HJET and BRP Analysis at EIC

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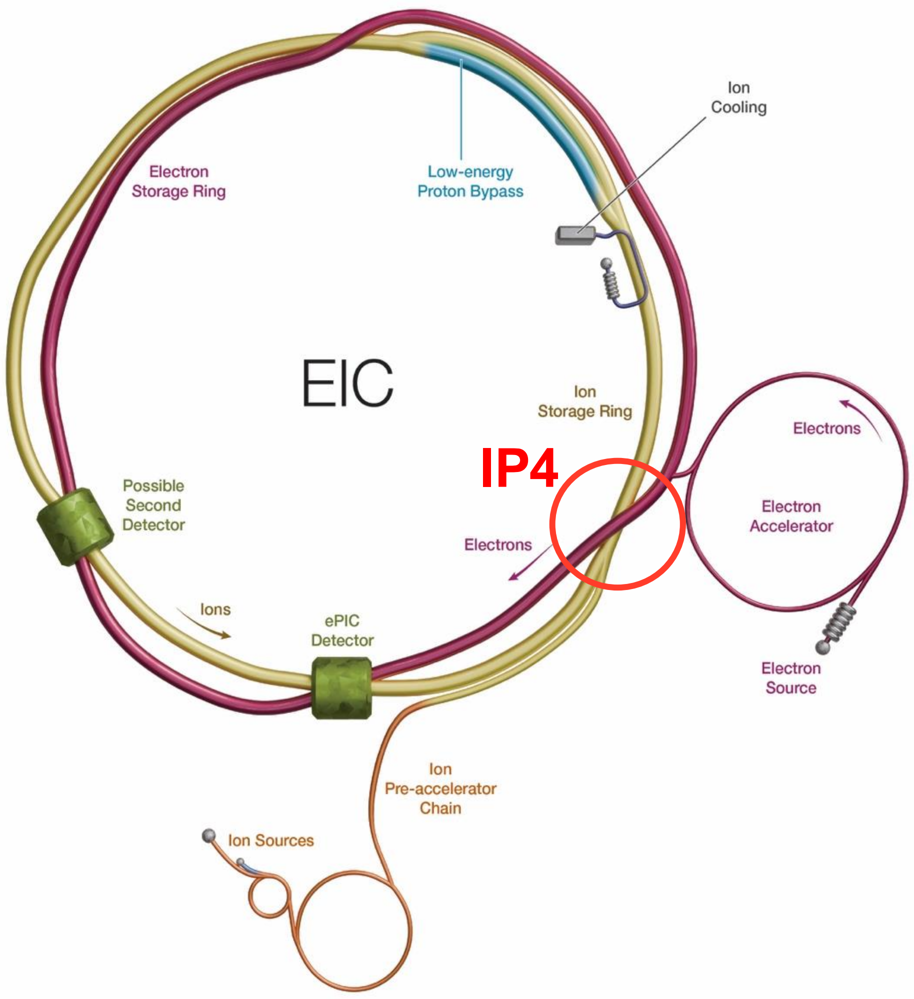
Absolute beam polarization at EIC

1. Precision requirements for beam polarization $\frac{\Delta P}{P} < 1\%$
2. The goal to determine absolute beam polarization
3. Instrument: Hydrogen Jet polarimeter (HJET) in IP4
4. Method:
   - Elastic scattering of pp
   - Use CNI
5. Absolute proton beam polarization calibration relies on measured nuclear polarization of hydrogen jet using Breit-Rabi polarimeter



Beam polarization determination

- A polarized proton beam scatters elastically from the polarized H target with known polarization Q.
- Scattered recoil protons are counted in the left and right detectors.
- The target spin direction is periodically reversed. Combining measurements for both target-spin signs cancels first-order left/right detector acceptance and efficiency asymmetries.
- With the beam polarization averaged out, the target asymmetry is

$$\epsilon_{tgt} = \frac{L-R}{L+R} = A_y\, Q$$

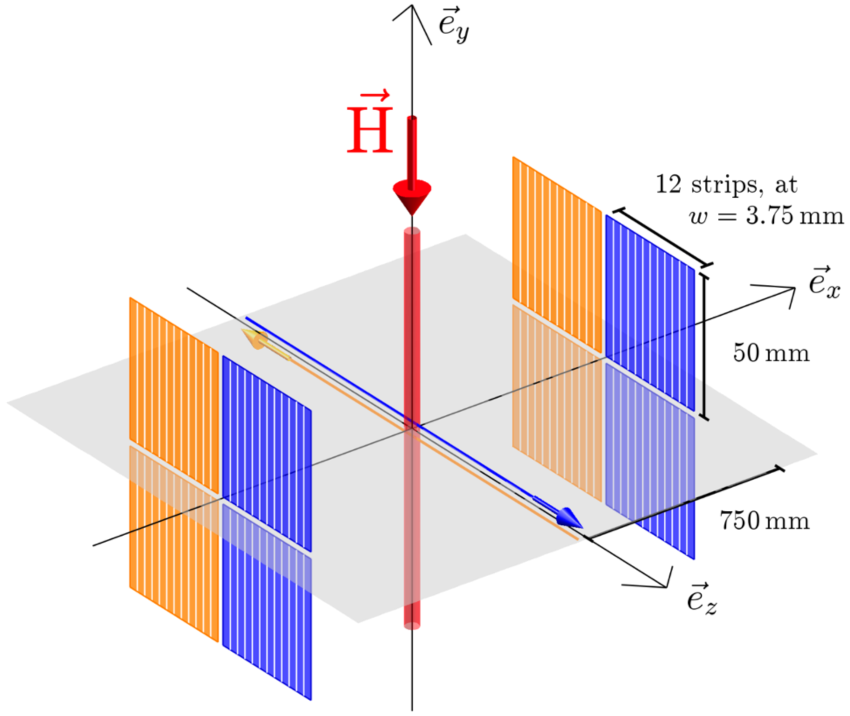
- The corresponding beam asymmetry is measured from the same elastic (pp) events:

$$\epsilon_{beam} = A_y P$$

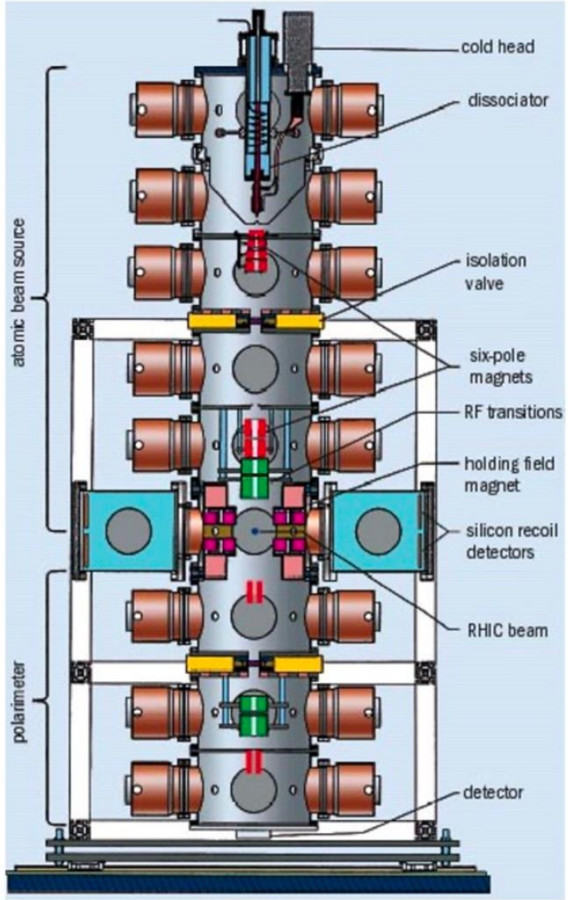
- In elastic scattering of identical protons, the analyzing power A_y is the same whether the beam proton or target proton is polarized.

$$\boxed{P = \frac{\varepsilon_b}{\varepsilon_t} Q}$$

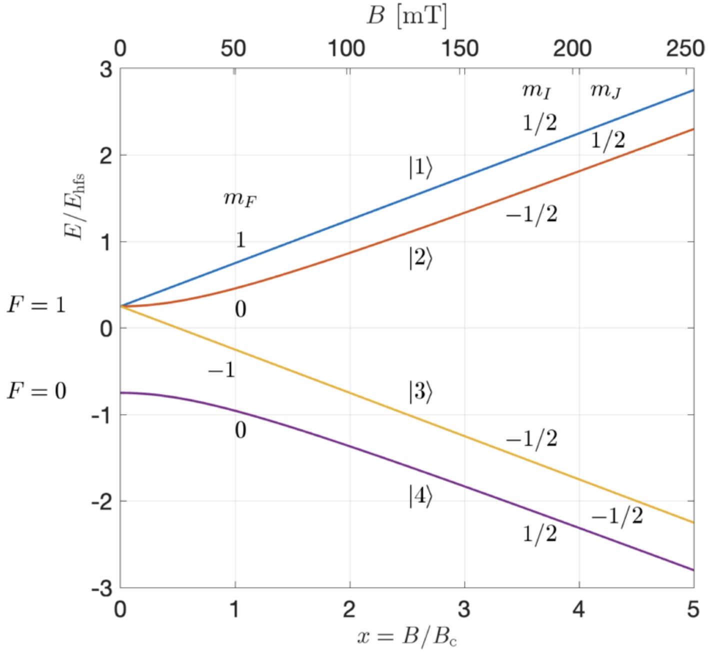
- **Essential to know target polarization Q**

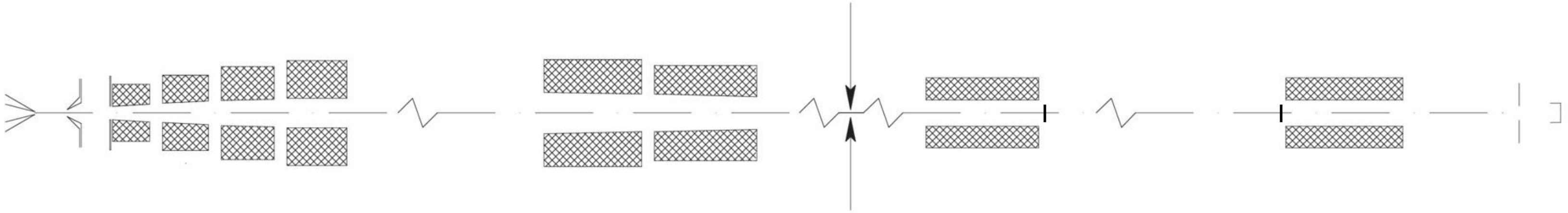


HJET overview



- Polarized atomic hydrogen source
- Sextupole magnets
- ABS transition units
  - WFT makes transition 1 → 3
  - SFT makes transition 2 → 4
- BRP transition units SFT, WFT
- RHIC 120 mT → EIC 400 mT
- Breit-Rabi detector





Magnet system design

T. Wise, et al. An optimization study for the RHIC polarized jet target, Nucl. Instrum. Methods Phys. Res. A., Volume 556, Issue 1, 2006 https://doi.org/10.1016/j.nima.2005.09.042.

Target polarization determination

Equally populated states exit nozzle

1. RF transition units in ABS
   - ABS Transition efficiencies ε_{ij}^{A}
   - Desired states: 1+4 or 2+3

2. Target polarization
   - Transmissions σ^{tgt}_{i} to the target
     - determined from simulations
   - ABS Transition efficiencies ε^{A}_{13} , ε^{A}_{24}
     - extracted from signals in BRP detector

1. $Q_i(B_0)$ = nuclear polarization state $|i\rangle$

$$Q = \frac{\sum_{i=1}^{4} n_i \cdot Qi(B_0)}{\sum_{i=1}^{4} n_i}$$

Transition 2 → 4

$$\begin{pmatrix} n\sigma_1^A \\ n\sigma_2^A \\ n\sigma_3^A \\ n\sigma_4^A \end{pmatrix} \rightarrow \begin{pmatrix} n\sigma_1^A \\ n(\sigma_2^A\varepsilon_{24}^A + \sigma_4^A(1-\varepsilon_{24}^A)) \\ n\sigma_3^A \\ n(\sigma_4^A\varepsilon_{24}^A + \sigma_2^A(1-\varepsilon_{24}^A)) \end{pmatrix}$$

Transition 1 → 3

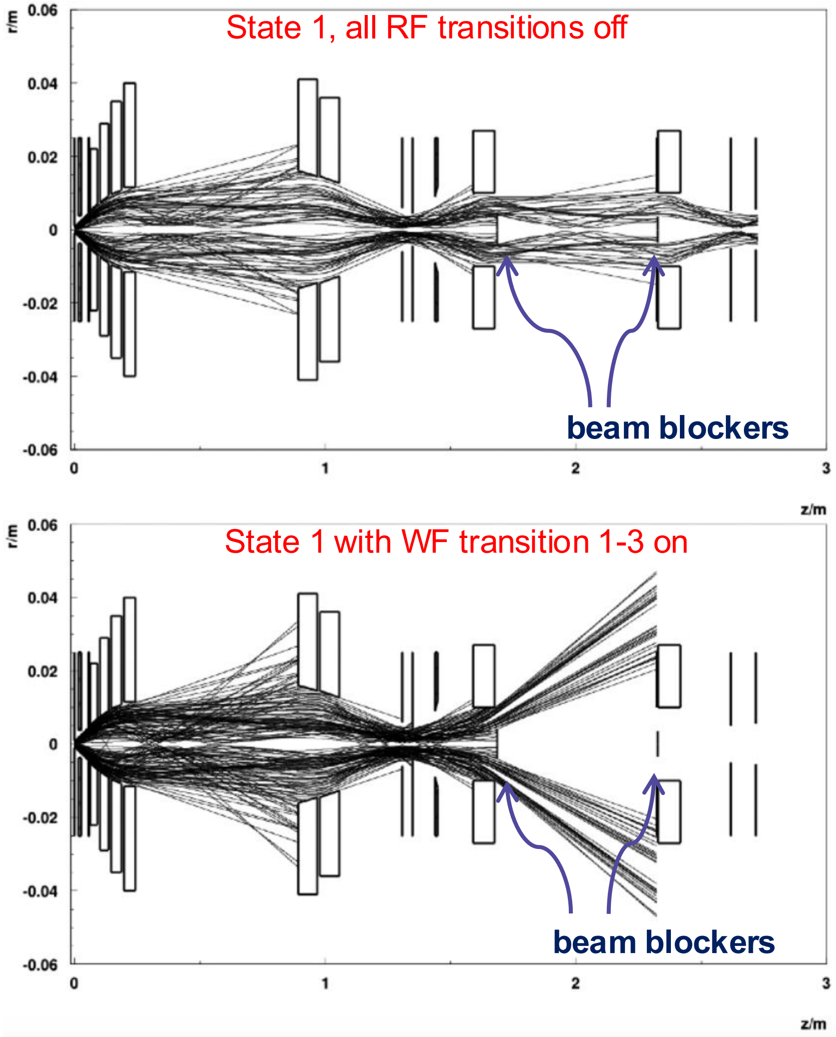
$$\begin{pmatrix} n\sigma_1^A \\ n\sigma_2^A \\ n\sigma_3^A \\ n\sigma_4^A \end{pmatrix} \rightarrow \begin{pmatrix} n(\sigma_1^A\varepsilon_{13}^A + \sigma_3^A(1-\varepsilon_{13}^A)) \\ n\sigma_2^A \\ n(\sigma_3^A\varepsilon_{13}^A + \sigma_1^A(1-\varepsilon_{13}^A)) \\ n\sigma_4^A \end{pmatrix}$$

Target polarization:

$$Q^{+}_{|1\rangle+|4\rangle} = \frac{\sigma_1^{tgt}Q_1(B_0)+(\sigma_2^{tgt}\varepsilon_{24}^{A}+\sigma_4^{tgt}(1-\varepsilon_{24}^{A}))Q_2(B_0)+\sigma_3^{tgt}Q_3(B_0)+(\sigma_4^{tgt}\varepsilon_{24}^{A}+\sigma_2^{tgt}(1-\varepsilon_{24}^{A}))Q_4(B_0)}{\sigma_1^{tgt}+\sigma_2^{tgt}+\sigma_3^{tgt}+\sigma_4^{tgt}}$$

$$Q^{-}_{|2\rangle+|3\rangle} = \frac{(\sigma_1^{tgt}\varepsilon_{13}^{A}+\sigma_3^{tgt}(1-\varepsilon_{13}^{A}))Q_1(B_0)+\sigma_2^{tgt}Q_2(B_0)+(\sigma_3^{tgt}\varepsilon_{13}^{A}+\sigma_1^{tgt}(1-\varepsilon_{13}^{A}))Q_3(B_0)+\sigma_4^{tgt}Q_4(B_0)}{\sigma_1^{tgt}+\sigma_2^{tgt}+\sigma_3^{tgt}+\sigma_4^{tgt}}$$

Simulation code: Tracking calculations



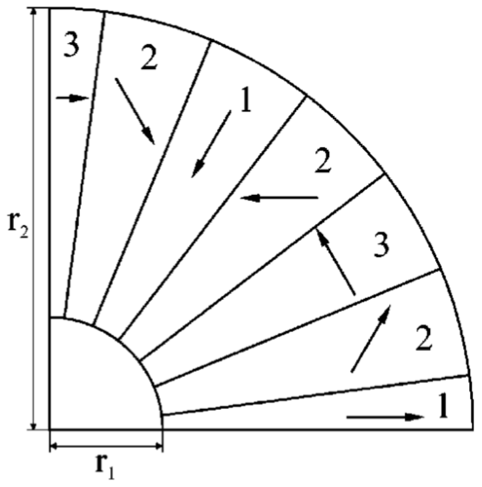
T. Wise, et al. An optimization study for the RHIC polarized jet target, Nucl. Instrum. Methods Phys. Res. A., Volume 556, Issue 1, 2006 https://doi.org/10.1016/j.nima.2005.09.042.

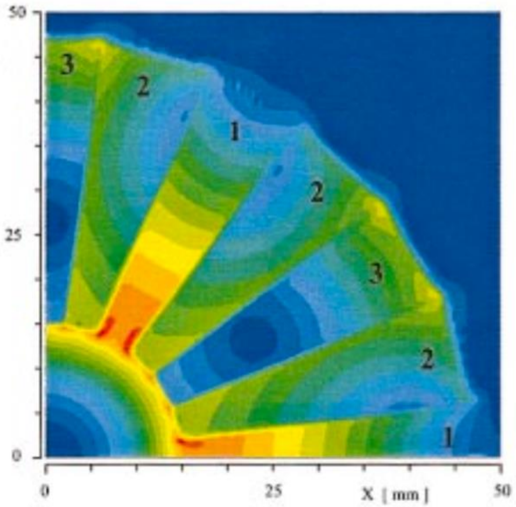
Simulation code originally developed for RHIC HJET has been recuperated

- **Z. Zhang** is working on updating the code for EIC use

- Monte Carlo particle-tracking simulation
  - Atoms launched from source with randomized position/angle/velocity
  - Propagates each track step-by-step down the beamline: through real magnet/RF/apertures and blocker geometry
  - Surviving populations per hyperfine state are counted to predict transmission and intensity at the target

Sextupole magnets used in simulation





24 segmented permanent sextupole magnet design

- Magnetization axis of each segment advances azimuthally by angle $\pi/3$
- Three different materials (slide 19) with varying remanence
- Higher order multipoles strongly suppressed
- Pole-tip field of 1.6-1.7 T

A. Vassiliev, et al. 24 segment high field permanent sextupole magnets, *Rev. Sci. Instrum.* 71, 3331–3341 (2000). https://doi.org/10.1063/1.1288264

- Magnet system of HJET:

Magnet	Length [mm]	r_1^{entr} [mm]	r_1^{exit} [mm]	r_2 [mm]	B_0^{eff} [T]
1	28.5	5.2	7.0	22.0	1.695
2	35.4	7.5	9.1	29.0	1.686
3	40.5	9.7	10.7	35.7	1.687
4	46.0	11.5	11.5	40.3	1.687
5	75.0	16.0	14.5	41.2	1.585
6	79.0	14.5	12.7	36.7	1.584
7	87.0	10.0	10.0	27.0	1.585
8	90.0	10.0	10.0	27.0	1.585

- Pole-tip field B_0^{eff} from composition and geometry magnets computed (see slide 19)
- B_0^{eff} used in the code

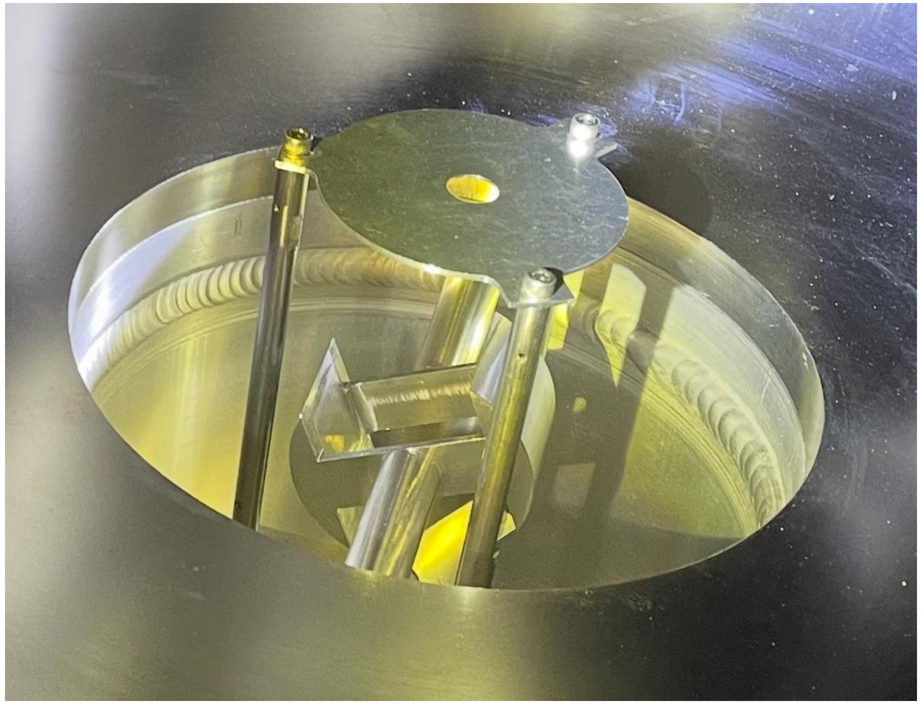
BRP: 16 combination transition scheme

Breit-Rabi polarimeter designed to enable:

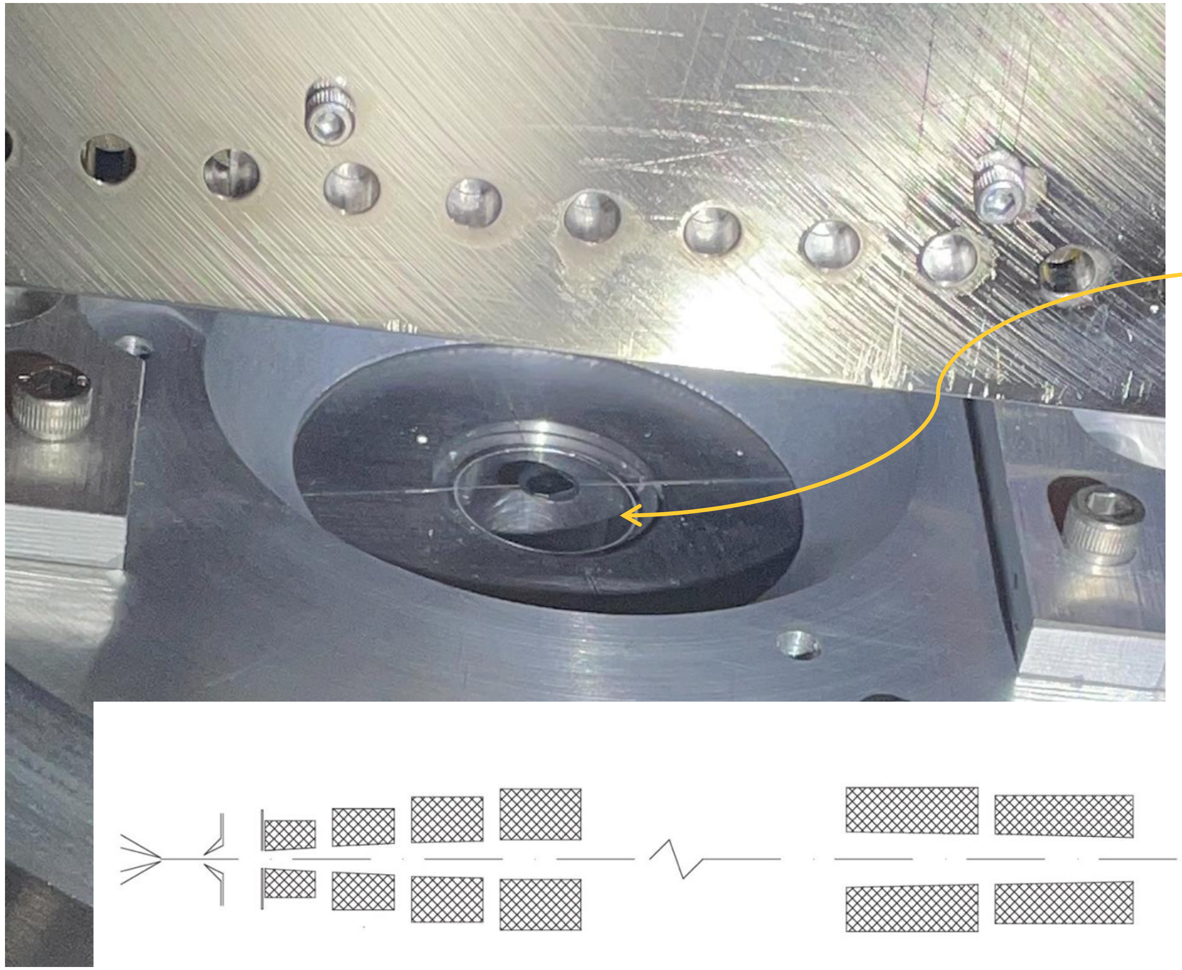
- Second set of WFT and SFT transition units installed in BRP
- Allows measurement of populations of unwanted hyperfine states
- 16 possible transition combinations:
  - 2 ABS transition units
  - 2 BRP transition units
  - Total: $2 \times 2 \times 2 = 16$ combinations
  - 16 independent signals measured at BRP detector

Measurement strategy:

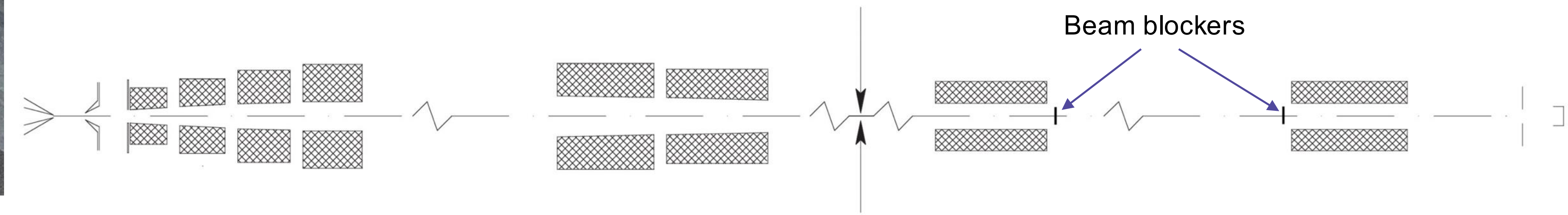
- Measure pressure difference: chopper open vs. chopper closed for 16 signals
  - Measured signals provide input to 16 equations
- Transition efficiencies extracted by solving equation system



Beam blockers



- Equation system simplified when blockers installed
- Two beam blockers in BRP stop weakly deflected states 3 and 4



Full equations with blockers installed

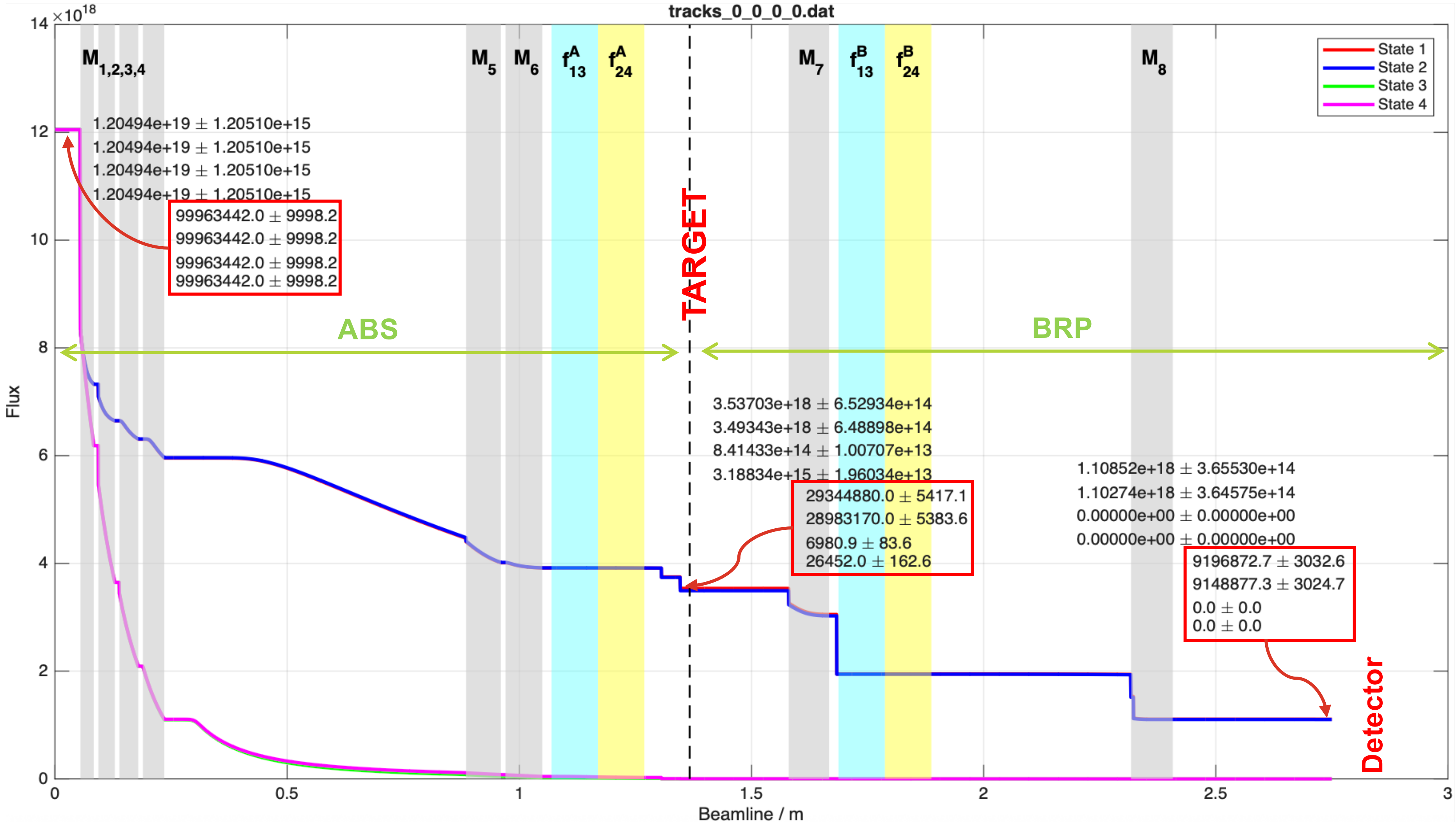
Different combinations of transitions on and off result in system of 16 equations

ABS WFT	ABS SFT	BRP WFT	BRP SFT	
0	0	0	0	$s_1 = (\sigma_1^A \sigma_1^B + \sigma_2^A \sigma_2^B) n$
0	0	0	1	$s_2 = \left(\sigma_1^A \sigma_1^B + \sigma_2^A \sigma_2^B \varepsilon_{24}^B\right) n$
0	0	1	0	$s_3 = \left(\sigma_1^A \sigma_1^B \varepsilon_{13}^B + \sigma_2^A \sigma_2^B\right) n$
0	0	1	1	$s_4 = \left(\sigma_1^A \sigma_1^B \varepsilon_{13}^B + \sigma_2^A \sigma_2^B \varepsilon_{24}^B\right) n$
0	1	0	0	$s_5 = \left(\sigma_1^A \sigma_1^B + (\sigma_2^A \varepsilon_{24}^A + \sigma_4^A (1-\varepsilon_{24}^A))\sigma_2^B\right) n$
0	1	0	1	$s_6 = \left(\sigma_1^A \sigma_1^B + (\sigma_2^A \varepsilon_{24}^A + \sigma_4^A (1-\varepsilon_{24}^A))\sigma_2^B \varepsilon_{24}^B\right) n$
0	1	1	0	$s_7 = \left(\sigma_1^A \sigma_1^B \varepsilon_{13}^B + (\sigma_2^A \varepsilon_{24}^A + \sigma_4^A (1-\varepsilon_{24}^A))\sigma_2^B\right) n$
0	1	1	1	$s_8 = \left(\sigma_1^A \sigma_1^B \varepsilon_{13}^B + (\sigma_2^A \varepsilon_{24}^A + \sigma_4^A (1-\varepsilon_{24}^A))\sigma_2^B \varepsilon_{24}^B\right) n$

ABS WFT	ABS SFT	BRP WFT	BRP SFT	
1	0	0	0	$s_9 = \left((\sigma_1^A \varepsilon_{13}^A + \sigma_3^A (1-\varepsilon_{13}^A))\sigma_1^B + \sigma_2^A \sigma_2^B\right) n$
1	0	0	1	$s_{10} = \left((\sigma_1^A \varepsilon_{13}^A + \sigma_3^A (1-\varepsilon_{13}^A))\sigma_1^B + \sigma_2^A \sigma_2^B \varepsilon_{24}^B\right) n$
1	0	1	0	$s_{11} = \left((\sigma_1^A \varepsilon_{13}^A + \sigma_3^A (1-\varepsilon_{13}^A))\sigma_1^B \varepsilon_{13}^B + \sigma_2^A \sigma_2^B\right) n$
1	0	1	1	$s_{12} = \left((\sigma_1^A \varepsilon_{13}^A + \sigma_3^A (1-\varepsilon_{13}^A))\sigma_1^B \varepsilon_{13}^B + \sigma_2^A \sigma_2^B \varepsilon_{24}^B\right) n$
1	1	0	0	$s_{13} = \left((\sigma_1^A \varepsilon_{13}^A + \sigma_3^A (1-\varepsilon_{13}^A))\sigma_1^B + (\sigma_2^A \varepsilon_{24}^A + \sigma_4^A (1-\varepsilon_{24}^A))\sigma_2^B\right) n$
1	1	0	1	$s_{14} = \left((\sigma_1^A \varepsilon_{13}^A + \sigma_3^A (1-\varepsilon_{13}^A))\sigma_1^B + (\sigma_2^A \varepsilon_{24}^A + \sigma_4^A (1-\varepsilon_{24}^A))\sigma_2^B \varepsilon_{24}^B\right) n$
1	1	1	0	$s_{15} = \left((\sigma_1^A \varepsilon_{13}^A + \sigma_3^A (1-\varepsilon_{13}^A))\varepsilon_{13}^B \sigma_1^B + (\sigma_2^A \varepsilon_{24}^A + \sigma_4^A (1-\varepsilon_{24}^A))\sigma_2^B\right) n$
1	1	1	1	$s_{16} = \left((\sigma_1^A \varepsilon_{13}^A + \sigma_3^A (1-\varepsilon_{13}^A))\sigma_1^B \varepsilon_{13}^B + (\sigma_2^A \varepsilon_{24}^A + \sigma_4^A (1-\varepsilon_{24}^A))\sigma_2^B \varepsilon_{24}^B\right) n$

Transmission through HJET

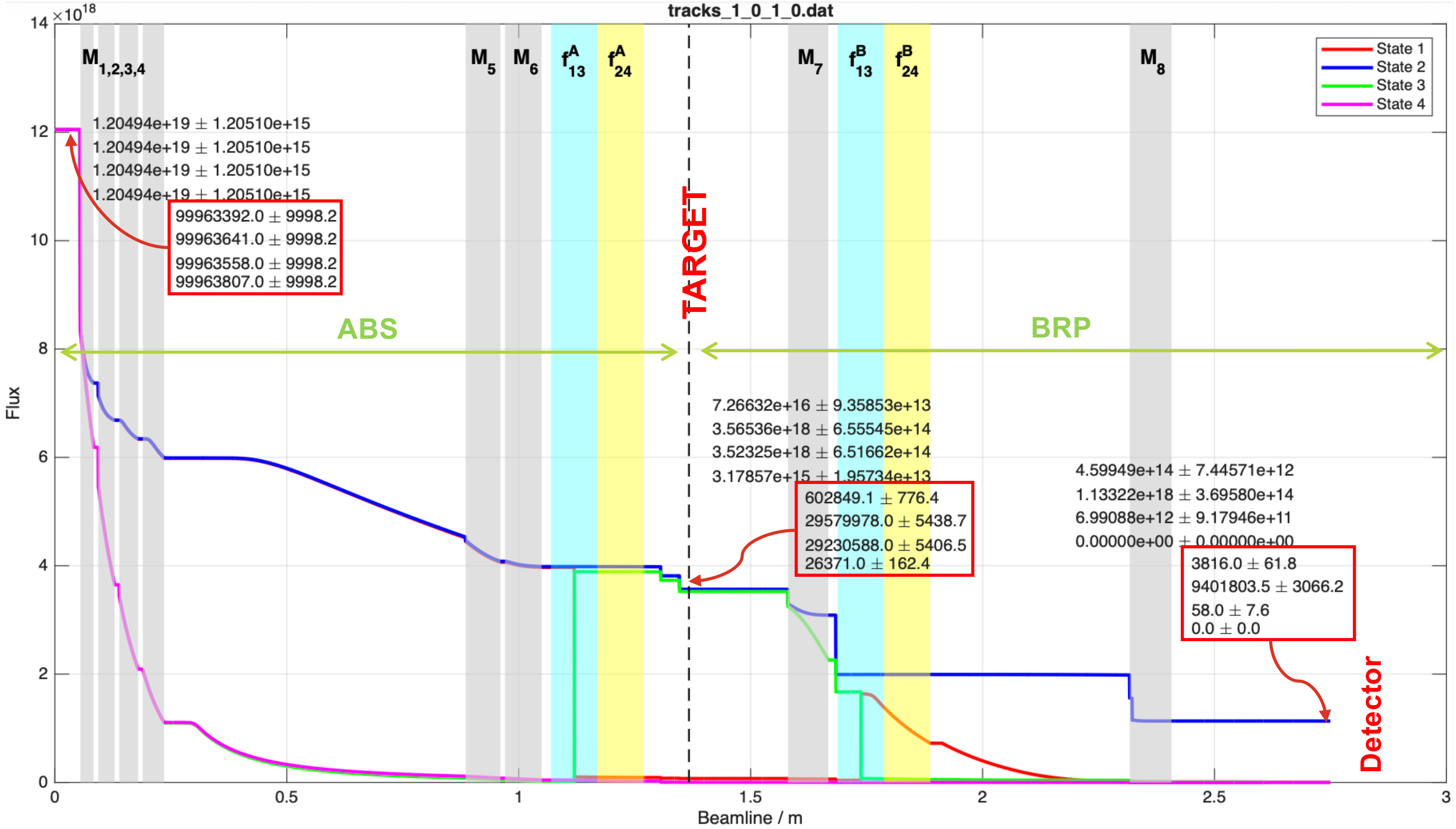
- Simulations give number of tracks along beamline
- Example shows evolution of spin states with all transitions off



Transmission through HJET

- Example shows evolution of spin states with WF transitions on:
  - ABS 1↔3
  - BRP 1↔3
- Transition efficiencies used:
  - $\varepsilon^{A}{}_{13} = 0.02$
  - $\varepsilon^{B}{}_{13} = 0.02$
- Target polarization:

$$Q = \frac{\sum_{i=1}^{4} n_i \cdot Qi(B_0)}{\sum_{i=1}^{4} n_i}$$



BRP Analysis: 4 vs 16 combinations

Transition units efficiencies extracted from system of equations

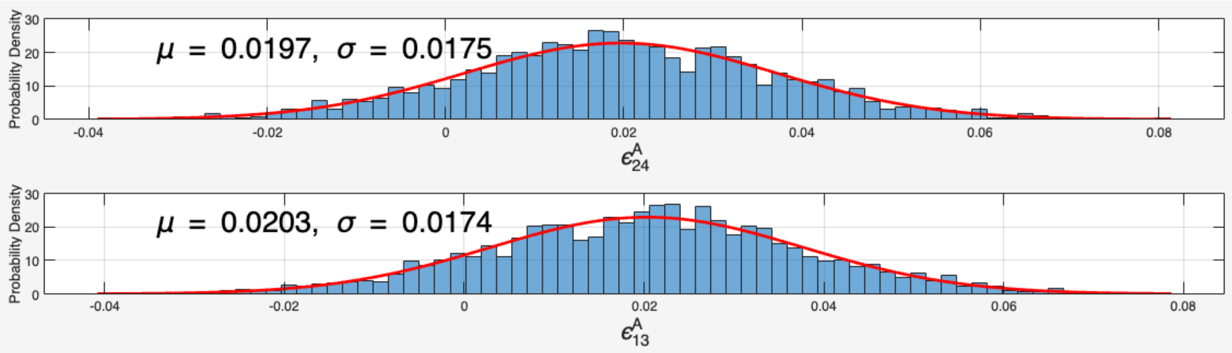
- Input simulated by Z. Zhang
- Output calculated with uncertainties using number of tracks
- ABS transition units allow for four possible RF transition combinations
- Including four transitions in the Breit-Rabi results in 16 total combinations
- Result confirms that transition efficiencies can be extracted from data

Transition efficiency	Simulation input	Extracted from solving system of equations	
		4 combinations	16 combinations
${\varepsilon_{24}}^{A}$	0.02	0.02014 ± 0.00006	0.02014 ± 0.00002
${\varepsilon_{13}}^{A}$	0.02	0.01982 ± 0.00006	0.01982 ± 0.00003

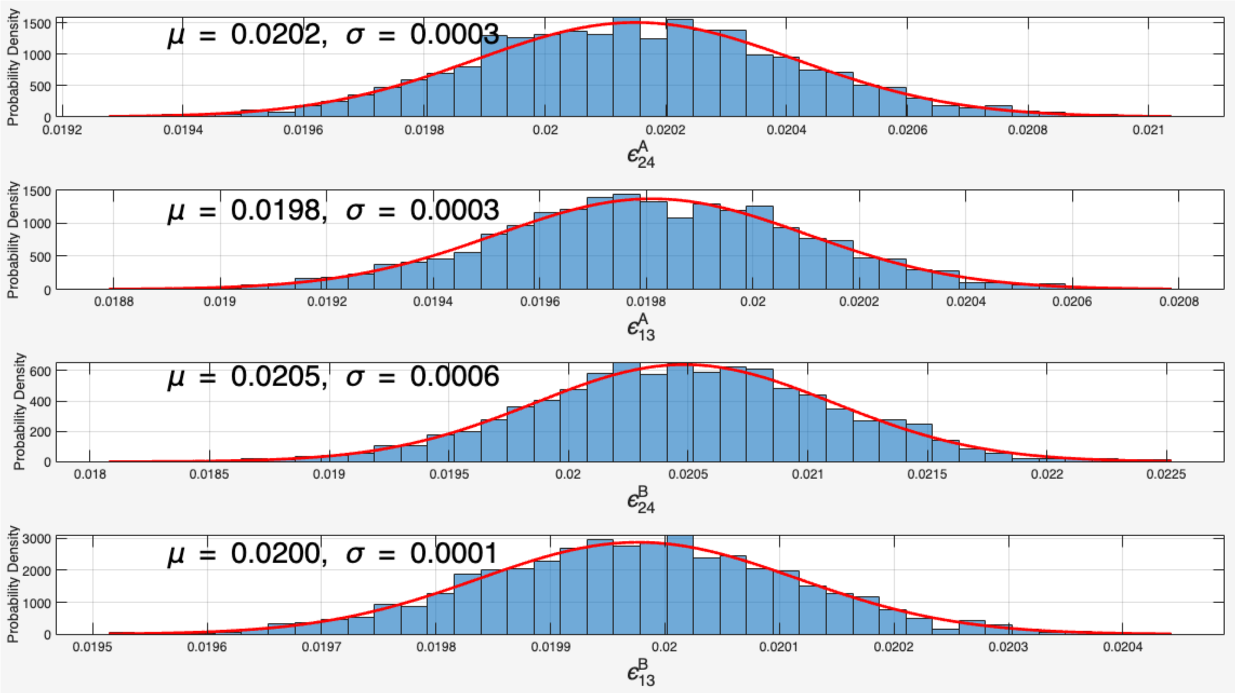
BRP Analysis: 4 vs 16 combinations

- Randomizing 16 simulated signals within the $\pm 3\sigma$ allows to test the solution stability
- 2000 sample were generated for each case

4 combinations



16 combinations



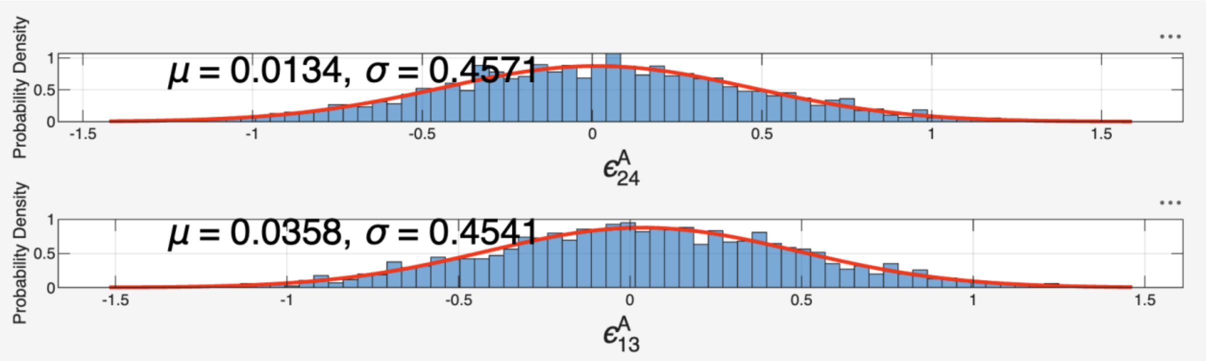
	Simulated input	4 equations output	16 equations output
${\varepsilon_{24}}^A$	0.02	0.0197$\pm$0.0175	0.0202$\pm$0.0003
${\varepsilon_{13}}^A$	0.02	0.0203$\pm$0.0174	0.0198$\pm$0.0003

The scenario with 16 combinations demonstrates substantially reduced errors

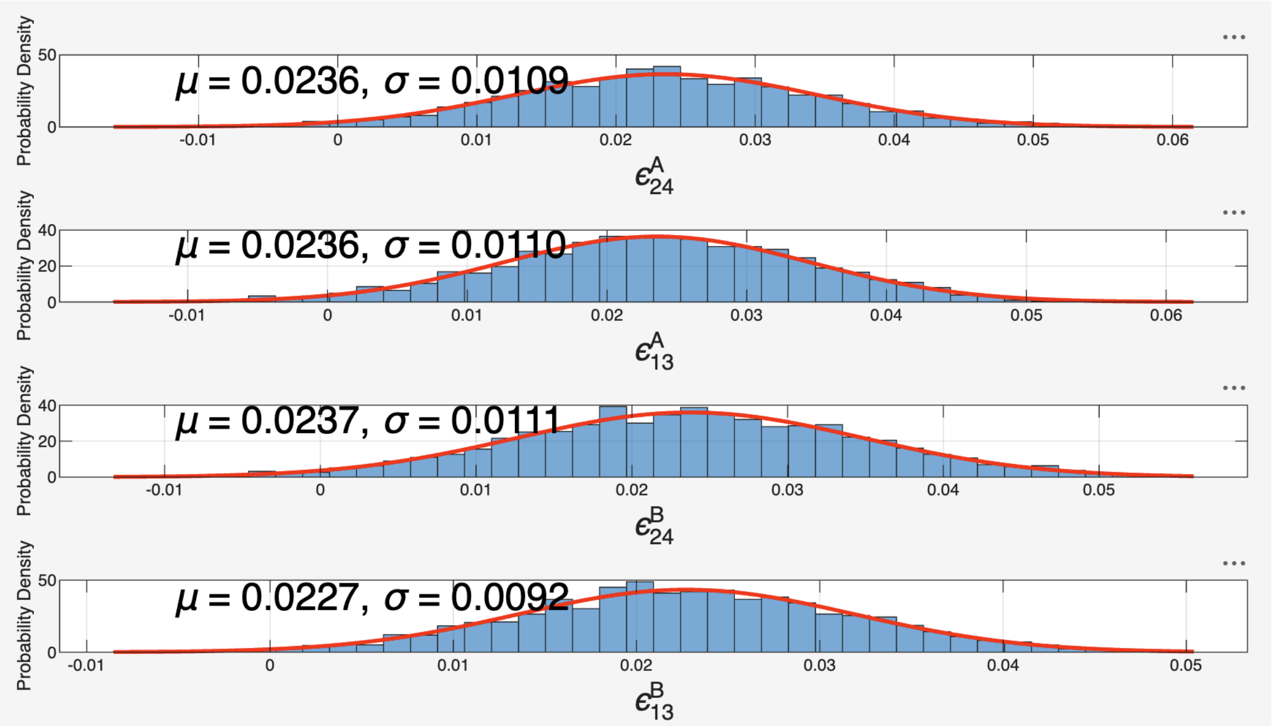
BRP Analysis: velocity less by 10%

- Case when atomic velocity is overestimated by 10%
- Randomizing 16 simulated signals within the $\pm 3\sigma$ & 2000 samples

4 combinations



16 combinations



	Simulated input	4 equations output	16 equations output
${\varepsilon_{24}}^A$	0.02	0.0134 ± 0.454	0.024 ± 0.011
${\varepsilon_{13}}^A$	0.02	0.0358 ± 0.457	0.024 ± 0.011

Error in velocity estimate by 10% considerably reduces precision

Systematic impact: H_2 molecular content

H_2 is main systematic contribution to total target polarization

- Determining the molecular fraction in atomic beam is essential
- Unpolarized H_2 molecules systematically reduce target polarization

ANKE study results:

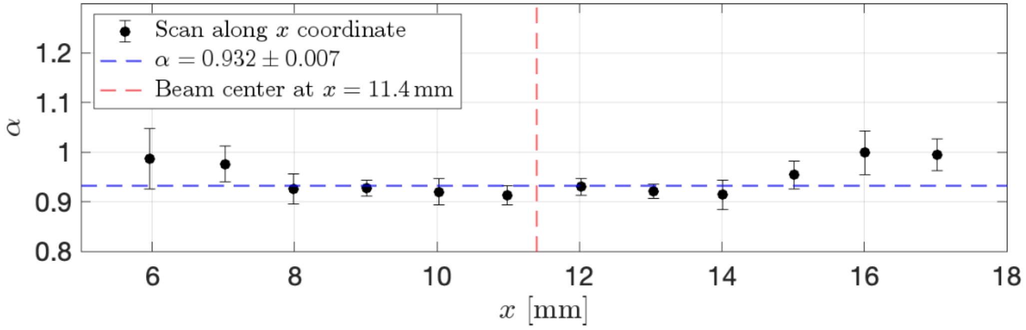
- $\alpha = 0.934 \pm 0.006$
- $\alpha = \frac{\rho_{\text{atom}}}{\rho_{\text{atom}} + 2\rho_{\text{mol}}}$
- $\frac{\rho_{\text{mol}}}{\rho_{\text{atom}}} = 0.035 \pm 0.003$

Result:

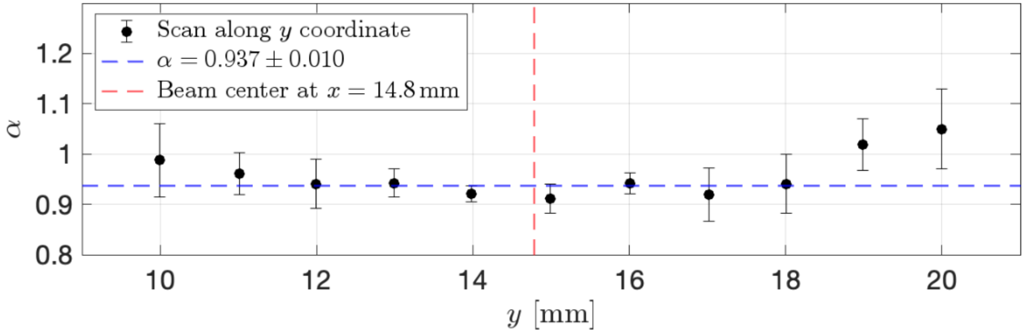
- 3.5% molecular content is present in atomic beam
- About 7% of unpolarized nucleons in target

Frequent and routine measurement of molecular content is required at EIC

Degree of dissociation across orthogonal spacial profiles of atomic beam, ANKE data reanalyzed.



(a) Scan along x



(b) Scan along y

F. Rathmann, et al., "Eliminating beam-induced depolarizing effects in the hydrogen jet target for high-precision proton beam polarimetry at the Electron-Ion Collider," (2025), 2508.01366.

Summary and Outlook

- Simulation code used to construct HJET was revived
- BRP essential for absolute target polarization
  - Knowledge of transmissions and transition efficiencies required to determine target polarization
  - Transmissions to target extracted from simulations
  - Transition units efficiencies extracted using 16 signals from BRP detector
- QMA will be used to measure molecular content in atomic beam at EIC
- Measurement of holding field
- Measurement of sextupole tip field
- Code will be rewritten in modern computer environment
- Technical paper in preparation

Spare slides

Sextupole magnets: Pole tip field computation

- Magnetic flux density inside sextupole magnet:

$$B(r) = B_0 \left(\frac{r}{r_1}\right)^2,$$

where r_1 is inner radius, B_0 pole-tip field, r distance from axis.

- For cylindrical $2N$-multipole magnet, assembled from M segments:

$$B_0 = J H_n K_n,$$

where J is remanent magnetization of material, $n = N + \nu M = 3$, $(\nu = 0)$,

$$H_n = \frac{n}{n-1}\left[1 - \left(\frac{r_1}{r_2}\right)^{n-1}\right],\ K_n = \frac{\sin[\frac{(n+1)\epsilon\pi}{M}]}{(n+1)\pi/M}$$

- For conical bores with linear taper over length L

$$r_1(z) = r_{1,in} + \frac{z}{L}\left(r_{1,\mathrm{out}} - r_{1,\mathrm{in}}\right) \qquad \overline{H_3} = \frac{1}{L}\int_0^L H_3(r_1(z), r_2)\,dz$$

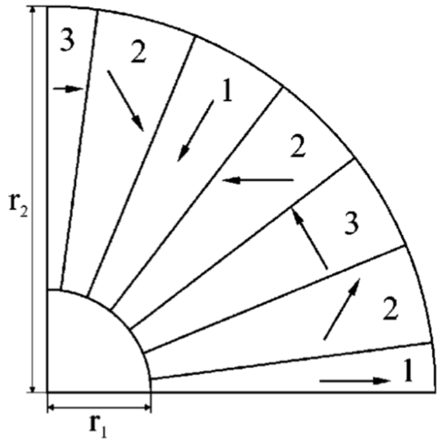
- For $n = 3$

$$\overline{H_3} = \frac{3}{2}\left[1 - \frac{r_{1,\mathrm{in}}^2 + r_{1,\mathrm{in}} r_{1,\mathrm{out}} + r_{1,\mathrm{out}}^2}{3r_2^2}\right]$$

$$B_0^{\mathrm{eff}} = J K_3\, \overline{H_3}$$

Three different materials with varying remanence:

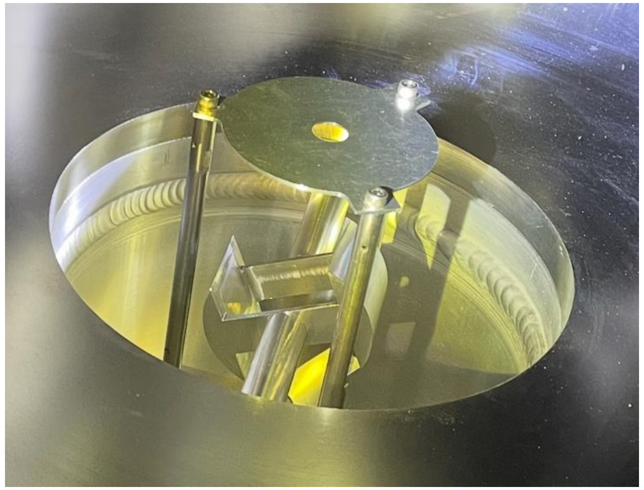
Fraction	Material	Remanence [T]
6/24	VACODYM 510HR	1.41
12/24	VACODYM 383HR	1.28
6/24	VACODYM 400HR	1.16



A. Vassiliev, et al. 24 segment high field permanent sextupole magnets, *Rev. Sci. Instrum.* 71, 3331–3341 (2000). https://doi.org/10.1063/1.1288264

BRP Analysis: Run26 Data

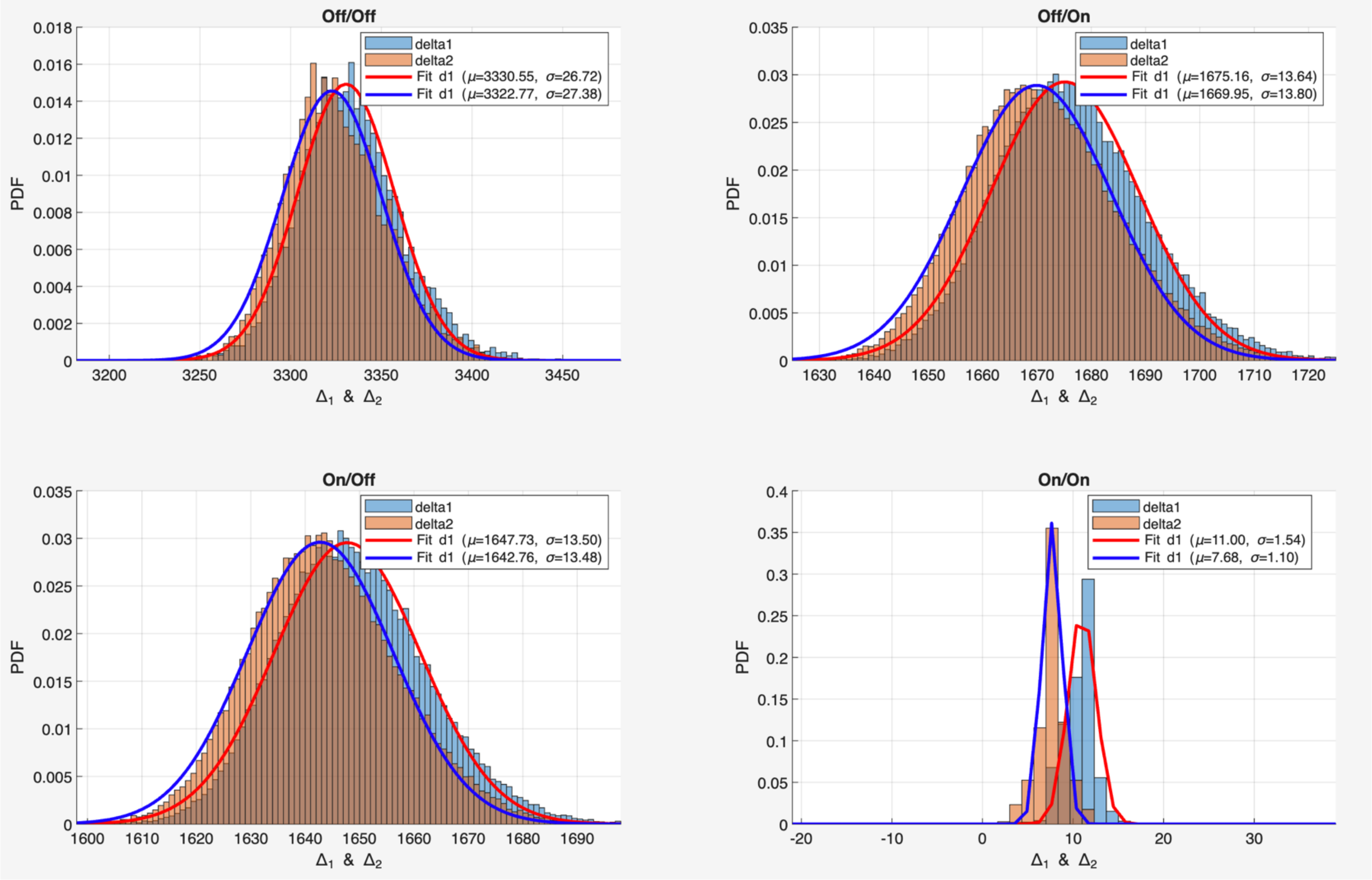
- Only ABS transition units currently running
- Signal of SFT-ABS/WFT-ABS off/off was included in sequence
- Fast rotating cylindrical chopper



- Each chopper period yields two open/closed signals pairs

$$\Delta_i = s_{open,i} - s_{closed,i}$$

- $\Delta_1 > \Delta_2$ consistently



BRP Analysis: Run26 Data

Results of current analysis compared with new approach

- $\cos(2\theta) = 0.92120$ in case of $B_0 = 120\ \mathrm{mT}$
- New analysis includes 4 transmissions to target

	Fit of experimental data, 4 signals
	$Q^{+}_{\lvert 1\rangle+\lvert 4\rangle} = \frac{\left(\sigma_1^{\mathrm{tgt}} - \sigma_3^{\mathrm{tgt}}\right) + \left(\sigma_2^{\mathrm{tgt}} - \sigma_4^{\mathrm{tgt}}\right)\cos(2\theta)\left(1 - 2\varepsilon_{24}^{\mathrm{A}}\right)}{\sigma_1^{\mathrm{tgt}} + \sigma_2^{\mathrm{tgt}} + \sigma_3^{\mathrm{tgt}} + \sigma_4^{\mathrm{tgt}}}$ $Q^{-}_{\lvert 2\rangle+\lvert 3\rangle} = \frac{\left(\sigma_1^{\mathrm{tgt}} - \sigma_3^{\mathrm{tgt}}\right)\left(2\varepsilon_{13}^{\mathrm{A}} - 1\right) - \left(\sigma_2^{\mathrm{tgt}} - \sigma_4^{\mathrm{tgt}}\right)\cos(2\theta)}{\sigma_1^{\mathrm{tgt}} + \sigma_2^{\mathrm{tgt}} + \sigma_3^{\mathrm{tgt}} + \sigma_4^{\mathrm{tgt}}}$
${\varepsilon_{24}}^{A}$	0.0090 $\pm$ 0.0007
${\varepsilon_{13}}^{A}$	-0.0018 $\pm$ 0.0007
Q^{+}_{1+4}	0.9515$\pm$0.0088
Q^{-}_{2+3}	-0.9579$\pm$0.0097