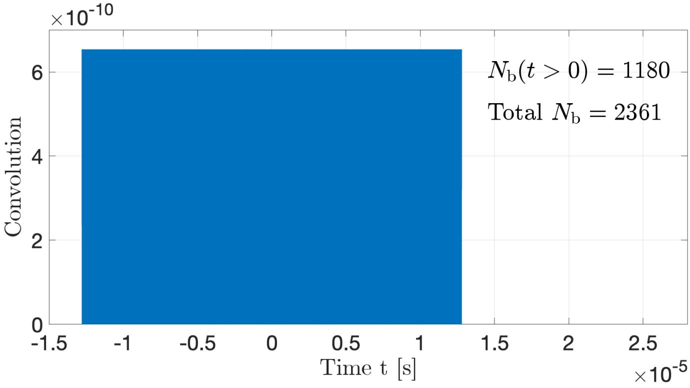
- Time period between two adjacent bunches: $\tau_\mathrm{b} = \frac{\tau_\mathrm{rev}}{N_b} = 10.85\,\mathrm{ns}$
- Number of stored bunches $N_b = 1180$
- Bunch frequency $f_\mathrm{b} = \frac{1}{\tau_\mathrm{b}} = 92.2081\,\mathrm{MHz}$



Gaussian convoluted with (finite) series of delta functions

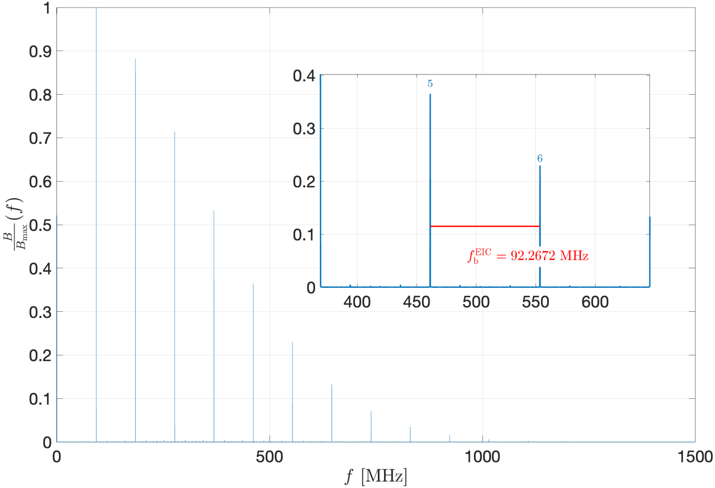
Total beam current as function of time t given by

$$I(t) = \int_{-\infty}^{\infty} f(t-\xi) \sum_{k=-\infty}^{\infty} \delta\left(\xi - k\frac{\tau_{\rm rev}}{N_{\rm b}}\right) {\rm d}\xi \tag{6}$$



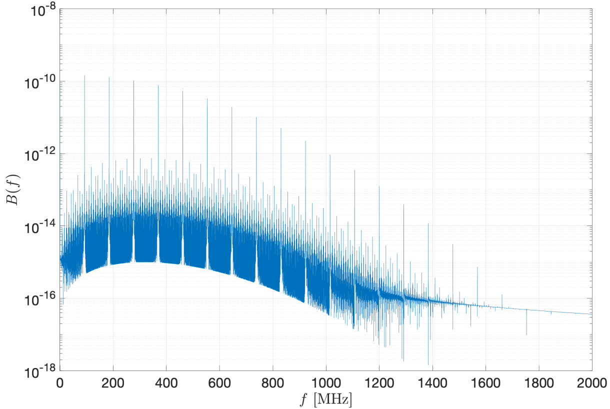
Produced radio-frequency fields

- Single-sided amplitude spectrum of FFT



Amplitudes of radio-frequency fields

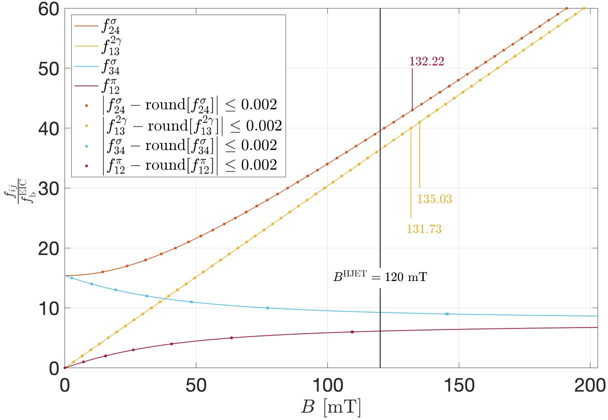
- RF field amplitudes at EIC $\approx 10\times$ larger compared to RHIC
  $\Rightarrow$ increased transition probability due more photons ($n_\gamma \propto B^2$).
- Frequency spacing in spectrum will become much larger
  $\Rightarrow$ fewer contributing resonances.



Hydrogen hyperfine transitions from bunch fields

Depolarization occurs when $\left|\frac{f_{ij}}{f_b^{\text{EIC}}} - n\right| \leq 0.002\,,\ n \in \mathbb{N}$

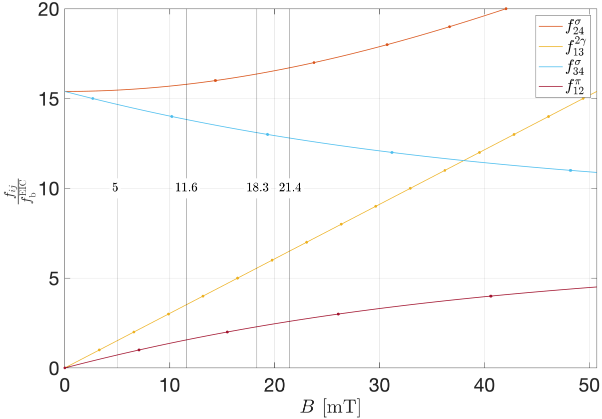
- For $B < 200\,\text{mT}$, all transitions below harmonic number 50 will contribute!



Hydrogen hyperfine transitions from bunch fields

How about the small B region?

- At RHIC, this region was inaccessible, as spacing of $f_{13}^{2\gamma} \approx 0.3\,\text{mT}$.
- At EIC, at $\approx 5\,\text{mT}$, spacing is of $f_{13}^{2\gamma} \approx 3.3\,\text{mT}$.



Conclusion and outlook

Conclusion

- Depolarization:
  - RHIC: harmonic numbers > 100 were ignored.
  - EIC: All depolarization transitions of H appear at harmonic numbers < 50.
  - EIC: If we stay in 120 mT region, field accuracy $\lesssim 1$ mT required.
  - Contrary to situation at RHIC, smaller B may be an option for EIC.
- Extend study of beam-induced depolarization to D and ^{3}He atoms.

Outlook: Other things that need to be looked into

1. How does beam-induced $\vec{B}$ field affect target polarization? $\rightarrow$ in progress
2. Zero-crossings along the vertical axis of the source.
   - Revisit magnetic field calculations of HJET holding field $\rightarrow$ in progress.
3. Polarization measurements with all transition units in ABS and BRP.
4. Tracking of atoms in HJET & sextupole magnet systems
   - Recuperated tracking code used for HJET design from Michelle/Paolo $\rightarrow$ to make it work is time consuming

References I

[1] M. Diermaier et al., Nature Commun. **8**, 5749 (2017).

[2] A. Airapetian et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **540**, 68 (2005).

[3] N. Ramsey, *Molecular Beams*, Oxford University Press, 1956.

Spare slides

Critical field for hydrogen hyperfine splitting I

Zeeman region:

- magnetic flux density at which energy separation between different hyperfine levels becomes comparable to Zeeman splitting.
- referred to as *critical magnetic field* or *Breit-Rabi field* B_c
- Breit-Rabi formula (energy levels of hydrogen atom in external magnetic field:

$$E_{F,m_F} = -\frac{E_{\mathrm{hfs}}}{2(2I+1)} + g_J \mu_B m_J B \pm \frac{E_{\mathrm{hfs}}}{2}\sqrt{1 + \frac{2m_F x}{F} + x^2}\,,\text{where} \qquad (7)$$

- E_{hfs} is hyperfine splitting energy
- I is nuclear spin (for H, $I = \frac{1}{2}$)
- g_J is Landé g-factor
- μ_B is Bohr magneton
- m_J is magnetic quantum number
- m_F is total angular momentum quantum number
- $x = \frac{g_J \mu_B B}{E_{\mathrm{hfs}}}$
- $F = I + J$ is total angular momentum (for H, $J = \frac{1}{2}$)

Critical field for hydrogen hyperfine splitting II

For H:

- hyperfine splitting energy E_{hfs} (1420 MHz):
$$E_{\mathrm{hfs}} \approx 5.874 \times 10^{-6}\,\mathrm{eV} \tag{8}$$
- Critical field B_c is when Zeeman energy $g_J \mu_B B$ is comparable to E_{hfs}. With $g_J \mu_B B_c \approx E_{\mathrm{hfs}}$, we get:
$$B_c \approx \frac{E_{\mathrm{hfs}}}{g_J \mu_B} \tag{9}$$
- For H, $g_J \approx 2$ (approximately for electron), and $\mu_B \approx 5.788 \times 10^{-5}\,\mathrm{eV/T}$. Thus,
$$B_c \approx \frac{5.874 \times 10^{-6}\,\mathrm{eV}}{2 \times 5.788 \times 10^{-5}\,\mathrm{eV/T}} \approx 50.7\,\mathrm{mT} \tag{10}$$