Atomic Beam Source simulation

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Motivation

- Gain a deeper understanding of the RHIC HJET working process and the function of each component.
- Validate the equations used to determine occupation ratios and transition efficiencies (with further details to be provided by Vera).
- Develop a new compact polarized Atomic Beam Source (ABS) at the AGS for the EIC.
- Enhance absolute beam polarimetry at the AGS to reach a polarization precision of $\sim 1\%$.
- Enable higher-precision polarization measurements and potentially reduce beam polarization losses at the AGS.

HJET and Breit–Rabi Polarimeter

Atomic Beam Source (ABS):

- Dissociates molecular hydrogen into atoms.

Sextupole Magnets:

- Permanent magnets provide strong radial field gradients.
- **States |1⟩ & |2⟩ → focused** into the beam.
- **States |3⟩ & |4⟩ → defocused and lost.**
- Produces a **well-collimated beam enriched in |1⟩ and |2⟩.**

RF Transitions:

- Additional RF transitions (e.g., 1–3, 2–4) selectively flip states.
- Enable preparation of **desired polarization (spin-up or spin-down).**
  - Example: flipping |2⟩ → |4⟩ yields a **pure spin-up target.**

Blockers:

Blockers stop **weakly deflected |3⟩, |4⟩ atoms** that leak through.

- Ensure **full rejection** of unwanted states.
- BRP compares beam intensities under different RF transitions.
- Blockers guarantee only **pure |1⟩, |2⟩ populations**, ensuring accurate polarization measurement.

Breit–Rabi Polarimeter (BRP):

Uses **additional RF transitions** (1–3, 2–4) and **sextupole magnets** downstream of the target.

Forms a system of linear equations to solve for:

- Occupation ratio (n_1/n_2)
- Transition efficiencies ($\varepsilon_{13}, \varepsilon_{24}$)

Requires strong rejection of unwanted states (|3⟩, |4⟩), achieved with sextupoles + beam blockers.

Enables accurate determination of **target polarization (near ±1)**.

ABSsim process

1. **Inputs (read at start)**

- current.abs: magnets, RF, skimmers, blockers, monitors, nozzle position (layout.zs)
- current.acpt: run states, gas type, compression-tube radius/position, Ntracks, theta_max policy
- current.veldis: temperature (btem), drift speed (vd), ftype, icos
- current.mesh: z step (dpl), total length (pl), per-z apertures
- current.sgen: source model parameters (Extended / Effusive / Molecular / DSMC / Other)

2. **Initialization**

- Load physical constants and focusing-sign per hyperfine state
- Build field map grid (fmap) and z-mesh (pmesh), including apertures rlim (outer) and rlim2 (inner blocker)
- Velocity PDF setup:
  - Define a shifted-Gaussian-with-power model controlled by (ftype, vd, temperature)
  - Normalize via adaptive integration (veldis.f), then build an equal-probability lookup table (vtable)
- Zero histograms: acceptance vs z, density maps, loss monitors, velocity sums
- Initialize random seed (fixed StGen.seed or time-based)

3. **Choose start generator (inten.SGflag)**

- One of: Extended, Effusive, Molecular, DSMC, Other
- Compute theta_max: if user set to -1 use geometry-based limit; otherwise use user value
- Precompute geometric acceptance factors (e.g., can the straight line reach first magnet)

4. **Track production loop (over StGen.Ntracks)**

- Sample initial position near nozzle (per chosen generator)
- Sample angles:
  - Draw x = cos(theta) in [cos(theta_max), 1] with probability proportional to x^icos (accept-reject)
  - Draw phi uniformly (Effusive uses vy = 0, i.e., 2D plane)
- Sample speed v via the velocity lookup table (GetVel)
- Build components: vz = v * cos(theta); vx, vy from sin(theta) and phi
- Set weights: wt2 = 1 / Ntracks; wt = wt2 / nstates; wt3 = wt / vz
- For each requested initial hyperfine state:
  - Set state s2.is and focusing sign s2.sg; clear per-track density cache
  - Call CalcTrack(x0, y0, z0, vx, vy, vz, is0)

5. **Per-track propagation (CalcTrack)**

- Set start z to nozzle plane: z := layout.zs (original code ignores passed z0)
- For each z step (delta z = pmesh.dpl):
  - Compute dt = dpl / vz
  - Integrator choice:
    - If no field at this z: straight flight
    - Else: Runge–Kutta step; on RK error mark lost and stop this track
  - Aperture checks (ring aperture region):
    - If r > rlim[z]: lost (outer cut) and stop
    - If r <= rlim2[z]: lost (inner blocker) and stop
  - Monitors: if this z-bin is tagged, fill radial hit histogram
  - Statistics:
    - acceptance[z] += wt
    - denshitmap(r, z, state)
    - If r <= compression-tube radius:
      - If z > 0.5 m, acceptrz[z] += wt
      - If the step crosses z_ctube, set ictflag = 1 (track is counted as transmitted)
  - RF transitions (if present at this z-bin):
    - With probability rfeff_h or rfeff_d, swap the configured state pair (e.g., 1<->3, 2<->4)
    - Update focusing sign s2.sg

6. **After each track/state**

- If ictflag == 1: add this track's contributions to global maps (adhitmap) and velocity sums
- Accumulate per-state transmission inten.tacpt[state] (with generator's geometric correction)

7. **Post-processing**

- Normalize density maps (densnorm) and loss monitors (lostnorm)
- Compute attenuation (RGA/IBS) if enabled (avedcalc, CalcAtten)
- Scan along z (downstream of first magnet) to find best z that maximizes acceptrz[z]
- Compute initial atom flow:
  - Qinit = 2.5e19 * flin * 2.0 * diss * facpt (atoms per second)
- Report intensities:
  - I(z) = Qinit * acceptrz[z] * atten_rga * atten_ibs
  - Print values at compression-tube z and at best z
- Write outputs to results/*.dat and close logs

Magnets:

c MAGNET TYPE
2
C Octopole fraction
0.0 0.0003
c ZPX | RPX | BPX | FF
0.0550 0.0052 1.6964748 0.00
0.0835 0.0070 1.6964748 0.00
c MAGNET TYPE
2
C Octopole fraction
0.0 0.0003
c ZPX | RPX | BPX | FF
0.0935 0.0075 1.6872231 0.0
0.1289 0.0091 1.6872231 0.0
c MAGNET TYPE
2
C Octopole fraction
0.0 0.0003
c ZPX | RPX | BPX | FF
0.1389 0.0097 1.6877409 0.0
0.1794 0.0107 1.6877409 0.0
c MAGNET TYPE
2
C Octopole fraction
0.0 0.0003
c ZPX | RPX | BPX | FF
0.1894 0.0115 1.6881129 0.0
0.2354 0.0115 1.6881129 0.0
c MAGNET TYPE
2
C Octopole fraction
0.0 0.0003
c ZPX | RPX | BPX | FF
0.8854 0.0160 1.5859745 0.0
0.9604 0.0145 1.5859745 0.0
c MAGNET TYPE
2
C Octopole fraction
0.0 0.0003
c ZPX | RPX | BPX | FF
0.9704 0.0145 1.5853938 0.0
1.0494 0.0127 1.5853938 0.0
c MAGNET TYPE
2
C Octopole fraction
0.0 0.0003
c ZPX | RPX | BPX | FF
1.5804 0.01 1.5856687 0.0
1.6674 0.01 1.5856687 0.0
c MAGNET TYPE
2
C Octopole fraction
0.0 0.0003
c ZPX | RPX | BPX | FF
2.3174 0.01 1.5 0.0
2.4074 0.01 1.5 0.0

RF Transitions:

C # RF Transitions
4
c trans | on/off
1-3 1-1 0 0.98 0.98
C ref.mag | position
6 0.02
C LENGTH
0.10

c trans | on/off
2-4 1-1 0 0.98 0.98
C ref.mag | position
6 0.12
C LENGTH
0.10

c trans | on/off
1-3 1-1 0 0.98 0.98
C ref.mag | position
7 0.02
C LENGTH
0.10

c trans | on/off
2-4 1-1 0 0.98 0.98
C ref.mag | position
7 0.12
C LENGTH
0.10

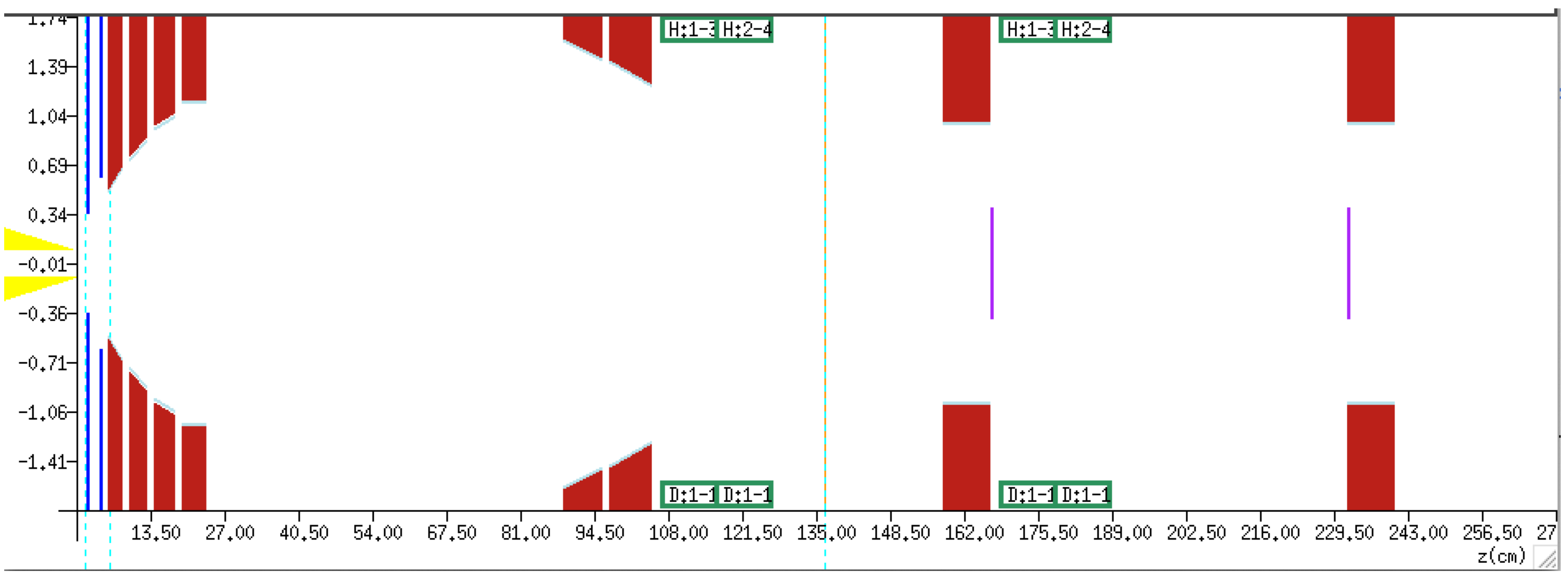
Skimmers:

c NSKI
2
c MREX | ZSKI | RSKI
0 0.0400 0.0060
0 0.0180 0.0035

Blockers:

C # of beam blockers
2
CC MREX | Zbl | Rbl
0 1.6674 0.004
0 2.3174 0.004

current.abs



current.veldis:

```
ICOS
 1.0
 VDRIFT
 1807.0
 BEAMTEMP
 20.0
CC    FUNC
2
```

current.acpt:

```
CC  RUN NUMBER |   STATE  | GAS (1=H, 2=D)
    378 1 1
CC  compression tube location and radius
  1.3344  0.01
INPUT FLUX
 1.25
 DISSOC EFF
 0.85
CC  attenuation
1.0  1.0
CC Starting Generator Choice 1=extended, 2=molecular,3=point-like
CC       4=DSMC file, 5=other file)
1
CC  Number of tracks
  1000000
CC  Random Seed (=0 uses time of day for random random seed)
  0
CC  Maximum Polar Angle considered (=-1 for automatic determination)
 -1
```

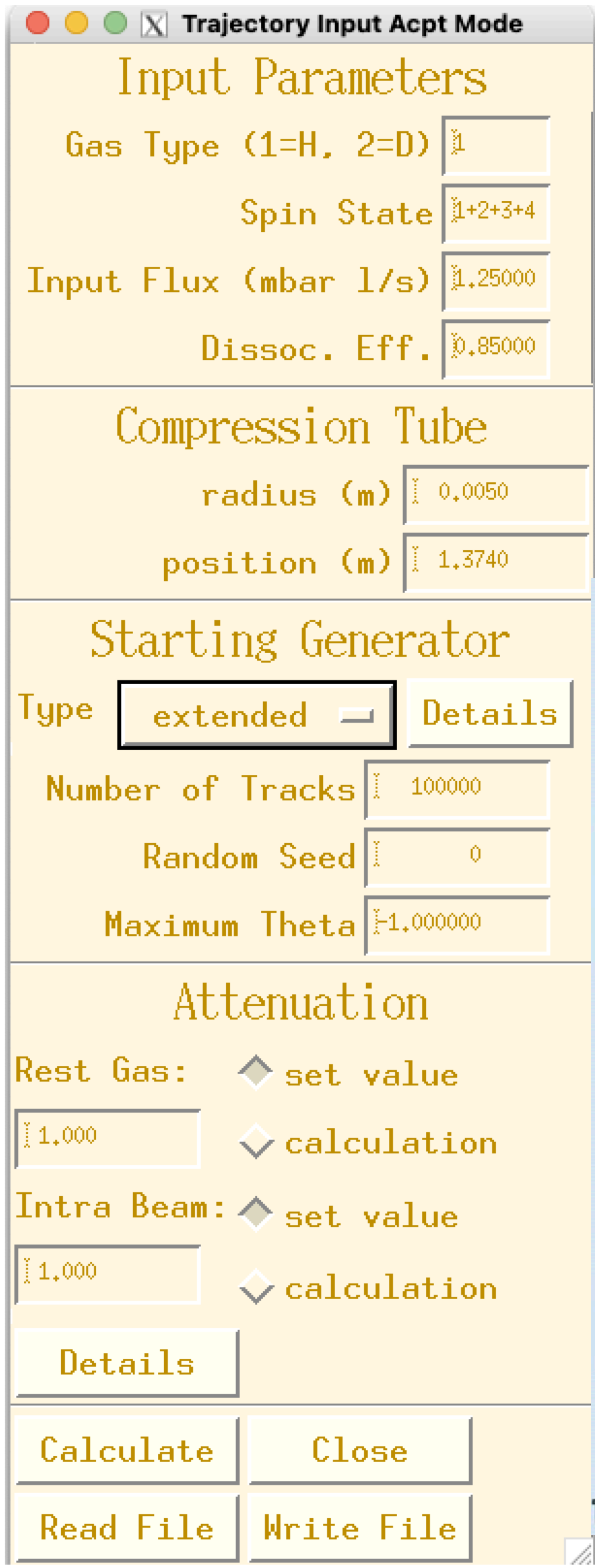
current.sgen:

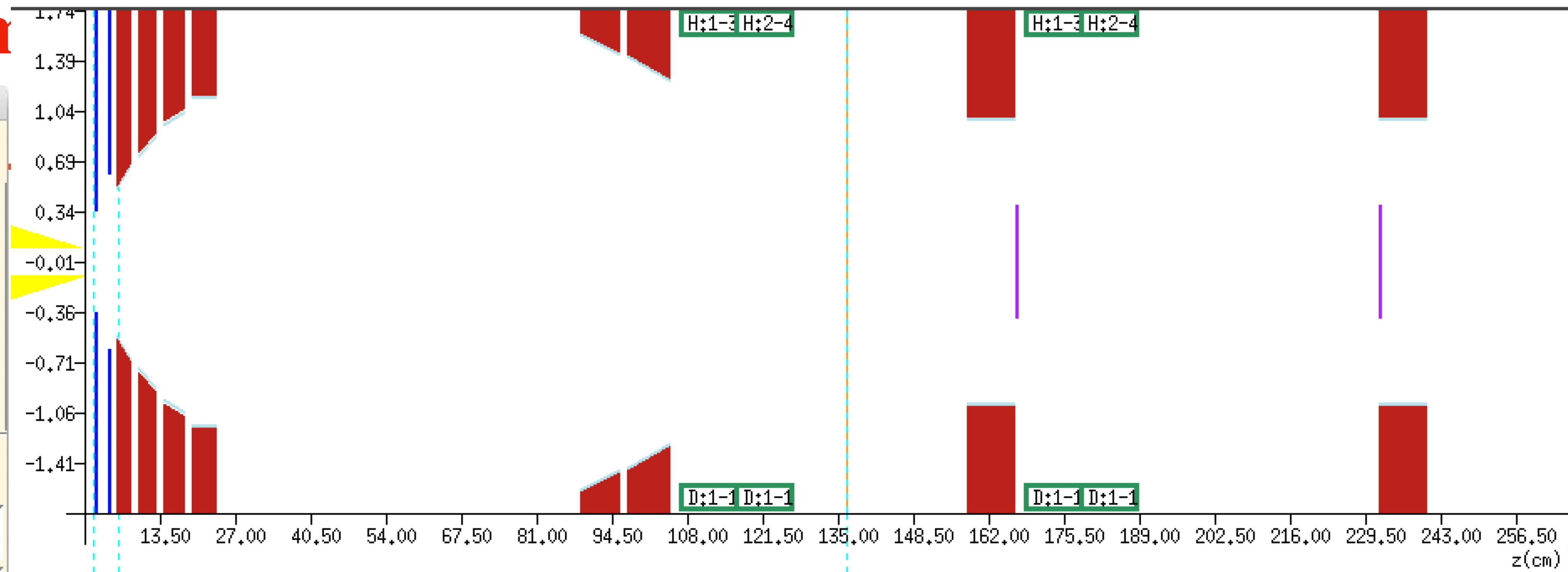
```
CC  Position of virtual nozzle for effusive (<-999 => automatic)
  0.00
CC  Position and radius of nozzle and collimator for molecular
  0.000  0.001
  0.05  0.005
CC  Position and radius of nozzle for extended
  0.000  0.001
CC  Magnet Acceptance for file input
  0.01094
CC  file name
  startgen.dat
CC  z position of starting plane for tracks
0.05
```

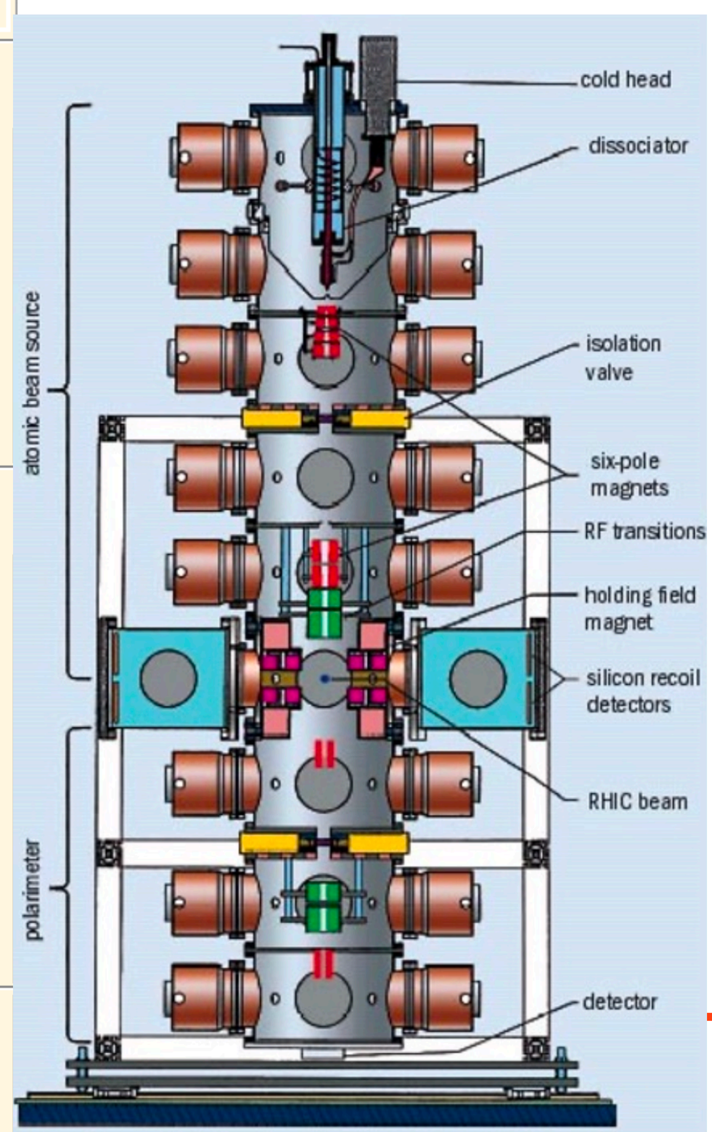
Velocity PDF： p(v) ∝ v^(ftype+1) * exp(- a0 * (v - b0)^2)； a0 = m/(2*kB*T)， b0 = v_drift。

Polar angle PDF（θ）： p_theta(θ) = K * cos(θ)^(icos) * sin(θ)， θ ∈ [0, θ_max]， K = (icos+1)/(1 - cos(θ_max)^(icos+1))。

Running ABSsim





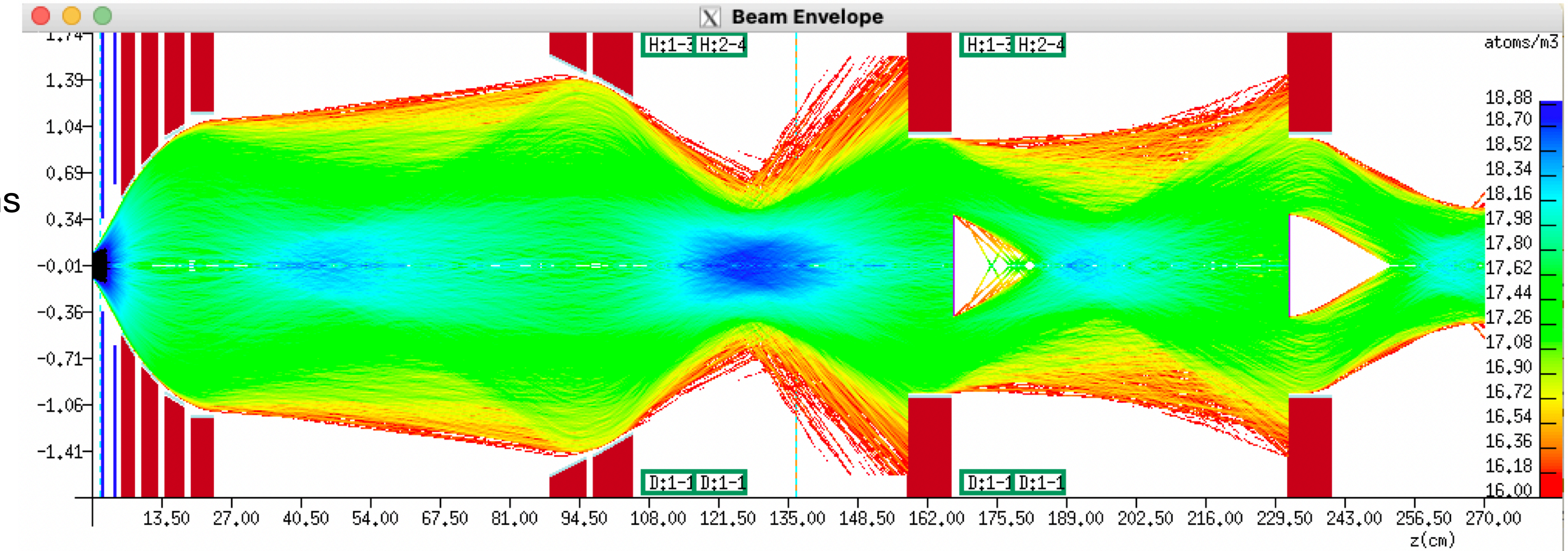


- **The ABSsim code has two modes of use:**
  - ➡ **scan.c:** command-line program, reads input files and writes results directly.
  - ➡ **scanshell.c:** launches a **graphical interface** to set parameters, run calculations, and view results.
- The height of the source is 3.6 m.
- The current HJET is incompatible with the AGS tunnel due to the overhead crane along the tunnel ceiling.
- A suitable sextupole magnet system must be simulated to find customized solutions. Goal is to achieve the highest possible target density at the interaction point.

Results from ABSsim

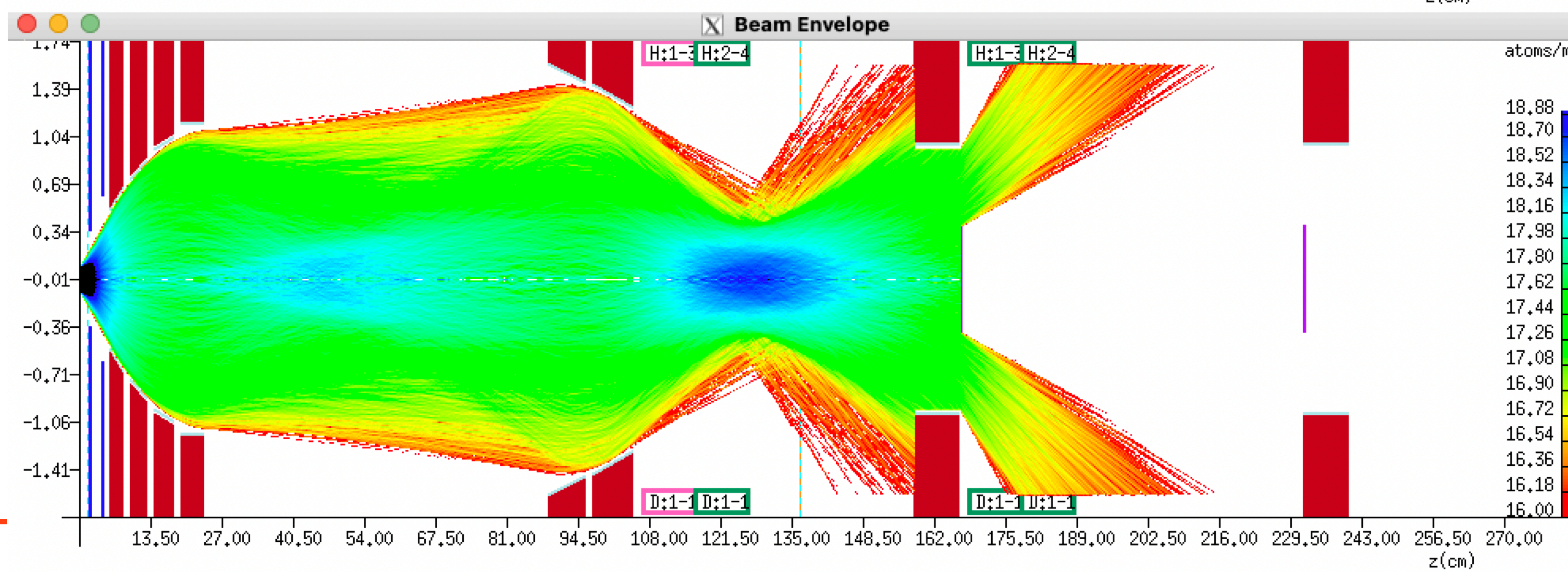
All RF transitions off

state |1> atoms

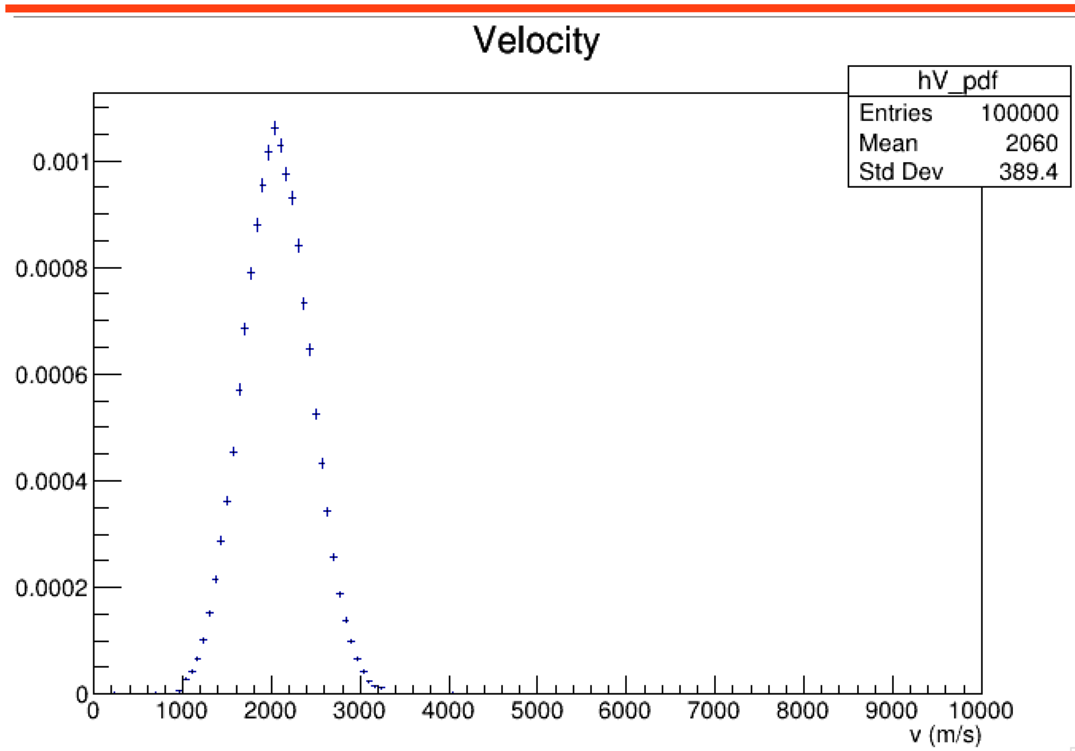


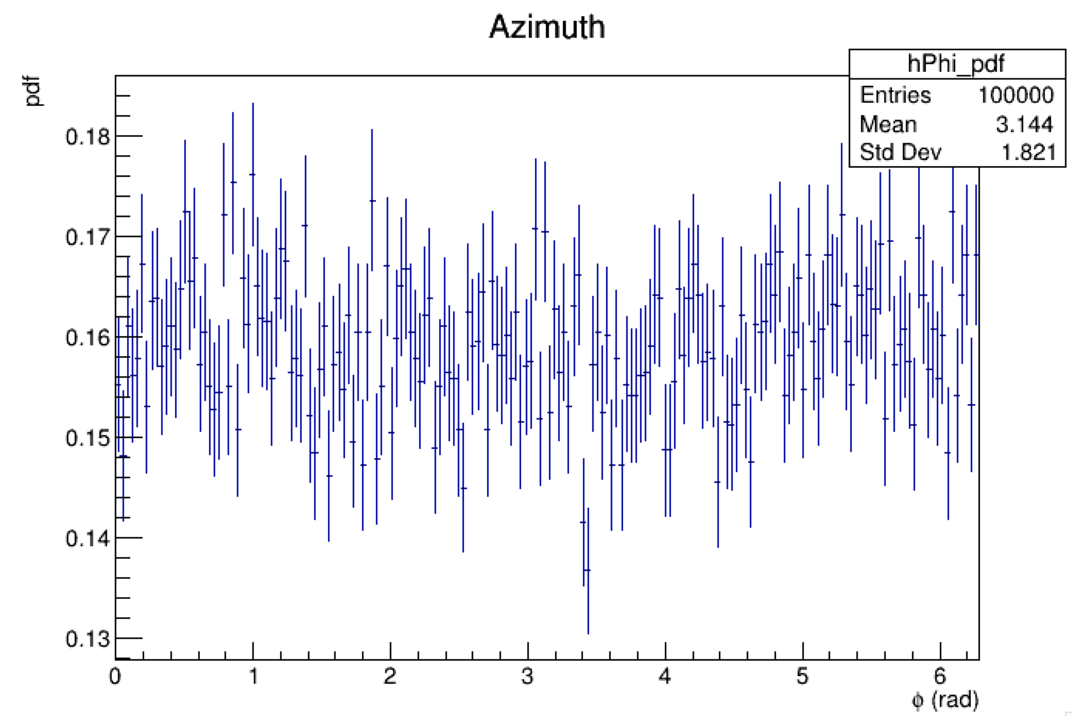
Only first RF transition 1–3 on

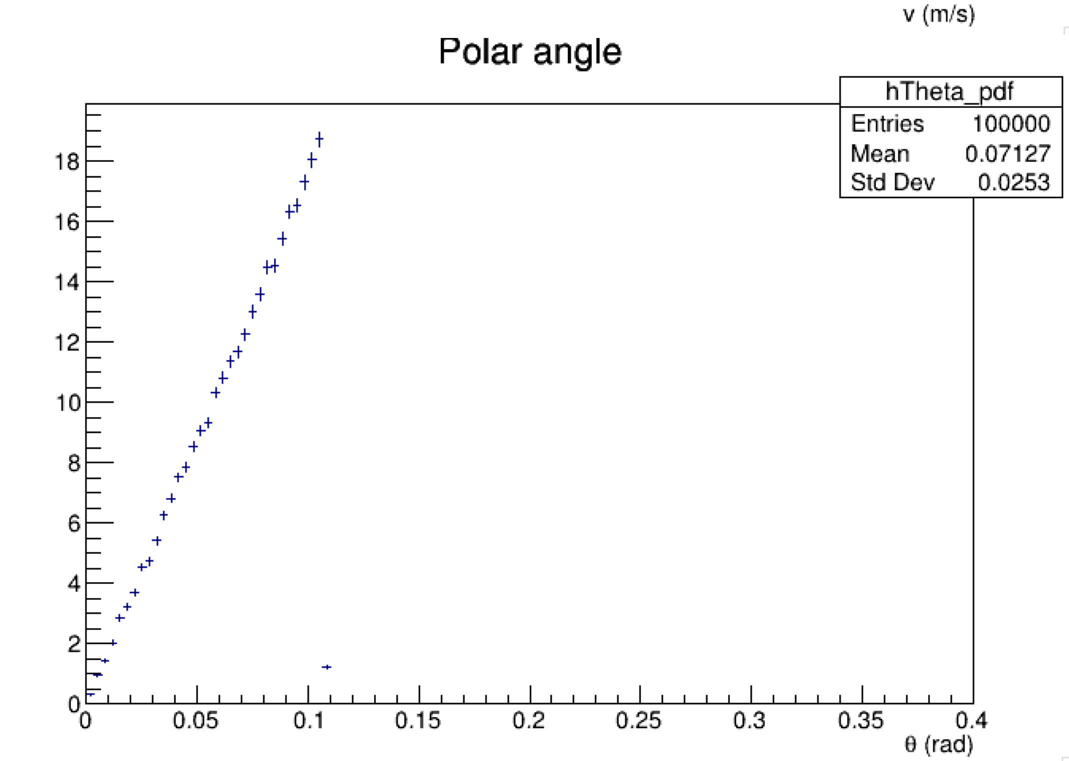
state |1> atoms

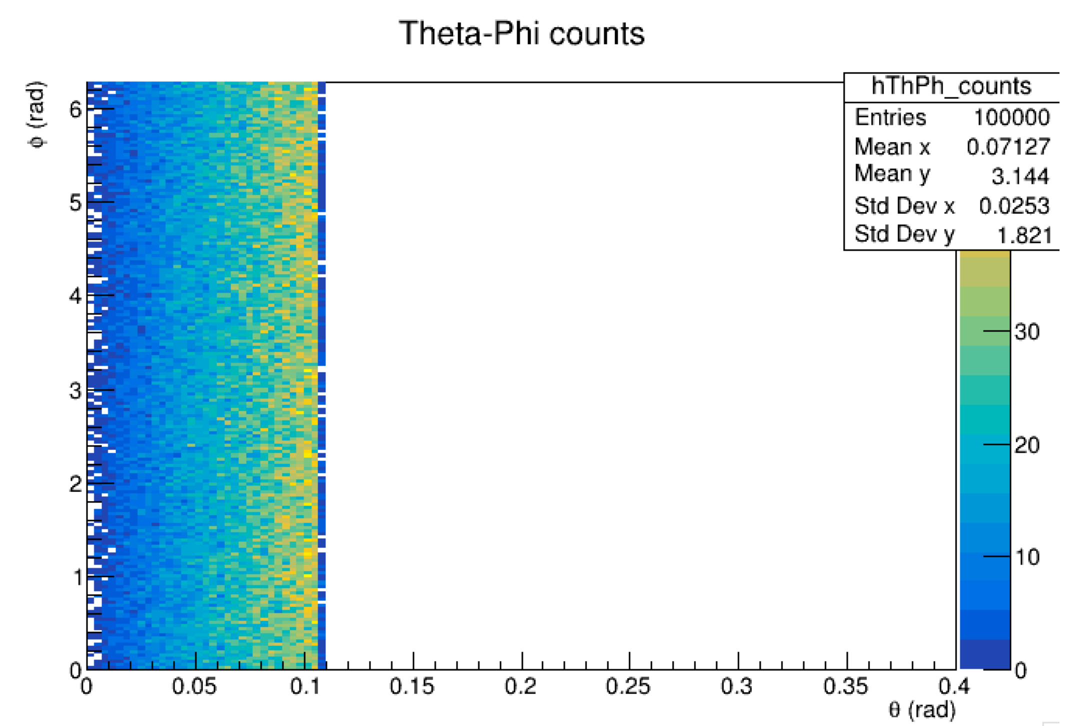


Results from ABSsim









Velocity PDF： $p(v) \propto v^{(ftype+1)} * \exp(-a0 * (v - b0)^2)$； $a0 = m/(2kBT)$， $b0 = v\_drift$。

Polar angle PDF （θ） ： $p\_theta(\theta) = K * \cos(\theta)^{(icos)} * \sin(\theta)$， $\theta \in [0, \theta\_max]$， $K = (icos+1)/(1 - \cos(\theta\_max)^{(icos+1)})$。

Next step

- Refine and verify ABSsim to improve both accuracy and computational efficiency.
- Validate the underlying equations used for determining occupation ratios and RF transition efficiencies (with detailed input from Vera).
- Migrate ABSsim to a modern programming environment (e.g., MATLAB) to ensure long-term usability and facilitate open-source distribution.
- Develop new algorithms to guide the design and optimization of the HJET for the EIC.