Update on Final Cooling Lattice

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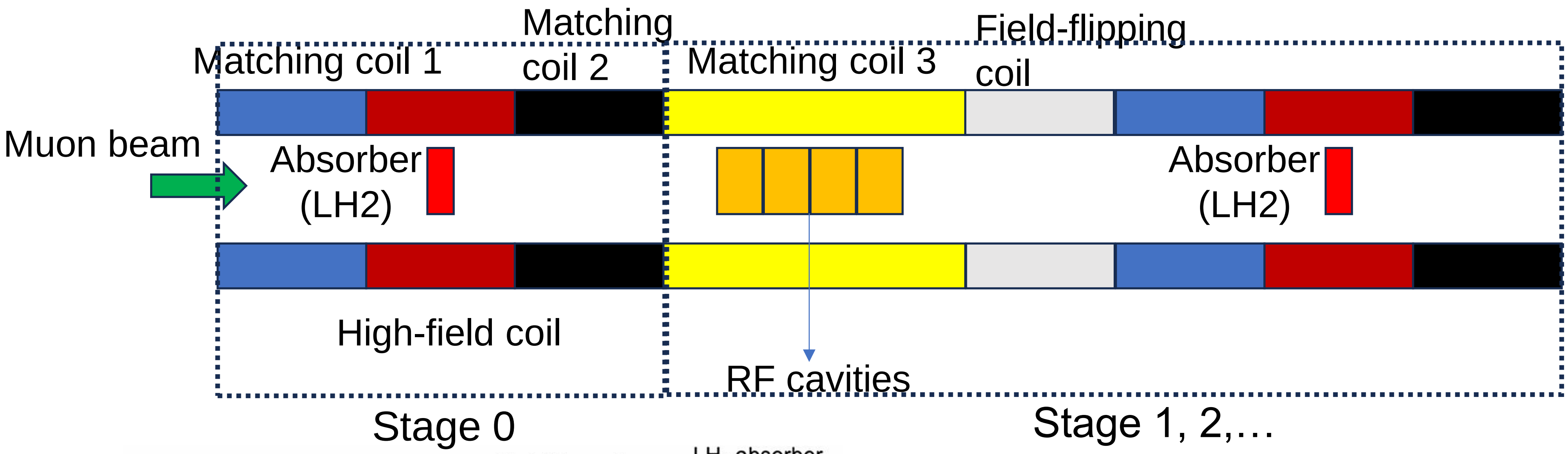
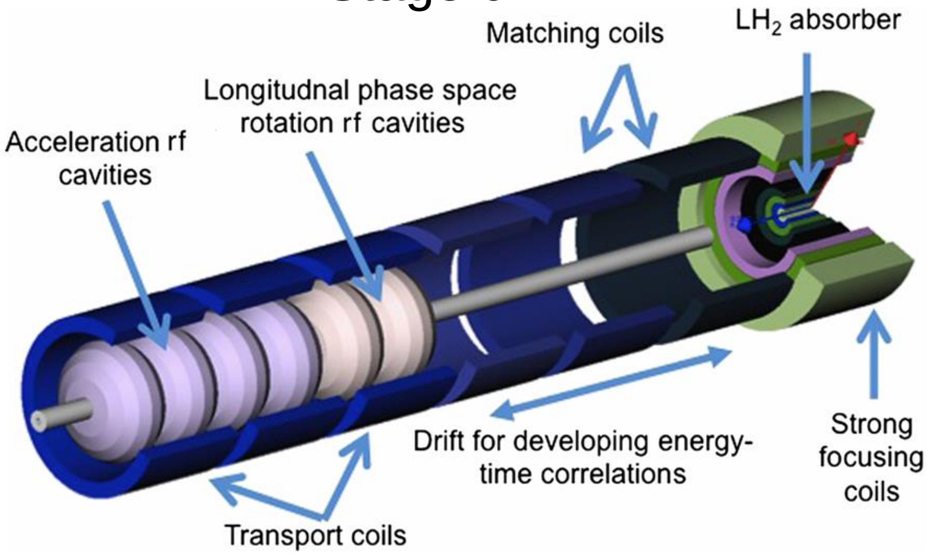
Reminder: Layout of final cooling cell



Beam pipe radius: 2 cm

Coil radius: 5 cm

Each cooling stage includes only one cooling cell.

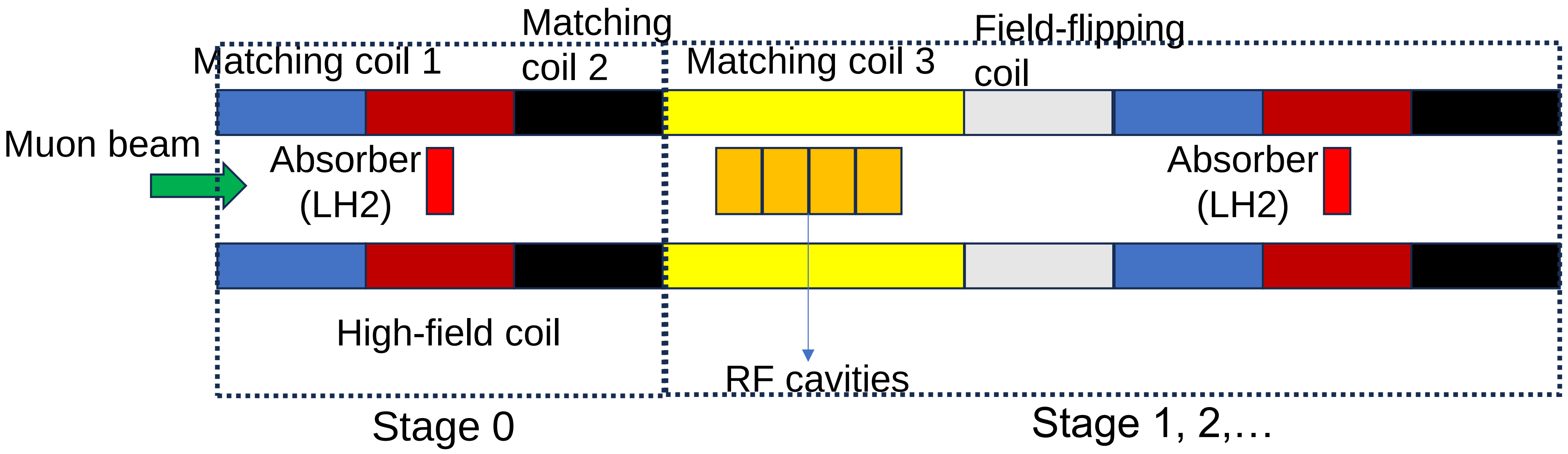


Final cooling cell in baseline of MAP (muon accelerator program)

Changes compared to baseline in MAP:

- ✓ No separate phase rotation RF cavities (RF phase is 0). All RF cavities are in acceleration mode.
- ✓ Stage 0 has no RF cavities.
- ✓ Field flips in every stage.
- ✓ Each cooling cell starts at the matching coil 3 and ends at the matching coil 2.

Reminder: Method of final cooling design



- Using differential evolution algorithm to minimize the target function: $\frac{\varepsilon_{T,final}}{\varepsilon_{T,initial}} + 0.75 \times \frac{N_{initial}}{N_{final}} + 0.25 \times \frac{\varepsilon_{L,final}}{\varepsilon_{L,initial}}$

- 14 parameters to adjust:

✓ Solenoid coils current and length
✓ Absorber length
✓ RF gradient, phase and number of RF cavities

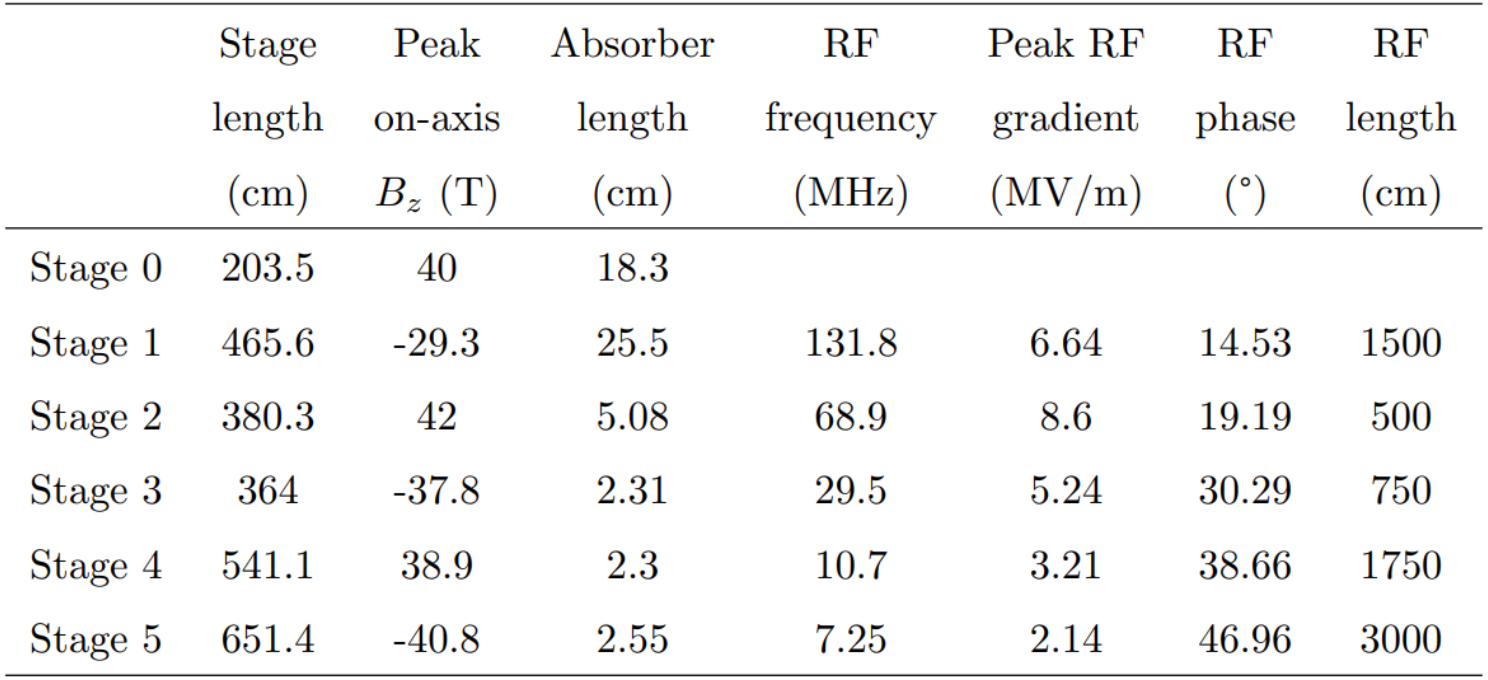
Reminder: last design

	ε_T (mm)	ε_L (mm)	ε_{6D} (mm^3)	Overall transmission
Start	0.1399	1.519	0.02972	
Stage 0	0.124	1.953	0.03022	99.6%
Stage 1	0.09702	4.207	0.0398	96.4%
Stage 2	0.0781	5.291	0.03274	86.9%
Stage 3	0.04755	10.73	0.02447	71.2%
Stage 4	0.03227	16.46	0.01743	62.5%
Stage 5	0.02239	24.77	0.01278	54.6%

- ✓ Try to reduce Bz.
- ✓ Try to reduce RF gradient.

Stage	Stage length (m)	Peak on-axis Bz (T)	LH absorber length (m)	RF frequency (MHz)	Number of RF cells	Maximum RF gradient (MV/m)	RF phase (°)	RF cell length (m)
Stage 0	1.564	38.5	0.2028					
Stage 1	3.1978	-24.5	0.2486	107.2	4	12.01	22.95	0.25
Stage 2	3.8672	46.5	0.05543	82.1	2	7.84	33.44	0.25
Stage 3	4.5955	-41.6	0.04289	28.2	3	6.09	6.96	0.25
Stage 4	4.4233	47.4	0.03439	12.3	5	5.06	55.33	0.25
Stage 5	4.6552	-50	0.029	11.2	8	2.8	41.93	0.25

Parameters of final cooling lattice

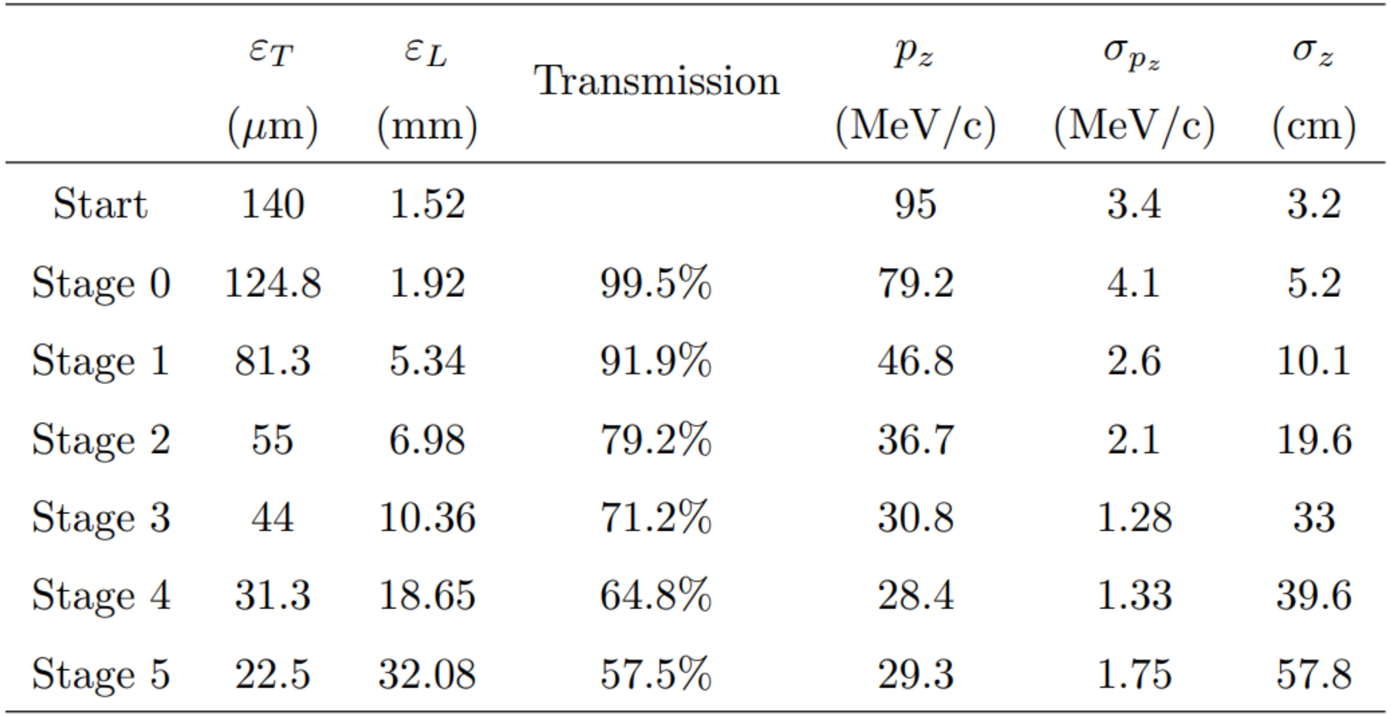


	Stage length (cm)	Peak on-axis B_z (T)	Absorber length (cm)	RF frequency (MHz)	Peak RF gradient (MV/m)	RF phase (°)	RF length (cm)
Stage 0	203.5	40	18.3				
Stage 1	465.6	-29.3	25.5	131.8	6.64	14.53	1500
Stage 2	380.3	42	5.08	68.9	8.6	19.19	500
Stage 3	364	-37.8	2.31	29.5	5.24	30.29	750
Stage 4	541.1	38.9	2.3	10.7	3.21	38.66	1750
Stage 5	651.4	-40.8	2.55	7.25	2.14	46.96	3000

Table 1: Main hardware parameters of the final cooling channel

- ✓ Maximum on-axis Bz is around 40 T, which is smaller than the previous design 50 T.
- ✓ The cooling channel consists of 5 stages with a length of ~26 m.
- ✓ RF frequency reduces from 131.8 MHz to 7.25 MHz. (probably need induction linacs for stage 4 and 5)
- ✓ RF gradient is approximately proportional to $\sqrt{f}$.

Final cooling performance

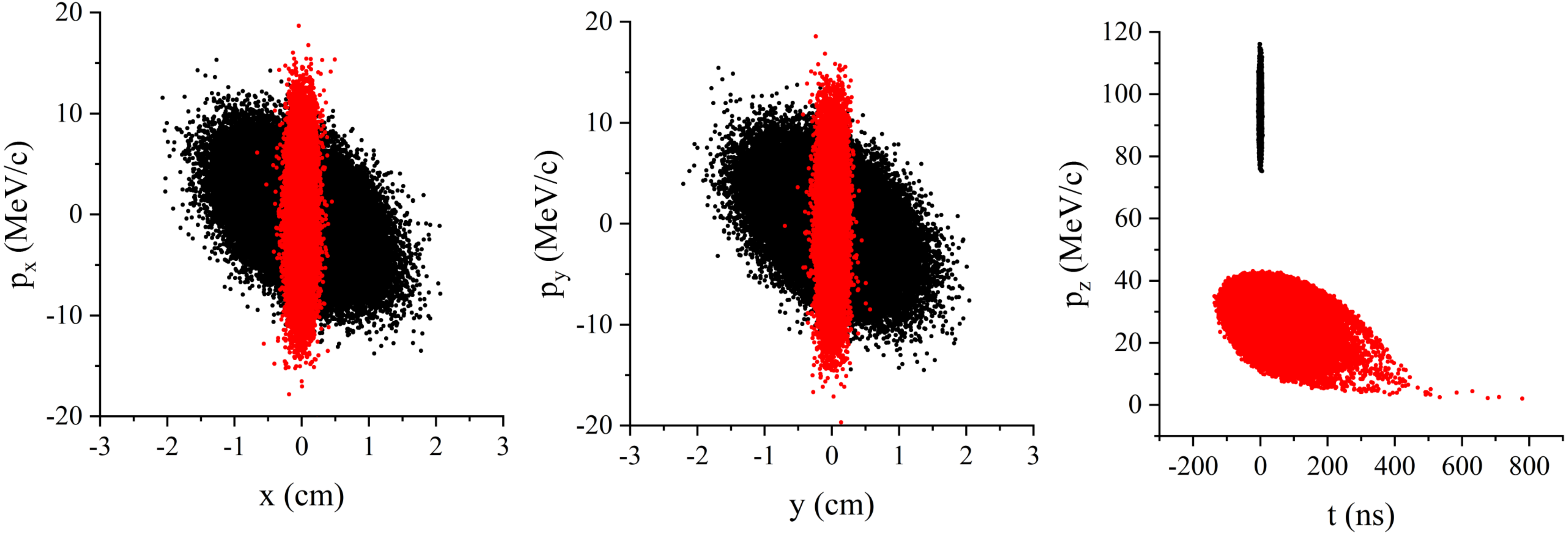


	ε_T (μm)	ε_L (mm)	Transmission	p_z (MeV/c)	σ_{p_z} (MeV/c)	σ_z (cm)
Start	140	1.52		95	3.4	3.2
Stage 0	124.8	1.92	99.5%	79.2	4.1	5.2
Stage 1	81.3	5.34	91.9%	46.8	2.6	10.1
Stage 2	55	6.98	79.2%	36.7	2.1	19.6
Stage 3	44	10.36	71.2%	30.8	1.28	33
Stage 4	31.3	18.65	64.8%	28.4	1.33	39.6
Stage 5	22.5	32.08	57.5%	29.3	1.75	57.8

Table 2: Cooling performance at the end of each stage

- ✓ Initial emittance is from the output of stage 10 of the updated 6D cooling https://arxiv.org/abs/2409.02613
- ✓ Reduce the transverse emittance to ~22.5 μm with longitudinal emittance of 32 mm. Overall transmission is 57.5%.
- ✓ Performance doesn’t include the absorber windows.

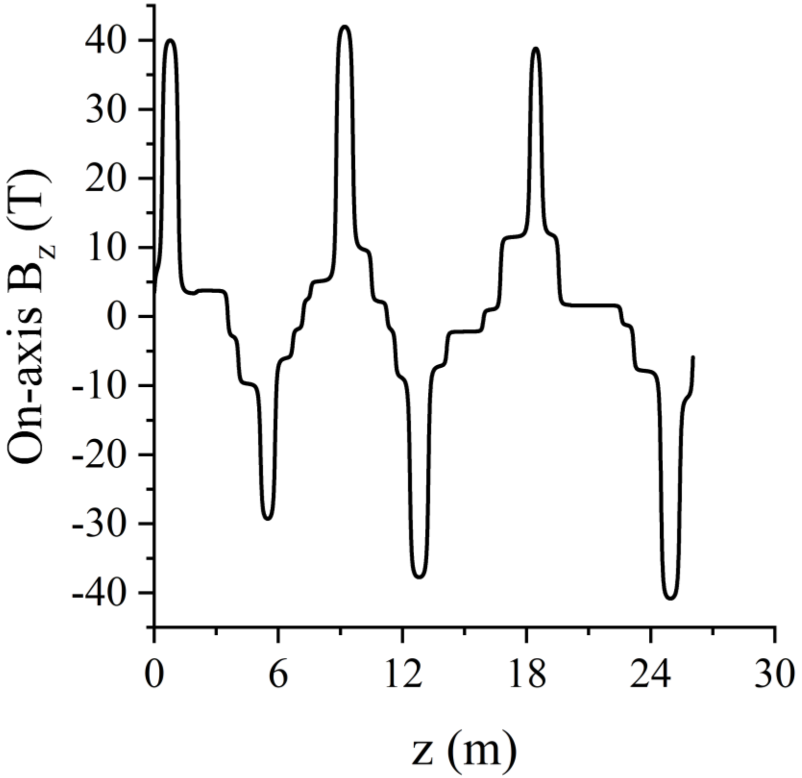
Particle distribution in phase space



Red dots: distribution at the start of the cooling channel
Black dots: distribution at the end of the cooling channel

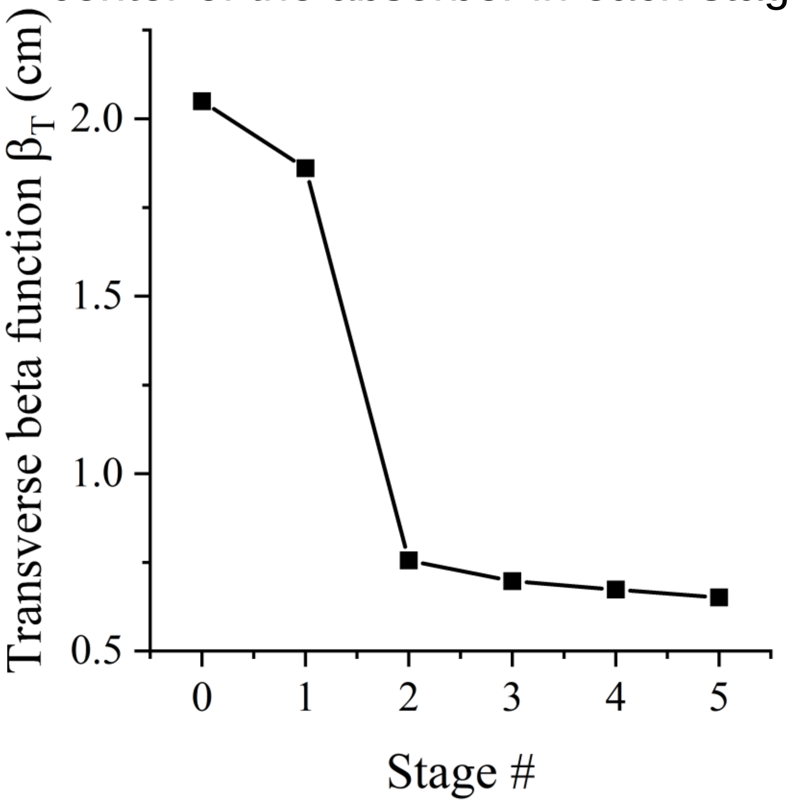
On-axis Bz and transverse beta

On-axis Bz along the cooling channel



✓ Field is continuous in each cooling stage.

Transverse beta function at the center of the absorber in each stage



✓ Transverse beta reduces from 2.05 cm (stage 1) to 0.65 cm (stage 5).

Cooling including the absorber windows

- Window material: silicon nitride (Si_3N_4), window radius: 2 cm

Window thickness (μm)	ε_T (μm)	ε_L (mm)	Transmission
0	22.5	32.08	57.5%
10	22.5	32	56.1%
20	22.8	32.1	55.6%
30	22.7	31.98	52.9%
40	22.8	31.4	51.6%
50	22.4	31.5	49.0%

✓ If we want transmission loss smaller than 2%, window thickness should be smaller than 20 μm.

Cooling including the absorber windows

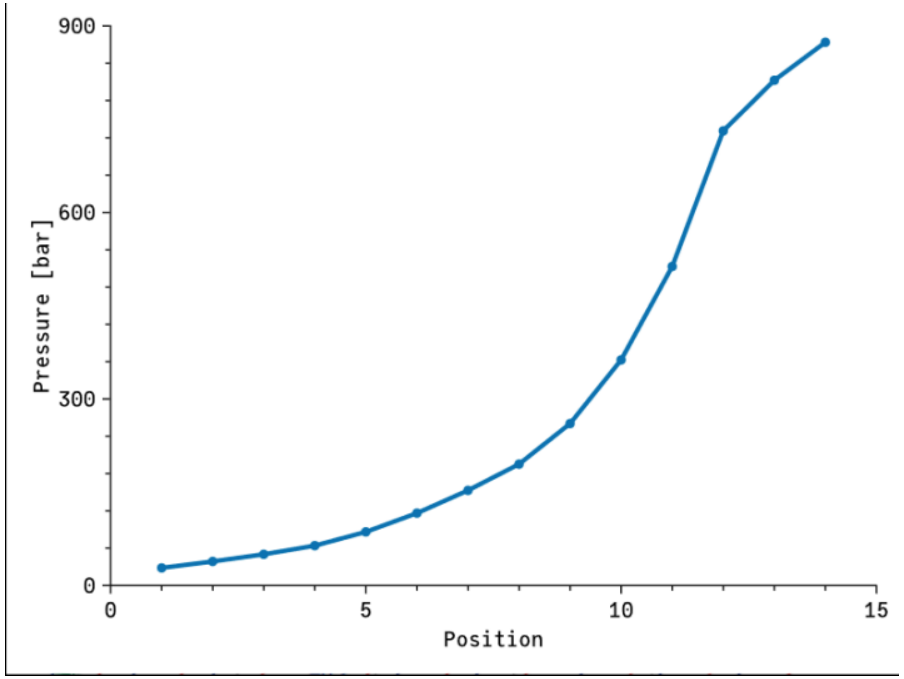
- Window material: beryllium (Be), window radius: 2 cm

Window thickness (μm)	ε_T (μm)	ε_L (mm)	Transmission
0	22.5	32.08	57.5%
10	22.3	32.0	57.3%
20	22.6	31.8	57.4%
30	22.2	31.9	56.2%
40	22.4	31.5	55.9%
50	22.1	31.5	54.6%

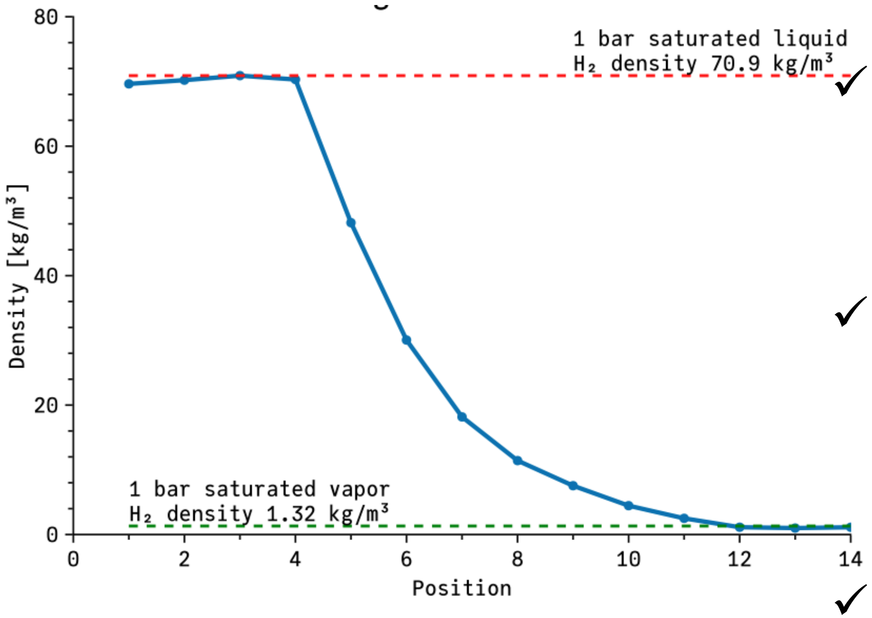
✓ If we want transmission loss smaller than 2%, window thickness should be smaller than 40 μm.

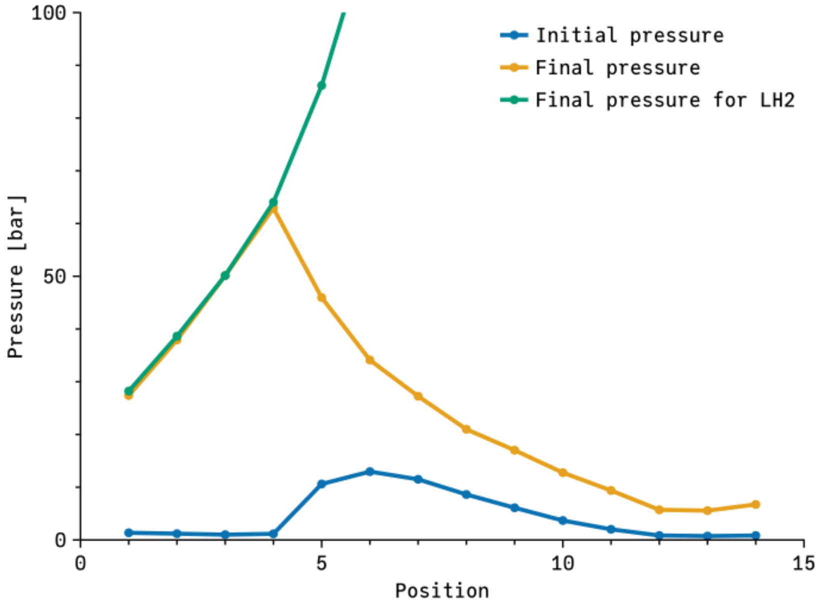
Pressure in liquid hydrogen absorber

- ➢ From Jose's presentation at IMCC annual meeting 2024



Very high pressure for liquid hydrogen absorber. (cooling lattice from Palmer's paper)





- ✓ There's very high pressure in liquid hydrogen absorber.
- ✓ Using vapor hydrogen (lower density) reduces pressure significantly.
- ✓ Need to redesign the cooling channel with vapor hydrogen.
- ✓ How will the vapor density affect the cooling performance?

Cooling performance vs. vapor density

- Cooling stage 5

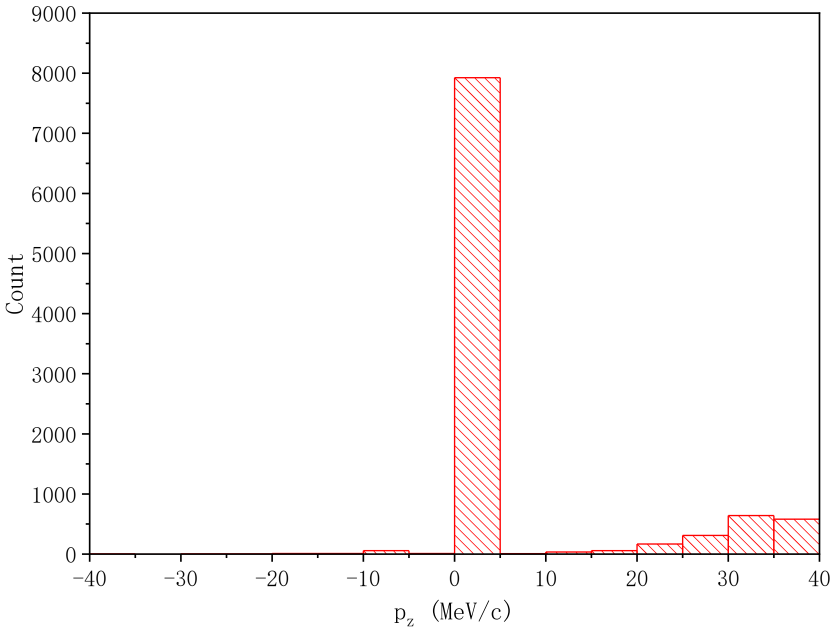
Vapor density (kg/m^3)	**ε_T (μm)**	**ε_L (mm)**	**Transmission**
70.8 (LH2)	22.5	32.08	57.5%
20*1.32=26.4	22.4	32.53	56.3%
15*1.32=19.8	22.2	33.4	57.4%
10*1.32=13.2	22.3	29.2	56.8%
5*1.32=6.6	24	30.5	52.4%

- ✓ Density of 1bar saturated vapor hydrogen: 1.32 kg/m^3
- ✓ Each vapor density needs a new cooling lattice.

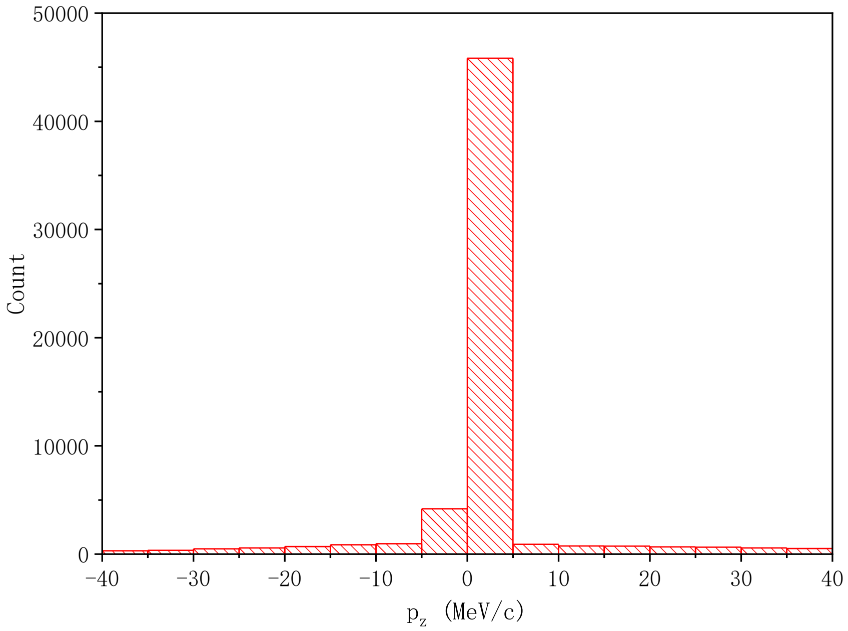
- ✓ For vapor density of 26.4, 19.8 and 13.2 kg/m^3, cooling performance is almost the same with the liquid hydrogen.
- ✓ For vapor density of 6.6 kg/m^3, cooling performance (especially transmission) is much worse.
- ✓ What is the reason for the beam loss of low-density vapor?

Reason of beam loss

Vapor density: 5*1.32=6.6 kg/m^3



Liquid density: 70.8 kg/m^3



- ✓ For final cooling, beam loss concentrates in pz around 0 (muons are stopped in the absorber).
- ✓ For vapor density of 6.6 kg/m^3, much more muons are stopped in the absorber.

Hardware parameters for different vapor density

Vapor density (kg/m^3)	Peak on-axis Bz (T)	Absorber length (cm)	RF frequency (MHz)	Number of RF cells	Maximum RF gradient (MV/m)	RF phase (°)	RF cell length (m)
70.8 (LH2)	40.8	2.55	7.25	12	2.14	46.96	0.25
20*1.32=26.4	43.4	5.4	6.05	11	2.31	35.58	0.25
15*1.32=19.8	38.8	9.1	5.5	14	1.87	46.88	0.25
10*1.32=13.2	40.2	6	8.08	12	1.26	31.32	0.25
5*1.32=6.6	44.2	14.1	8.6	13	1.58	25.53	0.25

- ✓ Although the case where vapor density is 6.6 kg/m^3 has the highest Bz, its cooling performance is still the worst.

Conclusion

- Updated final cooling lattice reduces the transverse emittance to 22.5 μm with longitudinal emittance of 32 mm. The transmission is 57.5% (without windows) .

- The maximum of on-axis longitudinal magnetic field is around 40 T.

- For the selection of window thickness (liquid hydrogen absorber, <2% transmission loss):

✓Silicon nitride (Si_3N_4): <20 μm

✓Beryllium (Be): <40 μm

- It seems vapor hydrogen absorber can be used in final cooling, but its density should be higher than 10*1.32=13.2 kg/m^3 (for cooling stage 5).