1. SM_2D: [illegible] [illegible] [illegible] [illegible]

[illegible] [illegible] [illegible]

[illegible] *1.0.0*

SM_2D [illegible]
[illegible]:
[illegible] [illegible] [illegible] [illegible] [illegible] [illegible]
[illegible]:
[illegible] S-[illegible] [illegible] (GPU [illegible])
[illegible]:
[illegible] [illegible] [illegible] ([illegible] [illegible])
[illegible]:
[illegible] [illegible] 1% [illegible] [illegible]

Table 1: [illegible] [illegible]

1.1. SM_2D[illegible] [illegible]?

1.1.1. [illegible] [illegible]: [illegible] [illegible] [illegible] [illegible]

SM_2D[illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible]. [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible].

1.1.2. [illegible] [illegible]

[illegible]([illegible])[illegible] [illegible]([illegible] [illegible])[illegible] [illegible] [illegible] [illegible]. [illegible] [illegible] [illegible] [illegible]: [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible]

- [illegible] [illegible] [illegible] [illegible] [illegible]

"[illegible](deterministic)"[illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible], [illegible] [illegible].

1.1.3. [illegible] [illegible]: [illegible] "[illegible]"[illegible]?

[illegible] [illegible] [illegible] [illegible] [illegible]:

[illegible] [illegible]: [illegible] [illegible] [illegible] [illegible]

- [illegible]: [illegible] [illegible]
- [illegible]: [illegible] [illegible] [illegible] [illegible] [illegible] ([illegible])

[illegible] [illegible] (SM_2D): [illegible] [illegible] [illegible] [illegible]

- [illegible]: [illegible] ([illegible] [illegible])
- [illegible]: [illegible] [illegible]

[illegible] [illegible] [illegible] [illegible] [illegible], [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible].

1.2. □□

SM_2D□ □□□ □□ □□ □□□ □□ □□□□ □□□ □□ □□□□□. □ □□□□ □□ □□ □□□ □□ GPU □□(CUDA)□ □□□□, □□□□ □□ □□ □□, □ □□□ □□□ □□, □ □□□□□ □□□ □□□□ □□ □□□ □□ □□□ S-□□ □□□ □□□□□.

—

1.3. C++ □□ □□□ (□□□□□ □□)

1.3.1. □□ C++ □□

1.3.1.1. “struct”□ □□□□?

struct (□□□)□ □□□ □□□ □□ □□ □□□□□□□. □□□ □□ □□ □□ □□□ □□□□□:

□□: “Person” □□□□ □□□ □□□ □ □□□□:
- □□ (□□□)
- □□ (□□)
- □ (□□)

□ □□□□ □□□□ □□□ □, □□, □□ □□ □□ □□□ □□□□.

1.3.1.2. “GPU □□”□□ □□□□?

GPU (□□□ □□ □□)□ □□ □□□ □□□ □□□□. □ □□□ □□ □□□ □□ GPU□ □□□□□□:
- GPU□ □□ □□ □□ □□□□□ □□
- □□ CPU□ □□□ □□□ □□□□□ □□
- □□□ □□□ □□□ □□ □□, 1,000□□ □□□ □□□ □□ □□ □□

1.3.1.3. “□□”□□ □□□□?

CUDA □□□□□□ □□□ GPU□□ □□□□ □□□□. □□□ □□ □□□ □□ □□□□ □□ □□ GPU □□□□ □□□□ □□□□□ □□□□.

1.3.1.4. “□□ □□(phase space)”□□ □□□□?

□□ □□□ “□□□ □□□ □□ □□”□□ □□ □□ □□□□. 2D□□□ □□□ □□□□□:
- □□□ □□□ □□□? (x, z □□)
- □□ □□□□ □□□? (□□ theta)
- □□□ □□ □□□□ □□□ □□□? (E)

1.3.2. □□□□ □□

□□□□	□
□□	C++17 with CUDA
□□ □□ □	15,000
GPU □□□	□□□□□□ 4.3 GB
□□□	□□□ □□ 1% □□, □□ □□ 15% □□
□□□	RTX 2080+ (Compute Capability 7.5+)

Table 2: □□□□ □□

1.3.3. □□

Contents

1.4. [illegible]

1.4.1. SM_2D[illegible]?

SM_2D[illegible]:

[illegible] GPU [illegible] (CUDA) [illegible] S-[illegible] **(**[illegible] **MCS,** [illegible], [illegible]**)** [illegible]

1.4.2. [illegible]

[illegible]: [illegible]. SM_2D[illegible].

[illegible]: [illegible] 1% [illegible].

[illegible]: [illegible].

1.4.3. [illegible]

[illegible]	[illegible]
`run_simulation.cpp`	[illegible]
`sim.ini`	[illegible]
`src/core/`	[illegible] ([illegible], [illegible], [illegible])
`src/physics/`	[illegible] (MCS, [illegible], [illegible])
`src/cuda/kernels/`	CUDA [illegible] (K1-K6 [illegible])
`src/lut/`	NIST [illegible]-[illegible]
`src/source/`	[illegible] ([illegible], [illegible])
`src/boundary/`	[illegible]
`src/audit/`	[illegible]
`src/validation/`	[illegible]
`src/utils/`	[illegible], [illegible]
`tests/`	[illegible] (GoogleTest)

Table 3: [illegible]

1.4.4. [illegible]: [illegible]

`src/core/`: [illegible] - [illegible] **`src/physics/`**: [illegible] **`src/cuda/kernels/`**: [illegible] GPU [illegible] **`src/audit/`**: [illegible] - [illegible]

[illegible]:

- core = [illegible]
- physics = [illegible]
- cuda/kernels = [illegible]
- audit = [illegible]

1.5. [illegible]

1.5.1. CUDA [illegible]

[illegible] 6[illegible] CUDA [illegible]. [illegible]:

[illegible]	[illegible]	[illegible]
1	K1	[illegible] ([illegible])
↓		
2	K2 + K3	[illegible]: [illegible] • K2: [illegible] • K3: [illegible]
↓		
3	K4	[illegible]: [illegible]
↓		
4	K5	[illegible]: [illegible]/[illegible]
↓		
5	K6	[illegible]: [illegible]/[illegible]
↻		[illegible]

Table 4: CUDA [illegible]

1.5.2. [illegible]: [illegible]?

K2 ([illegible])[illegible] - [illegible]. [illegible].

K3 ([illegible])[illegible] - [illegible]. [illegible] “[illegible]” [illegible].

[illegible] 3-5[illegible].

1.5.3. [illegible]

[illegible]	[illegible]
K1: ActiveMask	[illegible] (E < 10 MeV)
K2: CoarseTransport	[illegible] (E > 10 MeV)
K3: FineTransport	[illegible] ([illegible])
K4: BucketTransfer	[illegible]
K5: ConservationAudit	[illegible]
K6: SwapBuffers	[illegible]/[illegible]

Table 5: CUDA [illegible]

1.5.4. [illegible]

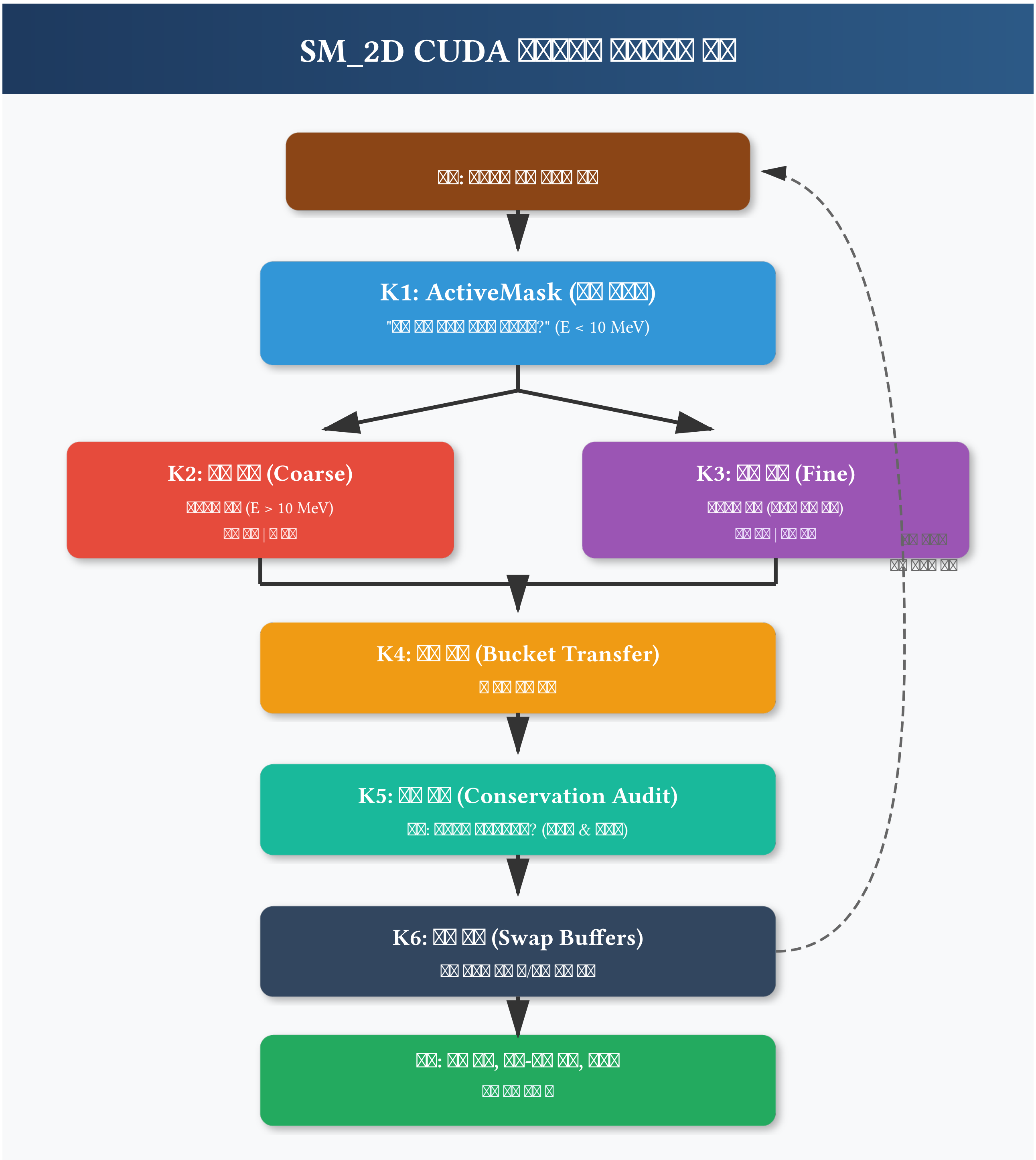

Figure 1: CUDA [illegible] - [illegible]

1.6. [illegible]

1.6.1. [illegible]

1.6.2. [illegible]: “[illegible]”[illegible]?

[illegible]. [illegible]:

[illegible]: [illegible]? (x, z [illegible]) [illegible]: [illegible]? (theta [illegible]) [illegible]: [illegible]? (E)

[illegible] “[illegible]”[illegible] [illegible](bin)[illegible].

□□□ 4□□ □□ □□□□ □□□□□:

□□	□□
θ (□□)	$-90°$□□ $+90°$□□ 512□ □□ - □□□ □□ □□□□ □□□□□ □□□
E (□□□)	0.1□□ 250 MeV□□ 256□ □□ (□□ □□) - □□□ □□□ □□ □□□□ □□□□ □□□
x_sub	□ □ □ 4□ □□ □□ (□□□ □□) - □ □ □□□ □□
z_sub	□ □ □ 4□ □□ □□ (□□ □□) - □ □ □□□ □□

Table 6: 4□□ □□ □□ □□

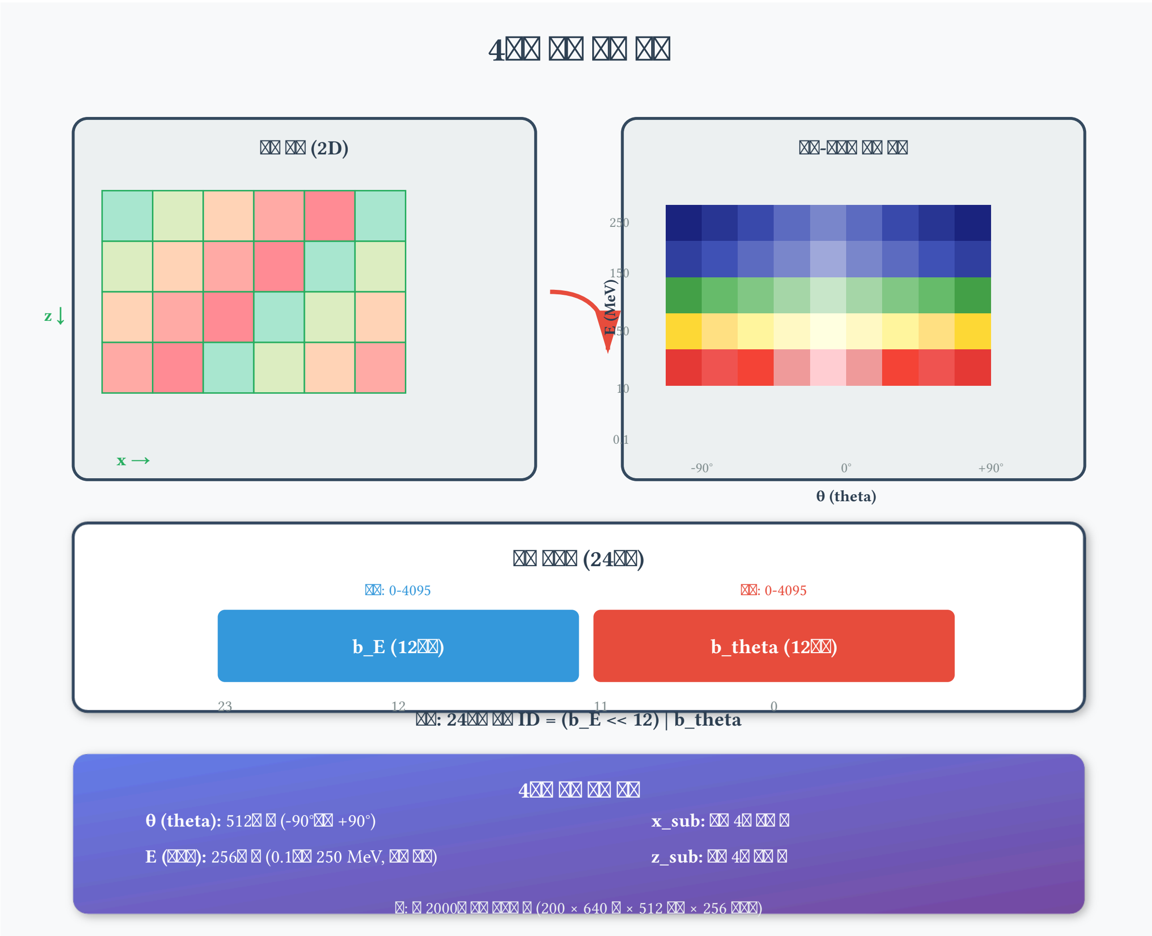

Figure 2: 4□□ □□ □□□ □□ □□□□ □□□ □□

1.6.3. □□(Bins) □□□□

□□□ □□ □□□□ □□ □□□ □□□□□:

☒☒ ☒☒	☒☒☒ ☒☒
255	250 MeV - ☒☒ ☒☒☒
200	200 MeV - ☒☒☒☒
150	100 MeV - ☒☒ ☒☒☒
100	50 MeV - ☒☒ ☒☒
50	10 MeV - ☒☒☒ ☒☒ ☒☒
20	1 MeV - ☒☒☒☒
0	0.1 MeV - ☒☒ ☒☒☒

Table 7: ☒☒☒ ☒☒ (☒☒ ☒☒, ☒ 256☒)

1.6.4. ☒☒ ☒☒☒☒: ☒ ☒☒ ☒☒☒☒?

☒☒ ☒☒ vs ☒☒ ☒☒:

☒☒ ☒☒: ☒☒ ☒☒☒ ☒☒☒ ☒☒☒ ☒☒
- ☒☒: ☒☒☒☒☒☒ ☒☒☒ ☒☒☒ ☒☒☒☒ ☒☒
- ☒: 0-1 MeV☒ 100-101 MeV☒ ☒☒ ☒☒☒ ☒☒

☒☒ ☒☒: ☒☒ ☒☒☒☒☒ ☒ ☒☒ ☒☒
- ☒☒: ☒☒☒ ☒☒☒ ☒☒☒ ☒ ☒☒☒
- ☒: 0-1 MeV☒ 100-101 MeV☒☒ 10☒ ☒ ☒☒ ☒☒

☒☒☒ ☒☒ ☒☒☒☒ ☒☒☒☒ ☒☒ ☒☒☒☒ ☒☒☒ ☒☒ ☒☒☒ ☒☒☒☒☒!

1.6.5. ☒☒-☒☒ ☒☒☒

```
// 24☒☒ ☒☒ ID = (b_E << 12) | b_theta
uint32_t block_id = encode_block(theta_bin, energy_bin);

// ☒☒☒ ☒☒ ☒☒☒ ☒☒ 512☒ ☒☒ ☒☒
uint16_t local_idx = encode_local_idx_4d(theta_local, E_local, x_sub, z_sub);
```

1.6.6. ☒☒ ☒☒: ☒☒-☒☒ ☒☒☒

☒☒(Dense) ☒☒: ☒☒ ☒☒☒ ☒☒☒ ☒☒☒☒ ☒☒ (☒☒) ☒☒-☒☒(Block-sparse): ☒☒☒ ☒☒☒☒ ☒☒☒ ☒☒

☒☒: ☒☒☒ ☒☒☒☒☒
- ☒☒: ☒☒☒ ☒☒ ☒☒☒☒ ☒☒ ☒☒ ☒☒
- ☒☒: ☒☒☒ ☒☒☒ ☒☒☒ ☒☒

☒☒: 70% ☒☒ ☒☒☒ ☒☒!

1.6.7. ☒☒☒ ☒☒

☒☒☒ ☒☒	☒☒ ☒☒	☒☒
E > 10 MeV	☒☒ ☒ (K2)	☒☒ ☒☒, ☒☒☒ ☒☒☒ ☒☒
E <= 10 MeV	☒☒☒ ☒ (K3)	☒☒☒ ☒☒ ☒☒☒☒ ☒☒ ☒☒☒ ☒☒

Table 8: ☒☒☒☒ ☒☒ ☒☒

[illegible] [illegible]: [illegible] [illegible] [illegible]
[illegible] (0 mm)
├─ [illegible] [illegible] (E > 10 MeV)
│ → K2 ([illegible] [illegible]) [illegible] - [illegible] [illegible]
│ → [illegible] [illegible] [illegible]
├─ [illegible] [illegible] [illegible] (E <= 10 MeV)
│ → K3 ([illegible] [illegible]) [illegible] - [illegible] [illegible]
│ → [illegible] [illegible] [illegible] [illegible]
│ → [illegible] [illegible] [illegible]
[illegible] [illegible] (150 MeV[illegible] [illegible] [illegible] 30 cm)

Table 9: [illegible] [illegible] [illegible]

1.6.8. [illegible] [illegible] [illegible]: [illegible] [illegible]
[illegible] [illegible] [illegible] [illegible] [illegible]:
- [illegible]: [illegible] [illegible]
- [illegible]: [illegible] [illegible] ([illegible] [illegible] [illegible])

[illegible] [illegible] [illegible] [illegible] [illegible]:
- [illegible]: [illegible] [illegible]
- [illegible]: [illegible] [illegible] [illegible] [illegible]

[illegible] [illegible] (SM_2D):
- [illegible] [illegible] [illegible] ([illegible] [illegible])
- [illegible] [illegible] [illegible] ([illegible] [illegible])
- [illegible]: [illegible] [illegible]!

1.7. [illegible] [illegible]

1.7.1. [illegible] [illegible] [illegible] ([illegible])

$$\sigma_{\text{theta}} = \left(13.6\frac{\text{MeV}}{\beta c p}\right) \times \sqrt{\frac{x}{X_0}} \times \frac{\left[1 + 0.038 \times \ln\left(\frac{x}{X_0}\right)\right]}{\sqrt{2}}$$

1.7.2. [illegible] [illegible]: [illegible] [illegible]?
[illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible].

[illegible] [illegible] [illegible]:
- [illegible] [illegible] [illegible] [illegible]([illegible] [illegible])[illegible] [illegible] [illegible] [illegible]
- [illegible] [illegible] [illegible] [illegible] [illegible] [illegible]

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- □□□□ □□□ □□ □□□□□ (□□ = □□ □□)
- □□ □□□ □□□□□ (□□□ □□□ □□ X_0 = 360.8mm □□)
- □□□ □□□ □□□□□ (□ □□ = □ □□)

X_0 (□): 360.8 mm - □□□ □□ "□□□ □□"□□□ 2D □□: $\frac{1}{\sqrt{2}}$ - 2D □□□□□ □□ 3D □□ □□

1.7.3. □□□ □□ (□□□□)

$\kappa = \frac{\xi}{T_{\max}}$□ □□□□ □ □□ □□:

κ (□□)	□□	□□
κ > 10	□□ (□□□□)	□□ □□ □□□ □□ - □ □□ □□
0.01 < κ < 10	□□□□	□□ □□ - □□□ □□
κ < 0.01	□□□	□□ □ □□□ □□ - □□□ □□

Table 10: □□□ □□ □□

1.7.4. □□ □□□□: □□□□ □□□□?

□□(**straggling**)□ "□□□ □□□ □□□□"□ □□□□□.

□□□□ □□□ □□□ □□□□□:

- □□ □□: □□ □□□ □□□ - □□□ □□ □□□ (□□□□)
- □□□ □□: □□□ □□ □□□ - □□□ □□ □□□□ (□□□)

□□□□ □ □□□□ □□□ □□ □□ □□□□ □□ □□□□. □□□ □ □□□□□ □□□□□□.

1.7.5. □□ □□: □ □□ □□ □□□□

κ□ "□□ □□ □□"□ "□□ □ □□"□ □□□ □□□□□:

□□ (κ > 10): □□ □□ □□ □□

- □ □□ (□ □□)□□ □□□ □□ □□
- □□ □□ □□ □□
- □□ □□

□□□□ (0.01 < κ < 10): □□

- □□□□□ □□□
- □□ □□ □□
- SM_2D□ □□□ □□□!

□□□ (κ < 0.01): □□ □ □□

- □ □□ □□□ □□
- "□□" □□□ □□ □□□ □□

1.7.6. □ □□

$$W \times \exp(-\sigma(E) \times \mathrm{d}s)$$

1.7.7. □□ □□□□: □ □□□□

□□□ □□□□ □□□□ □□□□ □□□ □□□□□ □□□□□.

□□□ □□ □□□□□:

- [illegible] [illegible] [illegible] [illegible] ([illegible])
- [illegible] [illegible] [illegible] ([illegible] [illegible])
- [illegible] [illegible] [illegible] [illegible]

[illegible] [illegible] [illegible]: "[illegible] [illegible] [illegible] [illegible] [illegible]?"

[illegible] [illegible] [illegible] ICRU 63.

1.7.8. [illegible] [illegible] (R [illegible])

$$\mathrm{d}s = \min(0.02 \times R, 1 \quad \mathrm{mm}, \mathrm{cell\_size})$$

[illegible] [illegible] [illegible] [illegible] [illegible] [illegible]-[illegible] LUT[illegible] [illegible].

1.7.9. [illegible] [illegible]: [illegible] [illegible]
[illegible] [illegible] [illegible] [illegible] "[illegible]"[illegible] [illegible]. [illegible] [illegible] [illegible] [illegible] [illegible] [illegible].

[illegible] [illegible]: [illegible] [illegible] [illegible] [illegible]: [illegible] [illegible]

[illegible]: [illegible] [illegible] [illegible] ([illegible] [illegible] [illegible] [illegible] [illegible] [illegible]) [illegible]
- [illegible] ([illegible] [illegible]): [illegible] [illegible] [illegible]
- [illegible] ([illegible] [illegible]): [illegible] [illegible] [illegible]
- [illegible] [illegible] [illegible] [illegible]!

1.8. [illegible] [illegible]

[illegible]	[illegible]	[illegible]
PsiC_in/out	[illegible] 1.1 GB	[illegible] [illegible] [illegible] - [illegible] [illegible] [illegible] [illegible]
EdepC	0.5 GB	[illegible] [illegible] - [illegible] [illegible] [illegible]
AbsorbedWeight	0.5 GB	[illegible]/[illegible] [illegible] - [illegible] [illegible]
AbsorbedEnergy	0.25 GB	[illegible] [illegible] [illegible] - [illegible] [illegible]
BoundaryLoss	0.1 GB	[illegible] [illegible] - [illegible] [illegible] [illegible]
ActiveMask/List	0.5 GB	[illegible] [illegible] [illegible] - [illegible]

Table 11: GPU [illegible] [illegible]

[illegible]: **4.3 GB GPU [illegible]**

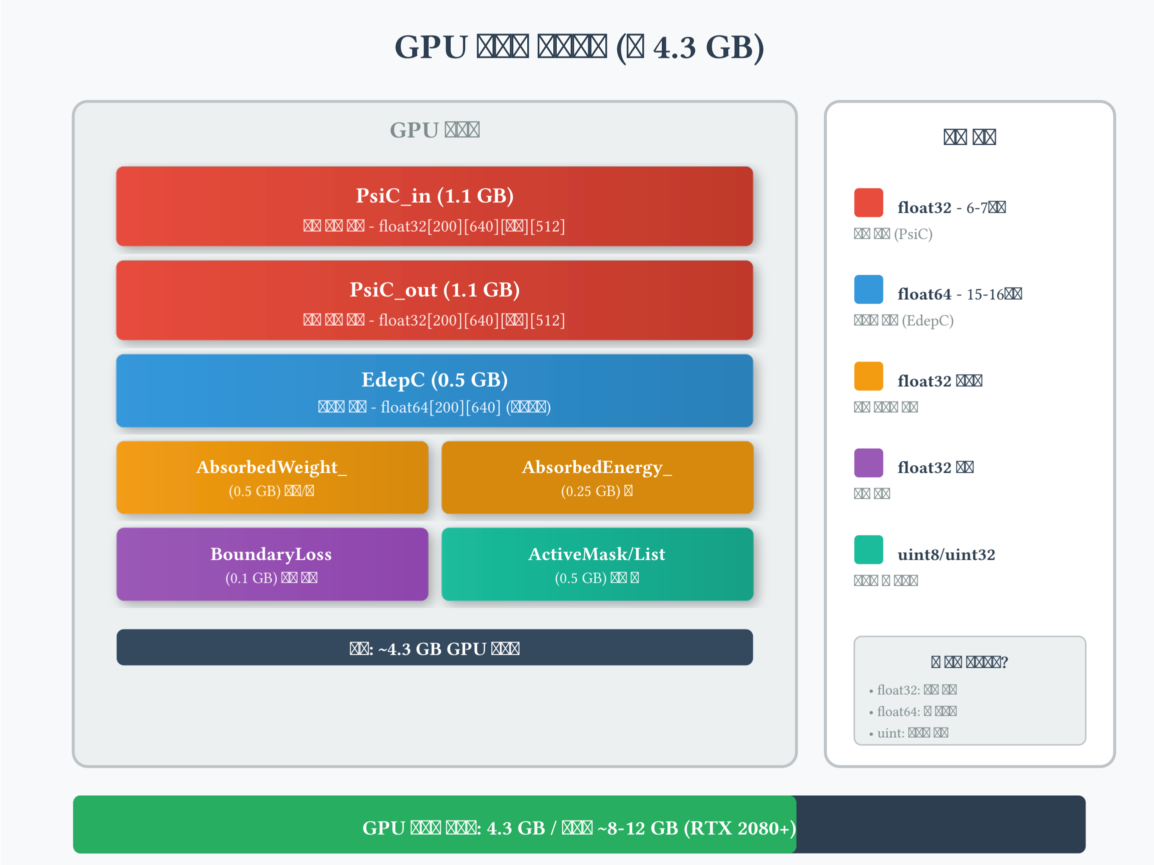

Figure 3: GPU ⊠⊠⊠ ⊠⊠⊠⊠ ⊠⊠⊠

1.8.1. ⊠ ⊠⊠⊠ ⊠⊠ ⊠⊠⊠⊠ ⊠⊠⊠⊠?

⊠⊠⊠⊠⊠⊠ ⊠⊠ ⊠⊠ ⊠⊠ ⊠⊠ ⊠⊠ ⊠⊠⊠ ⊠⊠ ⊠⊠⊠ ⊠⊠⊠⊠ ⊠⊠⊠ ⊠⊠⊠⊠⊠.

⊠ ⊠⊠⊠ ⊠⊠⊠ ⊠⊠⊠⊠⊠:

- ⊠⊠ (⊠⊠)
- ⊠⊠ (⊠⊠ ⊠⊠)
- ⊠⊠⊠ (⊠⊠⊠ ⊠⊠ ⊠⊠⊠)
- ⊠⊠⊠ ⊠⊠ “⊠⊠” (⊠⊠)⊠ ⊠⊠⊠ ⊠⊠⊠

4.3 GB⊠ ⊠ 1⊠ 3,100⊠ ⊠⊠ ⊠⊠ ⊠⊠⊠ ⊠⊠⊠ ⊠ ⊠⊠⊠!

1.9. ⊠⊠⊠ ⊠⊠

⊠⊠ ⊠⊠	⊠⊠	⊠⊠⊠ ⊠⊠
⊠⊠⊠ ⊠⊠ ⊠⊠	±2%	⊠⊠: ⊠⊠ ⊠⊠⊠ ⊠⊠⊠⊠ ⊠⊠ ⊠⊠
⊠⊠ ⊠⊠⊠ (⊠⊠ ⊠⊠)	±15%	⊠⊠: ⊠ ⊠ ⊠⊠⊠ ⊠⊠
⊠⊠ ⊠⊠⊠ (⊠⊠⊠)	±20%	⊠⊠: ⊠⊠⊠ (⊠ ⊠⊠⊠⊠) ⊠⊠
⊠⊠ ⊠⊠	$< 10^{-6}$	⊠⊠ ⊠⊠: ⊠⊠⊠ ⊠⊠⊠⊠ ⊠⊠ ⊠⊠
⊠⊠⊠ ⊠⊠	$< 10^{-5}$	⊠⊠ ⊠⊠: ⊠⊠⊠⊠ ⊠⊠⊠⊠⊠⊠ ⊠⊠

Table 12: ⊠⊠ ⊠⊠ ⊠ ⊠⊠⊠ ⊠⊠⊠

⊠⊠ ⊠⊠: ⊠⊠

1.9.1. [illegible]: [illegible]

[illegible]:

[illegible] ±2%:

- [illegible] 2% [illegible]
- 2% [illegible]
- SM_2D[illegible] $< 1\%$ [illegible]!

[illegible] $< 10^{-6}$:

- [illegible]
- [illegible]
- SM_2D[illegible]!

1.10. [illegible]

[illegible]	[illegible]	[illegible]
EnergyGrid	core	[illegible] - [illegible] 256[illegible]
AngularGrid	core	[illegible] - [illegible] 512[illegible]
PsiC	core	[illegible] - [illegible]
RLUT	lut	[illegible]-[illegible] - [illegible]
PencilSource	source	[illegible] - [illegible]
GaussianSource	source	[illegible] - [illegible]
GlobalAudit	audit	[illegible] - [illegible]
BraggPeakResult	validation	[illegible] - [illegible]

Table 13: [illegible]

1.10.1. [illegible]: [illegible]?

[illegible].

[illegible]: [illegible]

- [illegible] = [illegible] ([illegible])
- [illegible] = [illegible] ([illegible])

[illegible]: `EnergyGrid` [illegible]

- [illegible]: 256[illegible]
- [illegible]: [illegible]
- [illegible]: [illegible]

1.11. [illegible]

[illegible] - [illegible] - [illegible] - [illegible] CUDA [illegible] - [illegible] API [illegible] - [illegible]

1.12. [illegible]

1.12.1. [illegible]

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☒☒☒ ☒☒ (Bragg Peak)

- ☒☒☒☒ ☒☒☒☒ ☒☒☒☒ ☒☒☒☒ ☒☒, ☒☒☒ ☒☒☒☒ ☒☒☒ ☒☒ ☒☒☒. ☒ ☒☒☒ ☒☒☒.

=

CSDA ☒☒ (CSDA Range)

- “☒☒ ☒☒ ☒☒☒” - ☒☒☒ ☒☒☒ ☒☒ ☒☒☒ ☒☒ ☒☒☒☒☒.

=

☒☒☒☒ (Deterministic)

- ☒☒☒ ☒☒ ☒☒(☒☒☒☒☒) ☒☒ ☒☒☒ ☒☒.

=

☒☒ ☒☒ (Phase Space)

- ☒☒☒ ☒☒☒ ☒☒ ☒☒☒ ☒☒☒☒ ☒☒☒ ☒☒.

=

☒☒ (Straggling)

- ☒☒☒ ☒☒☒ ☒☒☒ ☒☒.

=

MCS

- ☒☒ ☒☒ ☒☒ - ☒☒☒☒ ☒☒☒ ☒☒☒.

=

LUT

- ☒☒ ☒☒☒ - ☒☒ ☒☒☒ ☒☒ ☒☒☒ ☒☒☒.

=

☒☒ (Kernel)

- GPU☒☒ ☒☒☒☒ ☒☒.

=

☒☒ (Bin)

- ☒☒☒☒ ☒☒☒☒ ☒☒☒☒ (☒☒☒ ☒☒ ☒☒).

=

☒☒ (Attenuation)

- ☒☒ ☒☒ ☒☒☒ ☒☒☒ ☒ ☒☒.

=

□□ (Cross-section)

- □ □□□□□ □□□ □□.

=

□□□ (Penumbra)

- □□□ □□ □□□□ □□.

1.13. □□□□

□□	□□
NIST PSTAR	□□□□ □□□ □ □□
PDG 2024	□□□ □□□□ □□
ICRU 63	□□□□ □ □□
Vavilov 1957	□□□ □□ □□

Table 14: □□□□

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SM_2D □□□ □□ □□ □□□ □□

MIT □□□□ - □□ 1.0.0