Hadron Beam Polarimetry for the Electron-Ion Collider

Where we stand, what the EIC changes, and what is still missing

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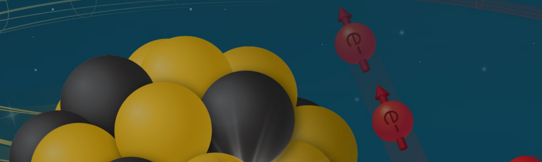


Outline

1. What the EIC requires, and the one absolute route
2. HJET and pC: where we stand today
3. What the EIC changes, and what we are building
4. $^{2}\mathrm{H}$, $^{3}\mathrm{He}$, Li: no polarimeter yet
5. Integration at IP4, and what it costs
6. Outlook: non-invasive SQUID polarimetry

The absolute scale is the hard part, and for three of four species it does not exist yet.

What the EIC requires

A science-pillar number, not a diagnostics preference

$P > 0.7$ with $\Delta P/P \leq 1\%$, for every polarized species

- Every spin asymmetry the EIC ever publishes is divided by this number. A 3% polarization scale error is a 3% error on the physics
- A typical RHIC HJET measurement, Run 33004, reached 7.5% in 370 min of beam [1, 2]
- Four species are foreseen: p, $^{3}\mathrm{He}$, (and later $^{2}\mathrm{H}$, $^{6}\mathrm{Li}/^{7}\mathrm{Li}$ [3])

Why this is hard above a few GeV

- At AGS, RHIC and EIC energies there is no scattering process whose analyzing power A_y is known well enough to give an absolute polarization at the few-percent level
- Analyzing power cannot be assumed. It has to be calibrated, in the machine, against a target of known polarization

Absolute polarimetry at collider energy is a calibration problem, not a counting problem.

Coulomb-nuclear interference, and the one absolute route

Identical-particle elastic scattering fixes the scale

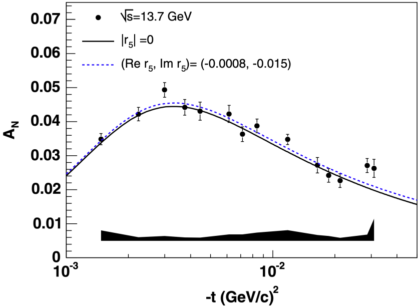
Interference of the two amplitudes

$$\varepsilon = \frac{L-R}{L+R} = A_y P, \quad A_y = \frac{2\,\mathrm{Im}(f^* g)}{|f|^2 + |g|^2}$$

- Spin-flip term from the electromagnetic amplitude that generates the anomalous moment, $\kappa = \mu/2jZ - m_p/m$ [4]
- A_y peaks at $t = \sqrt{3}\,t_C$: $-t \approx 3 \times 10^{-3}\,(\mathrm{GeV}/c)^2$ for pp

The calibration trick

- For *identical* particles A_y does not care which one is polarized, so it cancels [5]: $P = (\varepsilon_{\text{beam}}/\varepsilon_{\text{target}})\,Q$
- Q comes from the Breit-Rabi polarimeter, and must be independent of the interaction point: anything beam-induced that reaches the BRP feeds into the absolute scale



pp elastic $A_y(t)$ in the CNI region, $\sqrt{s} = 6.8$ and 13.7 GeV, measured with the RHIC HJET [6]

▸ amplitudes ▸ kinematics

→ V. Shmakova, *HJET and BRP Analysis at EIC*

The absolute polarimeter must be a jet of the same species as the beam.

HJET and pC today

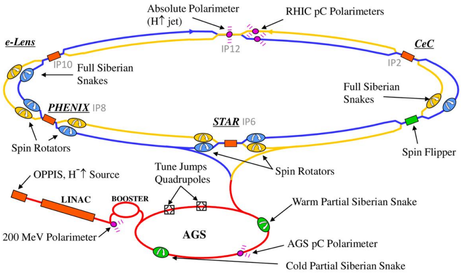
Two instruments, one system

HJET: absolute, slow

- Polarized H jet crossing the stored beam, $\vec{p}\vec{p}$ elastic in the CNI region
- Target spin reversed periodically against detector asymmetries
- **7.5%** in 370 min of beam, Run 33004, and p_y only

pC: fast, relative

- CNI off a $10\,\mu m$ ribbon, $4\,\mu g\,cm^{-2}$
- $30\,s$ for 2% statistical, 110 bunches
- Gives the polarization profile, which HJET cannot



Where the polarimeters sit in the RHIC/EIC chain

The jet must run *in parallel* with pC, not once: target orientation and thickness drift. Neither instrument delivers a polarization on its own.

What RHIC HJET actually delivered

Run 33004, blue beam, 21 January 2022

Jet polarization Q_{atom}	0.9700
Molecular fraction f_m	0.0300
$Q = (1 - f_m)Q_{\text{atom}}$	0.9409
Target asymmetry $\varepsilon_{\text{target}}$	0.0349 ± 0.0012
Beam asymmetry $\varepsilon_{\text{beam}}$	0.0192 ± 0.0012
Beam polarization P	0.517 ± 0.039
Rel. uncertainty $\Delta P/P$	**7.5%**

$A_y = 0.037 \pm 0.0013$, recoil energy 1.5 MeV to 6.0 MeV, $N = 5.01 \times 10^6$ events retained from 21.15×10^6 hits over $T_{\text{meas}} = 370$ min. Beam parameters from PRAB **29**, 021001 (2026), Table II [7].

Statistics, not systematics

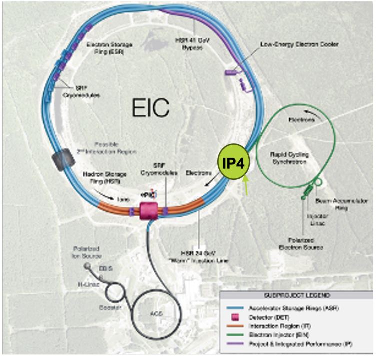
$$\left(\frac{\Delta P}{P}\right)^2 = \left(\frac{\Delta\varepsilon_{\text{beam}}}{\varepsilon_{\text{beam}}}\right)^2 + \left(\frac{\Delta\varepsilon_{\text{target}}}{\varepsilon_{\text{target}}}\right)^2$$

- Retained rate $226\,\text{s}^{-1}$, total detector rate $950\,\text{s}^{-1}$: only 24% of hits survive the CNI cut
- Occupancy $\sim 10^{-4}$ per bunch crossing, so pile-up is negligible and bunch assignment at 106.6 ns is unambiguous
- Jet: flux $12.4(2) \times 10^{16}$ atoms/s, thickness $1.3(2) \times 10^{12}$ atoms cm^{-2}, beam diameter ≈ 10 mm

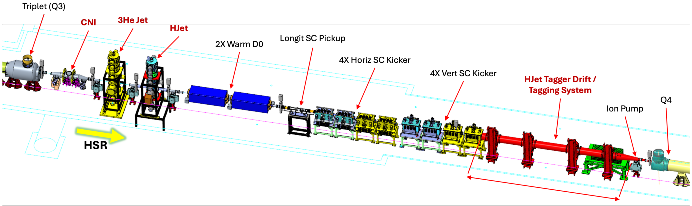
370 min of beam for 7.5%. Reaching 1% is a statistics problem before it is anything else.

HJET and pC in the EIC

The polarimeter straight at IP4



EIC full project scope; hadron polarimetry at IP4



IP4 lineup, polarimetry baseline review (BNL, Jan 2026)

- **HJET and pC are refurbished and upgraded** for EIC use: both instruments move from RHIC IP12 to IP4
- ^{3}He jet stands in the lineup, but is not yet on the project

The proton polarimeters transfer with the machine. The ^{3}He target still needs a home in the project.

From RHIC to the EIC

Two independent machine changes, three polarimeter problems

	RHIC	EIC
Spacing (ns)	106.6	11.027
f_b (MHz)	9.381	90.683
Bunches	120	1160
N_p (10^{11})	2.0	0.69
Current (A)	0.301	1.003

PRAB **29**, 021001 (2026), Table II [7]. One clock choice sets spacing, f_b and bunch count; the current follows from bunch count and N_p.

What follows, and from which change

- **Target survival** ← current: three times the load on a carbon strip already at its thermal margin
- **Bunch assignment** ← spacing: neighbouring bunches may carry opposite spin, a wrong pairing dilutes the asymmetry
- **Target depolarization** ← spacing: the $90.683\,$MHz harmonics reach the hyperfine transitions

Three separate failure modes, three separate answers. The next three slides.

Carbon strip targets under an EIC beam

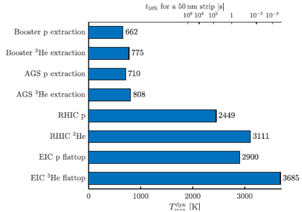
Beam heating is not the whole story

What RHIC operation showed

- Target lifetime is not explained by beam energy deposition alone. RF-induced strip-end heating and electromechanical response also drive it [8]
- Target temperature has never been measured directly; earlier attempts were inconclusive [9]

Measured, on the last RHIC beam

- Light through the existing viewports, 200 nm to 2100 nm; blackbody comparison gives **preliminary** 1760 K
- RHIC p at 2449 K is the anchor, a regime known to operate
- EIC p flattop 2900 K, EIC ^{3}He 3685 K: 1200 K above the proven point
- Mitigation: β_y 30 m $\rightarrow$ 240 m, longer targets, alumina holder [3]



Dynamic peak temperature per case; the upper axis converts it to $t_{50\%}$, the time to lose half of a 50 nm strip [8]

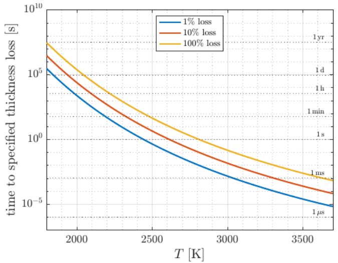
▸ mechanisms ▸ holder

The first direct temperature measurement of a polarimeter target, on the last RHIC beam.

Target lifetime, cycle by cycle

RHIC protons, the empirical anchor

- $(f_{\text{sub}})_{1\,\text{s}} \approx 0.011$ at $T^{\text{dyn}}_{\text{max}} \approx 2449\,\text{K}$
- Video gives $\Delta t_{\text{beam}} \approx 1.5\,\text{s}$ per pass, so an in-and-out cycle is $\approx 3\,\text{s}$: $(f_{\text{sub}})_{\text{cycle}} \approx 0.033$, about 3% of a $50\,\text{nm}$ strip per cycle
- Cycles to 50% loss: $N \approx 15$ at peak intensity, ≈ 120 cycle-averaged
- Observed: 2013 without fins, average 27. 2015 with fins, average 142, best 396. The estimate brackets the data



Time to remove 1%, 10% and 100% of a $50\,\text{nm}$ strip

The same $3\,\text{s}$ cycle at EIC flattop gives $(f_{\text{sub}})_{\text{cycle}} \approx 7.7$ for protons: **more than one full strip thickness per cycle**. Thinner strips do not help, since deposited energy, thermal mass and conduction all scale with thickness. Dwell time, width and scan speed are the controls.

Bunch assignment at 11 ns

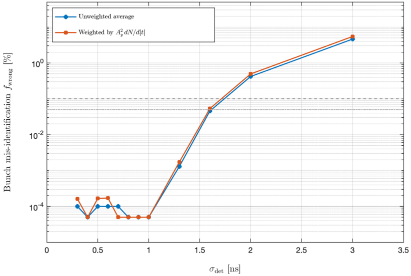
Which bunch produced this recoil?

The problem

- At RHIC, 106.6 ns spacing separates recoils by bunch without effort
- At 11 ns it does not. Adjacent bunches can carry opposite spin, so a misassigned event does not add noise, it dilutes the asymmetry

The handle: recoil energy and time of flight are correlated

- In the CNI region the recoil energy and its time of flight to the detector are correlated. Measure both and the pairing is constrained
- Monte Carlo under realistic EIC timing: $\sigma_{\mathrm{det}} \lesssim 1.5$ ns keeps mis-identification below 10^{-3}, i.e. $\Delta P/P < 0.1\%$ from this source alone. Sub-ns timing is **not** required



f_{wrong} vs. detector timing resolution σ_{det}; Fig. 8, guide-field design note (BNL, Jan 2026)

▸ the Monte Carlo

Solvable, and it sets a timing specification for the recoil detector.

A three-axis guide field for the HJET target

Target guide field up to $400\,\mathrm{mT}$

Why the field has to go up

- At the EIC bunch frequency the beam-field harmonics reach the hydrogen hyperfine transitions at the present $120\,\mathrm{mT}$
- Beam RF fields then drive resonant transitions: the target itself depolarizes, destroying the calibration
- A higher holding field moves the transitions off the populated harmonics: a resonance-free operating region

What the design adds beyond a stronger field

- Three orthogonal coil pairs, $\pm B_x$, $\pm B_y$, $\pm B_z$, one energized at a time: **full vector polarimetry**, where RHIC HJET measured p_y alone
- Field reversal separates the injected hyperfine states, $|1\rangle+|4\rangle$ vs. $|2\rangle+|3\rangle$

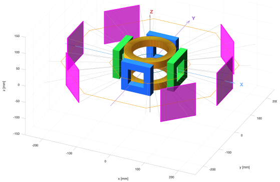


Fig. 1, guide-field design note (BNL, Jan 2026)

Details of the magnet and detector design are not yet public. See V. Shmakova, 09:40.

One magnet, three field orientations

The flexibility, quantified

Same field quality on every axis

Coil pair	$\langle B_\parallel \rangle$ (T)	$\sigma(B_\parallel)/\langle B_\parallel \rangle$
B_x	0.39997	8.7×10^{-3}
B_y	0.39997	8.7×10^{-3}
B_z	0.40003	8.3×10^{-4}

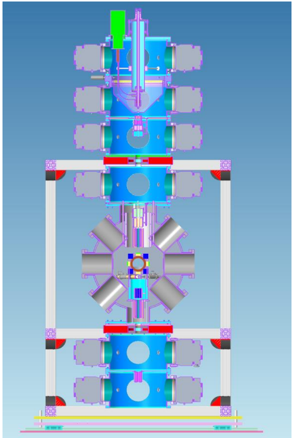
Table 4, guide-field design note (BNL, Jan 2026)

What switching buys

- p_y with B_y, as at RHIC; B_x and B_z add p_x and p_z: **the full polarization vector**
- $\pm$ reversal on every axis: instrumental asymmetries change sign, the physics does not
- The holding field leaves T_R and p_R untouched; deflection only remaps hit positions, handled in reconstruction

Any axis, either sign, one component at a time: systematics become sign-separable.

The target chamber



HJET assembly: atomic beam source above, target chamber, Breit-Rabi polarimeter below

What the EIC chamber has to do differently

- UHV shared with beam and jet; every magnet component vacuum compatible and low outgassing
- Clear bore of at least $100\,\mathrm{mm}$ along z, free of magnetic material, with 10σ clearance against the largest gold emittance at injection
- Interaction region at $z = 0$ free of magnet structure, to preserve azimuthal acceptance
- Six silicon modules in three opposing pairs at $r \approx 220\,\mathrm{mm}$, on the horizontal axis and the $\pm 45^\circ$ diagonals; active area $\approx 100\,\mathrm{mm} \times 100\,\mathrm{mm}$ each
- Coil legs pushed to $\pm 33.1\,\mathrm{mm}$, on the $\pm 22.5^\circ$ rays, so no conductor shadows a detector acceptance cone
- QMA $\approx 100\,\mathrm{mm}$ below the target, scanning $\pm 40\,\mathrm{mm}$ for the H_2 fraction

Constraints from the design note [1].

Beam-induced depolarization of the HJET target

Status of the published analysis, PRAB 29, 021001 (2026)

Where the field value comes from

- Phys. Rev. Accel. Beams **29**, 021001 (2026) [7] analyses the beam-induced field at the jet and the resulting hyperfine transition rates under EIC bunch structure, and addresses the choice of the holding-field value for the EIC

A. A. Poblaguev identified an error in the harmonic-amplitude normalization of that paper. We thank him for it. An Erratum is in preparation. The quantitative results change; the recommendation of an elevated holding field stands, on grounds the Erratum states.

→ A. Poblaguev, *Evaluation of Beam-Induced Depolarization of the HJET Target at the EIC*, Nucl. Instrum. Meth. A **1091**, 171776 (2026) [10]

Polarimetry for $^3\mathrm{He}$, deuterons, and lithium

Three species, three different instruments, none of them built

	absolute method	target	status
p	$\vec{p}\,\vec{p}$ CNI	H jet, exists	upgrade on project
$^2\mathrm{H}$	vector yes, tensor no	d jet, not built	no design
$^3\mathrm{He}$	$^3\mathrm{He}$–$^3\mathrm{He}$ CNI	cryo ABS, 95%	concept, not on project
$^6\mathrm{Li}/^7\mathrm{Li}$	$^7\mathrm{Li}$ is spin 3/2	reuse source ABS	open

$^3\mathrm{He}$: the closest to a design

Cryogenic ABS $\approx 95\%$, but target density $\sim 10^{10}\,\mathrm{cm}^{-3}$ is two orders below the H jet. A storage cell buys $\sim 10^{12}\,\mathrm{cm}^{-2}$: 1% in $\approx 1\,\mathrm{h}$ at $1\,\mathrm{A}$. MIT ABS design report [11].

▸ polarimetry in the AGS

The proton polarimeter has a project. The other three species do not.

The cryogenic $^3\mathrm{He}$ atomic beam source

How it works

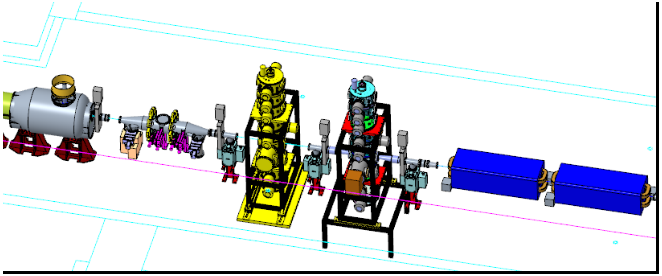
- Cryogenic chamber with a multi-channel plate nozzle at $1\,$K: ^{4}He evaporatively cooled in a small pot, $^3\mathrm{He}$ thermalized against it
- Four sets of permanent neodymium magnets, surface field $\approx 1\,$T, gradient $\approx 1\,$T/cm over $\approx 1\,$m
- One spin state defocused and pumped away, the other focused. Shimming magnets transport the polarized atoms adiabatically to the holding field
- Demonstrated $\approx 95\%$ at $\sim 10^{14}$ atoms cm^{-2}s^{-1}

Why a storage cell is unavoidable

- Free jet density $\sim 10^{10}$ cm^{-3} at $\approx 84\,$m/s, two orders below the hydrogen jet
- Cell raises thickness to $\sim 10^{12}$ cm^{-2}: 1% in $\approx 1\,$h at $1\,$A
- Relaxation: days in caesium-coated cells, $\mathcal{O}(1\,\mathrm{min})$ achieved in accelerator cells
- MEOP and SEOP saturate below 90%; gradient-polarized cryogenic beams can exceed 99%

The polarimeter section at IP4

Everything in one straight, counting house $23.5\,\mathrm{m}$ away



The IP4 polarimeter section: pC, the hydrogen jet and the $^3\mathrm{He}$ jet in one straight

Why everything moves here

- pC, the hydrogen jet, and later deuteron and $^3\mathrm{He}$ jets share one straight, so the spin rotation between instruments is minimized rather than modelled and corrected [3]
- HJET moves from IP12: tunnel 1012 → high bay → EIC tunnel 1004, refurbished on the way

One location, one detector line, one control system.

Shared systems, and what the upgrade buys

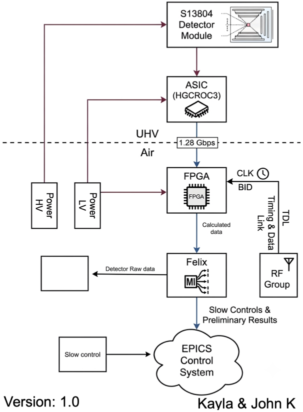
One detector line for HJET, pC and the Booster polarimeter

Detectors and controls

- One silicon strip detector line shared across HJET, pC and the Booster polarimeter: common front end, DAQ and calibration
- Two perpendicular measuring planes for position and energy, plus a veto layer against punch-through and prompt background
- EPICS 7 on the common EIC platform; safety functions in Allen-Bradley safety PLCs [1]

HJET upgrade

- Three-axis guide field, full vector $\vec{P}$
- New target chamber with enhanced detector acceptance and SC guide field system
- Quadrupole mass analyser for H_2 background determination



Detector to EPICS: S13804, HGCROC3, FPGA, Felix

Recoil detector acceptance at IP4

Six modules at $220\,\text{mm}$, and what they buy

Azimuthal coverage, not solid angle

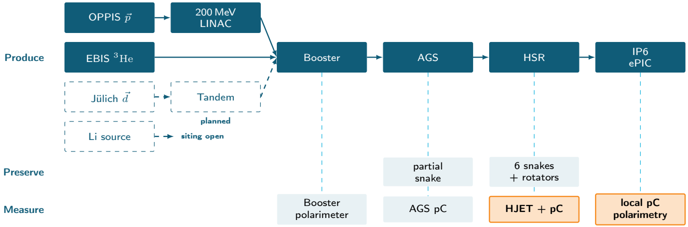
- Naively the solid angle scales as A/r^2, and moving the detectors from $750\,\text{mm}$ to $220\,\text{mm}$ would give $(750/220)^2$
- That gain is not available. The elastic pp analyzing power is sizable only in the CNI region, $|t| \sim 10^{-3}$ to 2×10^{-2} GeV^2, so the recoil angle is pinned near 90° and there is no polar-angle extension to win
- For a vertical component, $N(\phi) \propto 1 + A_y P_y \cos\phi$, so a detector at azimuth ϕ_i contributes to the inverse variance as $\cos^2\phi_i$. The figure of merit is $F_y \propto \sum_i \Delta\phi_i \cos^2\phi_i$
- Six modules in three opposing pairs, on the horizontal axis and the $\pm 45^\circ$ diagonals: **6.8$\times$ from azimuth alone**

Six modules at $220\,\text{mm}$ instead of $750\,\text{mm}$ $\rightarrow$ **6.8**$\times$ from azimuthal coverage; EIC intensity gives another **3**$\times$. Measurement time falls about **20**$\times$ [1].

Staged: Phase 1 is the horizontal pair with the B_y coils. Phase 2 adds the diagonals and the B_x, B_z systems. Duty-cycle cost of three-axis sequencing, $100\,\text{s}$ dwell and $5\,\text{s}$ switching, is about 4.8%.

The team, and the gaps

EPIOS: this R&D has to start now



HJET and pC, at BNL now

F. Rathmann, O. Eyser; E. C. Aschenauer, X. Chu, K. Hernandez, H. Huang, R. Porqueddu, P. Shanmuganathan, V. Shmakova, E. Shulga, A. Verderosa, Z. Zhang

^{3}He and beyond

P. MohanMurthy (MIT): ^{3}He atomic beam source. The rest of the measure row, d tensor polarimetry, Li, light-ion readout in Booster and AGS: needs attention.

$\rightarrow$ effort and timeline: F. Rathmann, Monday, Sources & Transport I

Summer projects, research stays, postdoc positions: come and talk to us during the workshop.

Outlook: non-invasive SQUID polarimetry

Reading the bunch magnetic moment instead of scattering off it

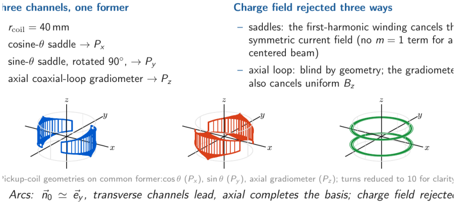
What a pickup could add

- Every scattering polarimeter costs beam and target lifetime. A SQUID magnetometer reads the flux of the bunch magnetic moment and takes nothing from the beam
- Three components (P_x, P_y, P_z), bunch by bunch, continuously, with an axial gradiometer for the longitudinal channel
- The spin tune ν_s becomes a machine diagnostic in its own right

Where it stands

- Concept, flux signal and matched-filter sensitivity worked out; modes are free induction decay, spin echo, phase lock
- Sensitivity budget uses **conservative, commercial DC SQUID parameters**
- Not a replacement for the absolute scale, a complement [12]

▸ sensitivity and modes



Three-channel pickup basis

arXiv:2606.22265

Summary

- $\Delta P/P \leq 1\%$ is a physics requirement, and above a few GeV it can only be met by calibrating the analyzing power in the machine, against a target of the same species
- pC has no absolute scale of its own, so the jet has to run beside it for the whole store. The EIC attacks that pair in three places at once: target survival, bunch assignment at 11 ns, and depolarization of the jet target itself
- All three have answers. The three-axis 400 mT guide field also buys full vector polarimetry, which RHIC never had
- $^{2}\mathrm{H}$, $^{3}\mathrm{He}$ and Li have no polarimeter yet. That is the largest gap in the programme, and the most open field for new people

The absolute scale rests on the target polarization Q, and on the Breit-Rabi measurement of it staying clean of the interaction point. That, and the beam-induced effects that threaten it, are the next two talks: V. Shmakova 09:40 and A. Poblaguev 10:00.

References I

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[8] F. Rathmann et al. Thermal and electromechanical response of ultra-thin carbon-strip polarimeter targets in relativistic bunched beams. *arXiv*, 2606.29005, 2026.

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[12] F. Rathmann. Quantum noninvasive three-component beam-spin polarimetry in the Hadron Storage Ring of the Electron-Ion Collider. *arXiv:2606.22265*, 2026.

Spare slides

Spare: CNI amplitudes in full

Non-flip and single spin-flip elastic amplitudes

$$f = \frac{i+\rho}{e^{i\delta_C}} - \frac{t_C}{t}\,\frac{e^{b_e t}}{e^{b_h t}} \approx i + \varrho - \frac{t_C}{t},$$

$$g = \frac{\sqrt{-t}}{2m_p}\left[\frac{R_S + iI_S}{e^{i\delta_C}} - \frac{\kappa\, t_C}{t}\cdot\frac{e^{b_m t}}{e^{b_h t}}\right]$$

- Coulomb phase $\delta_C = -Z\tilde{Z}\alpha(\ln|b_h t + b_e t| + \gamma)$, a few percent
- Electromagnetic and hadronic non-flip amplitudes equal near $-t_C = 8\pi|Z\tilde{Z}|/(137.036\,\sigma_{\text{tot}})$
- Anomaly $\kappa = \mu/(2jZ) - m_p/m$; the hadronic single spin-flip amplitude is $R_S + iI_S$

The approximation used on the main slide

$$A_y = \frac{(\kappa - I_S)\sqrt{-t_C}}{m_p}\cdot\frac{x^{3/2}}{x^2+1}, \qquad x = t/t_C$$

- $|I_S| > |R_S|$, so $\varrho I_S - R_S$ and ϱ^2 are dropped

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Spare: recoil kinematics and the inelastic window

Which recoil angles carry the asymmetry

$$\cos\theta_{\text{el}} = (1 + 2M/T)^{-1/2}\, W/P,$$
$$\cos\theta_{\text{in}} = (1 + 2M/T)^{-1/2}\left[W + (m + \tfrac{\delta}{2})\delta/T\right]/P$$

- $P = \sqrt{E^2 - m^2}$ the incident momentum, T the recoil kinetic energy, $W = E + M$
- δ is the lowest excitation or break-up of the incident mass: $p \to p + \pi$, or $^3\text{He} \to p + d$
- Events between θ_{el} and θ_{in} dominate the analyzing power at high energy

Why this matters for ^3He

- The ^3He break-up threshold is low, so the inelastic window opens early and fragments must be rejected event by event
- Energy loss scales with Z^2: singly charged p and d separate cleanly from $^3\text{He}^{++}$ in the QDC pulse-height spectrum
- The strip detectors therefore serve as tracker and veto at once

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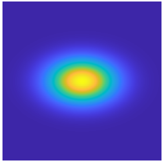
Spare: what actually limits the carbon strip

Three mechanisms, not one

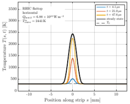
- **Beam heating.** Energy deposition, secondary-electron escape, one-dimensional conduction along the strip plus radiation
- **RF strip-end heating.** The ends glow before the centre, which beam heating alone cannot produce
- **Electromechanical force.** Visible strip displacement at force scales far below anything thermal

Sublimation is kinetics, not a threshold

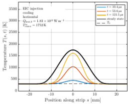
- Loss rate is continuous in T; the useful quantity is the time to remove a given fraction of a $50\,$nm strip
- Booster and AGS: no thermal concern in the injector chain



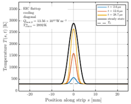
Particle-flux map at the target



RHIC flattop, horizontal.



EIC injection, after cooling.



EIC flattop, cooled emittance.

- steady state, $\partial T/\partial\tau = 0$: conduction to the ends and radiation balance the centered source (intermediat times and final profile)
- continuous exposure of the same strip element: conservative upper-limit benchmark, not normal operatio
- peak temperature set by the local $Q_{\mathrm{heat},0}$, essentially independent of orientation; inclination changes only the profile width via $\sigma_{\parallel}(\theta)$

$T^{\mathrm{ss}}_{\mathrm{center}} \simeq 2441\,\mathrm{K}$ **(RHIC)** $1752\,\mathrm{K}$ **(EIC injection)** $2892\,\mathrm{K}$ **(EIC flattop cooled)**

Static steady-state temperature profiles

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Spare: target holder, wakefields and RF heating

Why the holder material matters at 11 ns [3]

- Higher-order modes from pump ports, view ports and other openings become significant. RF-induced heating is expected to be more severe in the HSR than in RHIC, so shielding of these openings is essential
- CST simulations of wakefields, impedance and resistive-wall losses were run for both RHIC and EIC beam parameters
- At RHIC parameters, aluminium and alumina holders behave alike
- At EIC parameters the aluminium holder produces strong wakefield oscillations and impedance resonances; alumina, a dielectric, suppresses both

Consequences for the design

- New target chamber with a lock chamber, so targets can be exchanged without breaking vacuum
- Longer carbon targets; aluminium holder replaced by alumina
- Readout and detector choice for the carbon targets still open

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Spare: SQUID sensitivity and operating modes

F. Rathmann, arXiv:2606.22265 [12]

Two modes

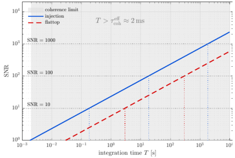
- **Static:** continuous vector reading with no tipping, from the stable spin axis around the ring
- **Dynamic:** tip, then free induction decay; a π pulse rephases the ensemble in a spin echo; phase lock holds the precession
- Six Siberian snakes set $\nu_s = 1/2$, so the signal sits at $f_{\text{rev}}/2$
- An axial gradiometer rejects the charge field by geometry and opens the longitudinal channel

Coherent integration gives an SNR linear in $P_\perp$ and $\sqrt{T}$. Sensitivity budget uses commercially available DC SQUID parameters.

- $P_\perp = P \sin\alpha \approx 0.021$ ($P = 0.7$, $\alpha = 30$ mrad); $T_{1\%} = (100/K_{\text{template}} P_\perp)^2$

Case	Analysis	$T_{1\%}$
Inj, 290	naive	18 days
Inj, 290	same-sign	73.9 s
Inj, 290	matched	18.5 s
Flat, 1160	naive	288 days
Flat, 1160	matched	4.93 min

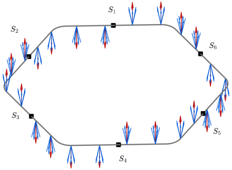
t full projection ($\sin\alpha = 1$): 6.5 ms (inj), 104 ms lat); the $1/\sin^2\alpha$ penalty buys non-invasiveness.



Matched-filter SNR vs T at both energies; dotted lines mark SNR $= 10, 100, 1000$ ($10\%, 1\%, 0.1\%$). Grey: $T > \tau_{\text{coh}} \simeq 2.04$ ms, handled as repeated cycles.

Matched filter reaches 1% in ~ 18 s (inj) and ~ 5 min (flat); mm tip angle, not hardware

Integration time to $\Delta P/P = 1\%$



Stable spin axis around the ring

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