Update on the Rectilinear Cooling Channel Design

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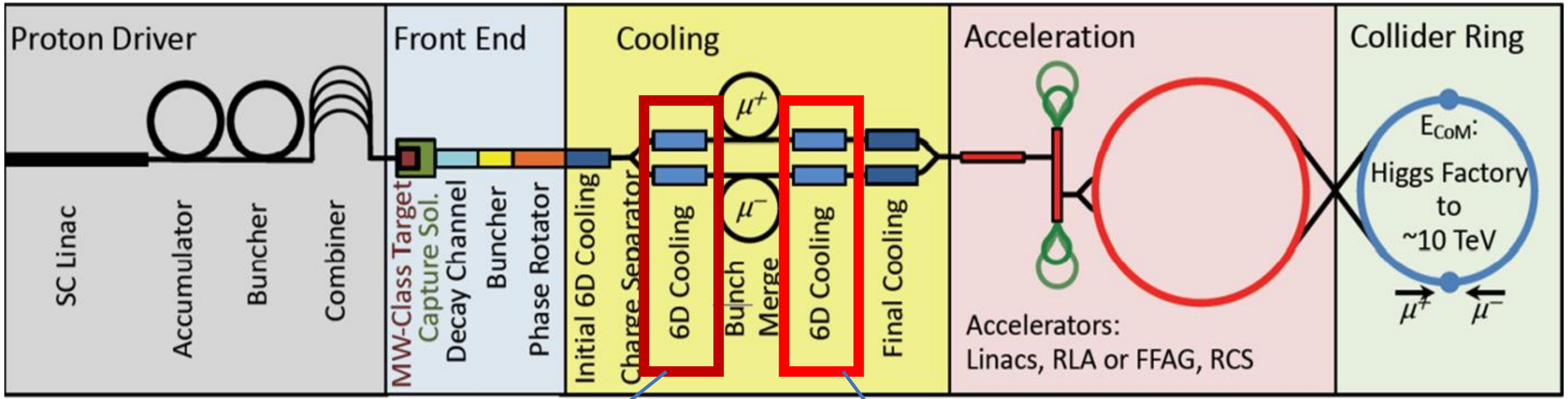
Muon Cooling for a Muon Collider



My present work. (before bunch merge)
Conceptual design starts. (4 or 5 stages)

Goal:

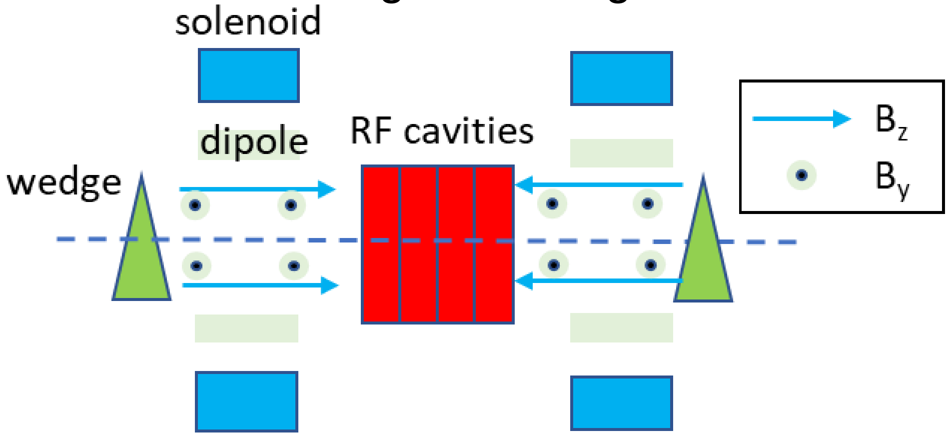
- Normalized transverse emittance: 17 to lower than 1.48 mm
- Normalized longitudinal emittance: 46 to lower than 2.35 mm

My previous work. (after bunch merge)
Conceptual design almost finishes. (10 stages, channel length: 428.8 m)

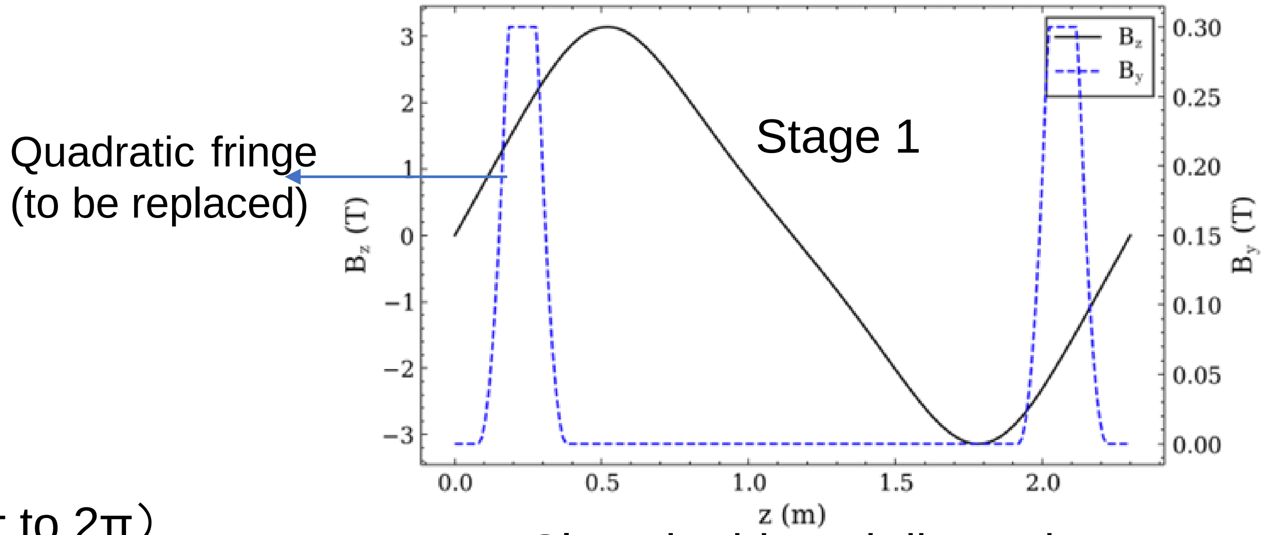
- Normalized transverse emittance: 5.129 to 0.1403 mm
- Normalized longitudinal emittance: 9.991 to 1.563 mm
- Channel transmission: 27.4% (including decay)

Cooling Stage 1~10 (after bunch merge)

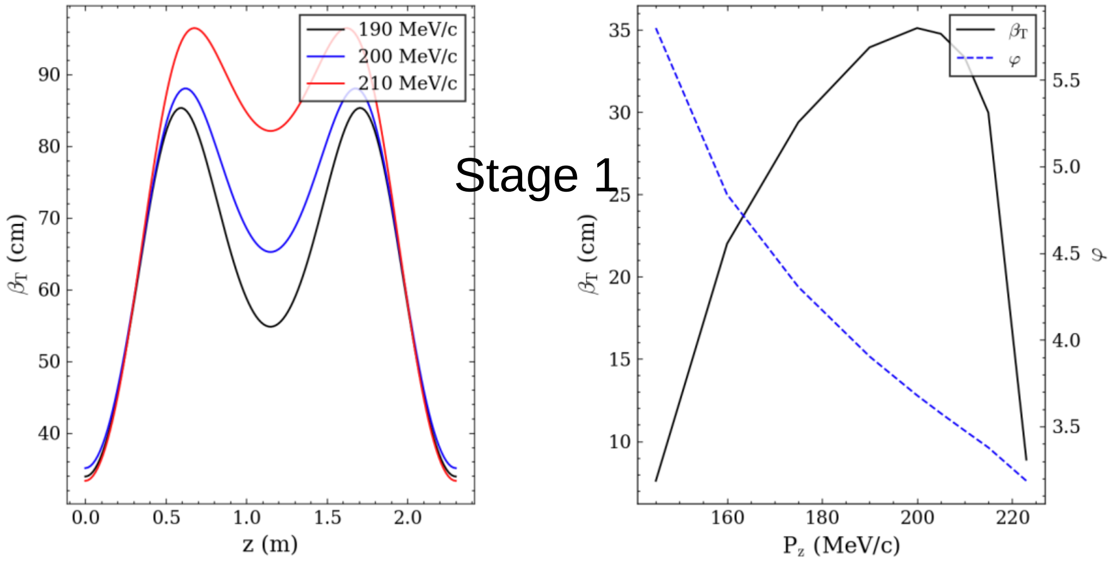
Cooling cell configuration



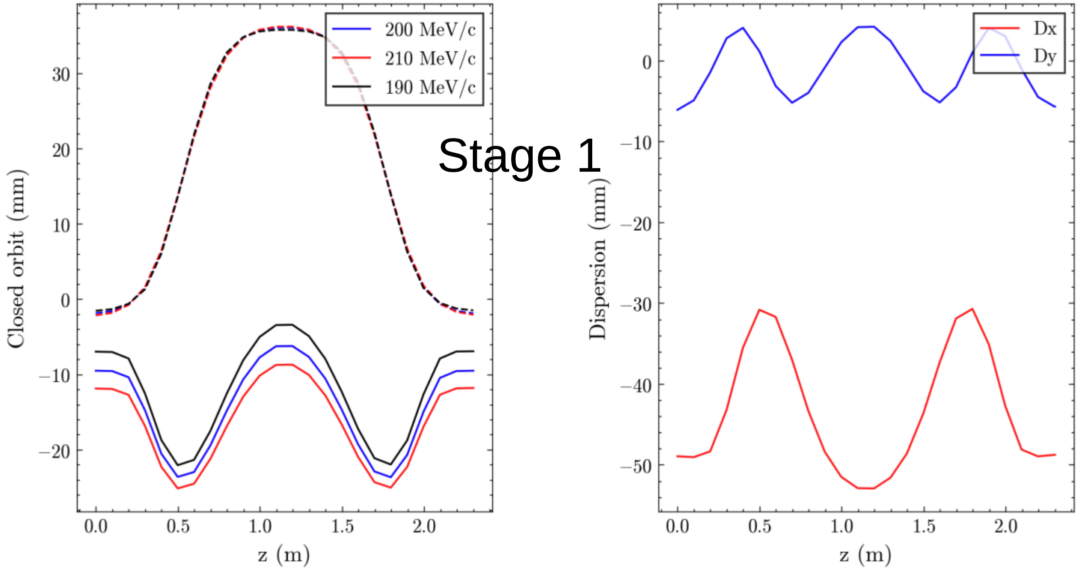
On-axis field



Beta evolution and momentum acceptance (π to 2π)



Closed orbit and dispersion

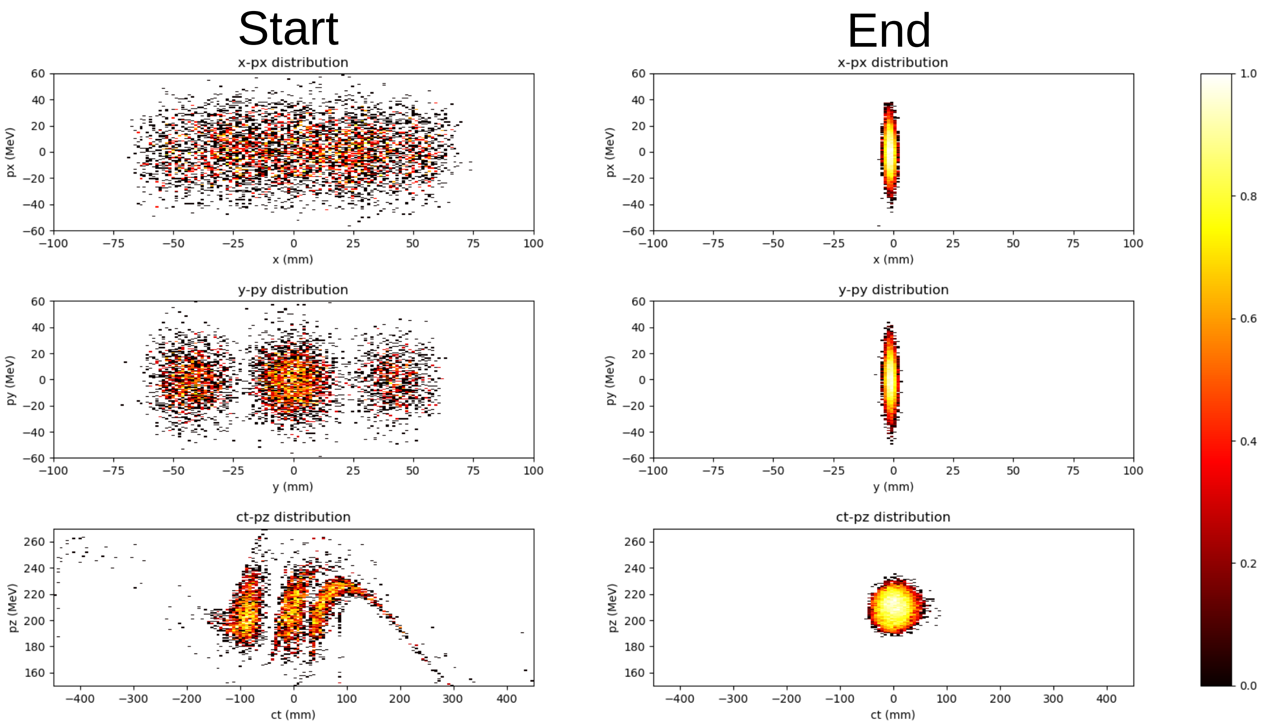


Cooling Stage 1~10 (after bunch merge)

➢ Cooling performance

	$\varepsilon_{T,sim}$ (mm)	$\varepsilon_{L,sim}$ (mm)	$\varepsilon_{6D,sim}$ (mm^3)	Transmission
Start	5.129	9.991	262.5	
Stage 1	2.898	8.583	73.60	86.1%
Stage 2	1.974	5.852	23.49	91.1%
Stage 3	1.449	3.251	7.067	88.8%
Stage 4	1.066	2.367	2.856	91.7%
Stage 5	0.7271	2.284	1.266	91.3%
Stage 6	0.4956	2.149	0.5374	88.2%
Stage 7	0.3549	2.075	0.2734	87.7%
Stage 8	0.2690	1.891	0.1403	88.4%
Stage 9	0.1831	1.767	0.05911	82.2%
Stage 10	0.1403	1.563	0.03057	83.5%

- ✓ Channel length: 428.8 m
- ✓ Normalized transverse emittance: 5.129 to 0.1403 mm
- ✓ Normalized longitudinal emittance: 9.991 to 1.563 mm
- ✓ Channel transmission: 27.4% (including decay)



Cooling Stage 1~10 (after bunch merge)

➢ Tentative parameters of the cooling cells (hardware parameters to be confirmed)

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10
Cell length (m)	2.3	1.8	1.4	1.1	0.8	0.7	0.6	0.6	0.6	0.6
Stage length (m)	55.2	61.2	63.0	48.4	55.2	42.0	38.4	26.4	26.4	12.6
Pipe radius (cm)	23	19	12.5	9.5	6	4.5	3.8	3.3	2.4	1.9
$B_{z,max}$ (T)	3.1	4.1	4.8	6.2	8.8	11.7	15.0	16.8	18.1	19.0
Solenoid coil center position (mm)	503.7	394.2	217.1	161.3	92.8	73.6	60.9	57.6	56.2	51.8
Solenoid coil length (mm)	128.8	125.2	158.7	153.6	139.6	128.5	100.4	93	100.9	99.1
Solenoid coil inner-radius (mm)	400	400	400	300	200	120.8	80.3	60.1	48.7	45.1
Solenoid coil thickness (mm)	500	500	500	400	400	241.6	200.8	180.3	146.1	135.3
Solenoid coil current (A/mm^2)	61.2	92.5	144.5	185.1	289.4	299.9	385.9	382	362	393.7
Transverse beta β_T (cm)	35	30	20	15	10	6	4	3	2.5	2
Dispersion (mm)	-49.3	-49.8	-43	-35.3	-16.9	-11.2	-9.2	-6.9	-6.3	-6.0
On-axis wedge length (cm)	37	32	24	20	12	11	9	8	7.5	7
Wedge apex angle (deg)	110	120	115	110	120	130	140	140	140	140
Wedge window thickness (μm)	100	100	100	100	50	20	10	10	5	5
Wedge window radius (cm)	18.3	13.1	10.8	9.9	4.9	3.6	2.3	2.1	1.9	1.8
RF frequency (MHz)	352	352	352	352	704	704	1056	1056	1056	1056
Number of RFs	6	5	4	3	5	4	5	4	3	3
RF length (cm)	19	19	19	19	9.5	9.5	6.5	6.5	6.5	6.5
Maximum RF gradient (MV/m)	25.2	24.0	24.9	25.8	23.0	30.4	25.0	30.0	33.7	32.2
RF phase (deg)	27.9	30.7	27.4	29.8	24.5	20.6	23.7	20.9	24.7	23.2
RF inner-radius (mm)	326.2	326.2	326.2	326.2	163.1	163.1	130.5	130.5	130.5	130.5
RF iris-radius (mm)	230	190	125	95	60	45	38	33	24	19
RF window thickness (μm)	50	50	50	50	50	20	10	10	5	5

Heat load in LH_2

➢ Rough calculation (assuming the Gaussian beam)

From $c = \frac{Q}{m\Delta T}$ and $Q = N\frac{dE}{dz}z$ where c is the specific heat capacity, Q is the energy deposit, m is the mass, ΔT is the temperature change, N is the particles number (10^13) and dE/dz is the energy loss per unit,

we get $\Delta T = \frac{N\frac{dE}{dz}}{2\pi\rho\sigma_x\sigma_y c}$ where ρ is the material density, σx and σy are beam size in 1 sigma.

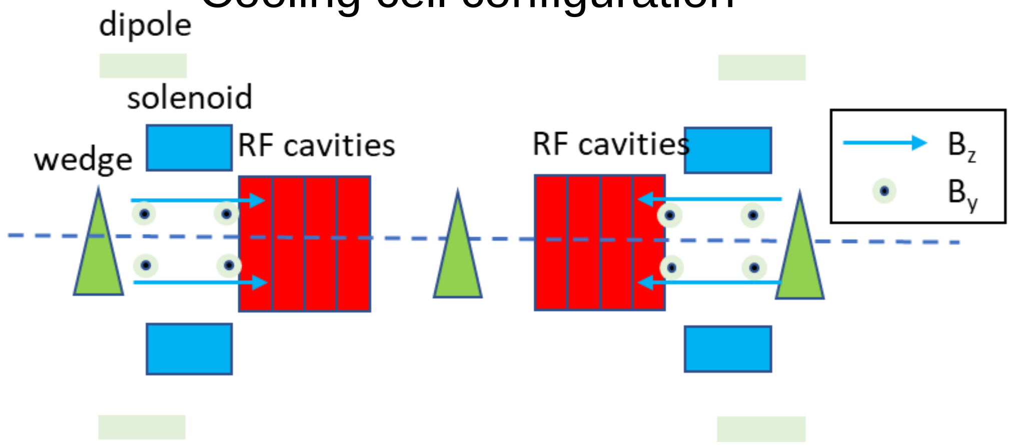
For the start of stage 1, the $\sigma_x = \sigma_y = 3\ cm$, then **ΔT=0.015 K (can be ignored)**

Thanks for Jose's correction!

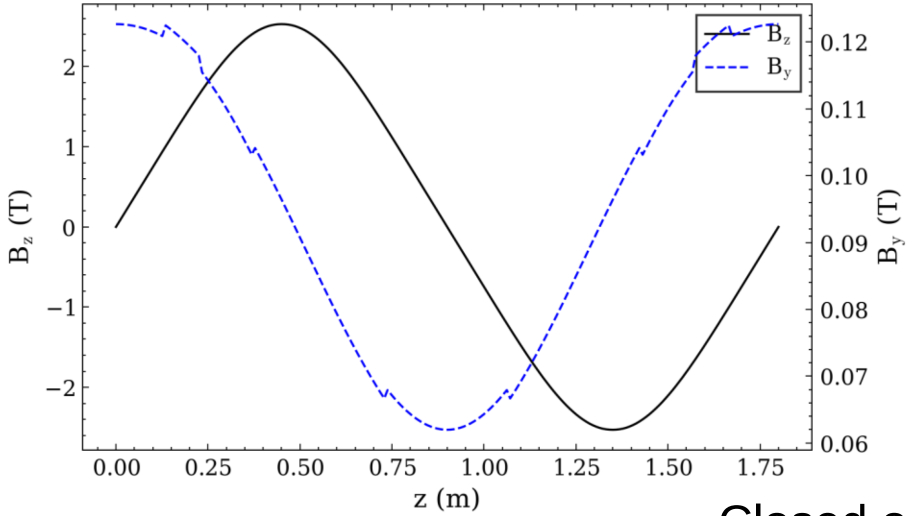
For the end of stage 10, the $\sigma_x = \sigma_y = 1\ mm$, then **ΔT=13.7 K (very huge)** **Try to use lithium hydride wedge instead?**

Cooling Stage 1 (before bunch merge)

Cooling cell configuration



On-axis field



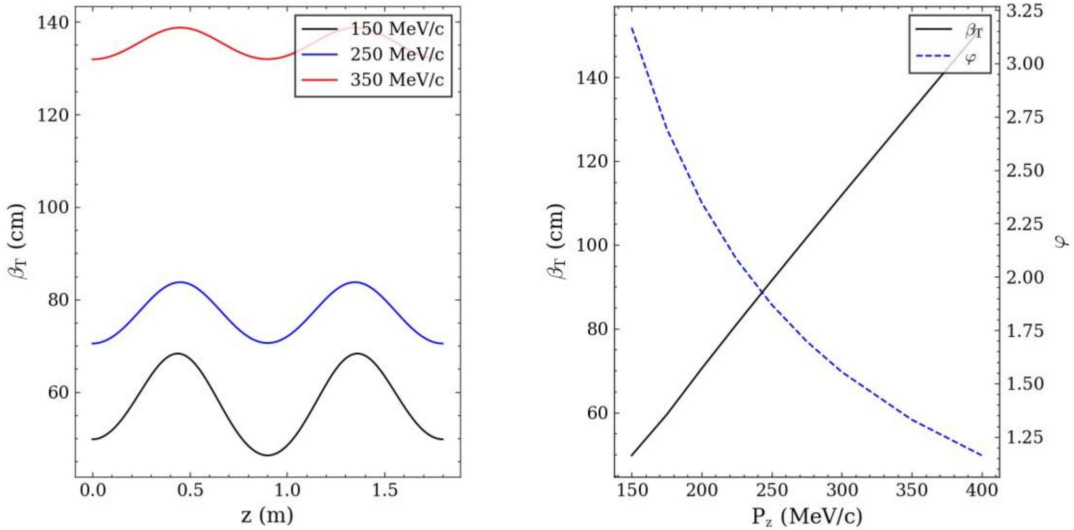
Maxwellian dipole fringe field

$$B_y = \frac{1 + e^z \cos y}{1 + 2e^z \cos y + e^{2z}},$$

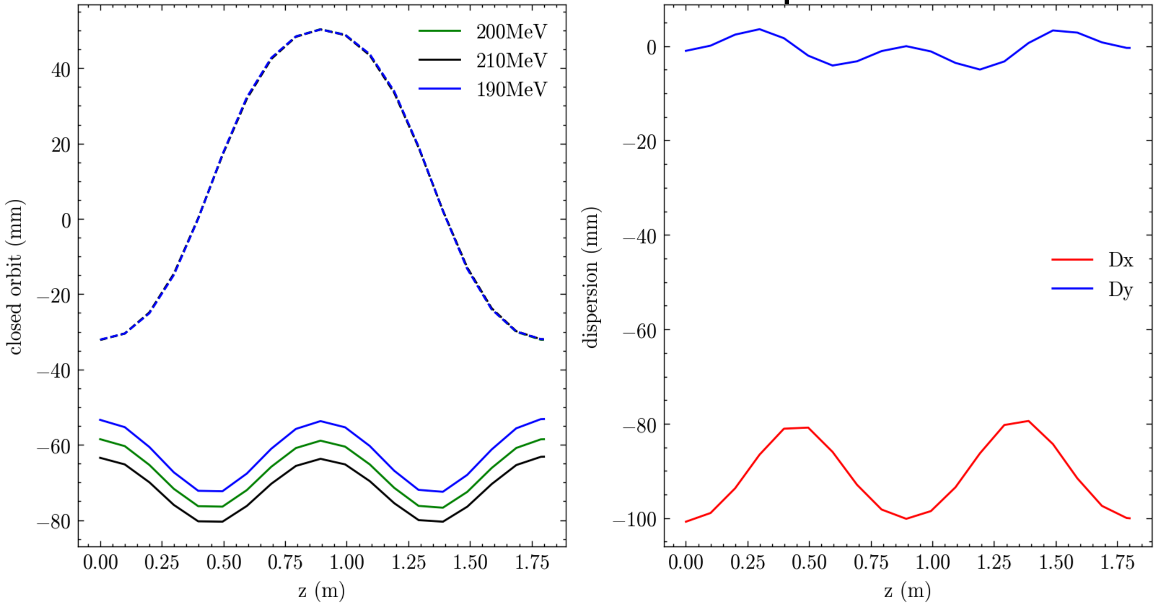
$$B_z = \frac{-e^z \sin y}{1 + 2e^z \cos y + e^{2z}}.$$

Ref: Analytical expressions for fringe fields in multipole magnets, PRST-AB, 18, 064001 (2015)

Beta evolution and momentum acceptance (0 to π）

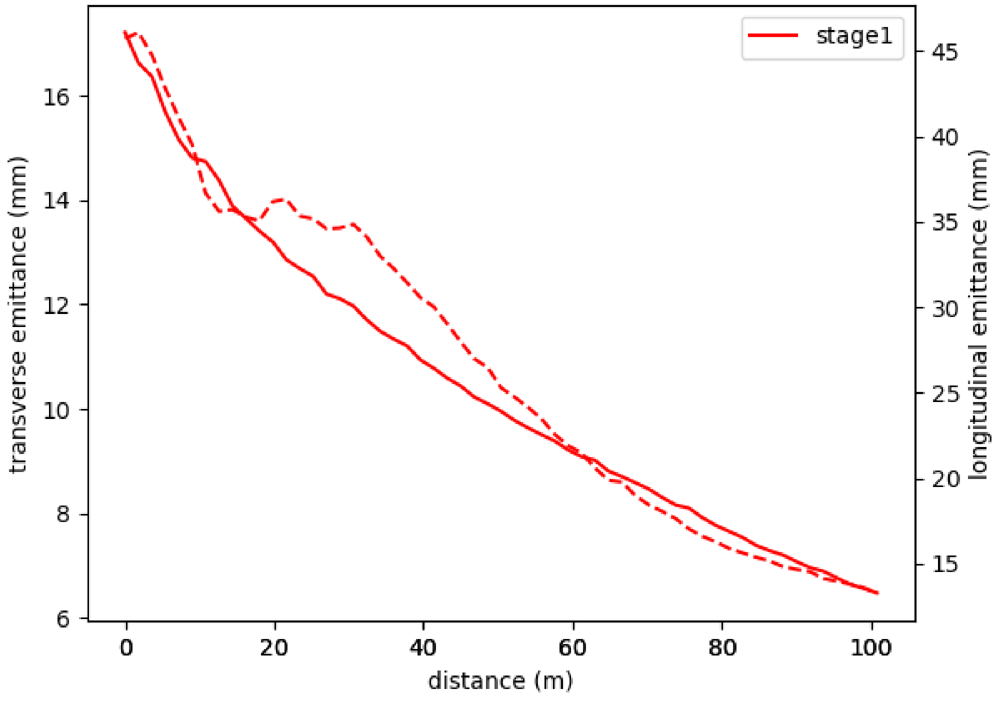


Closed orbit and dispersion

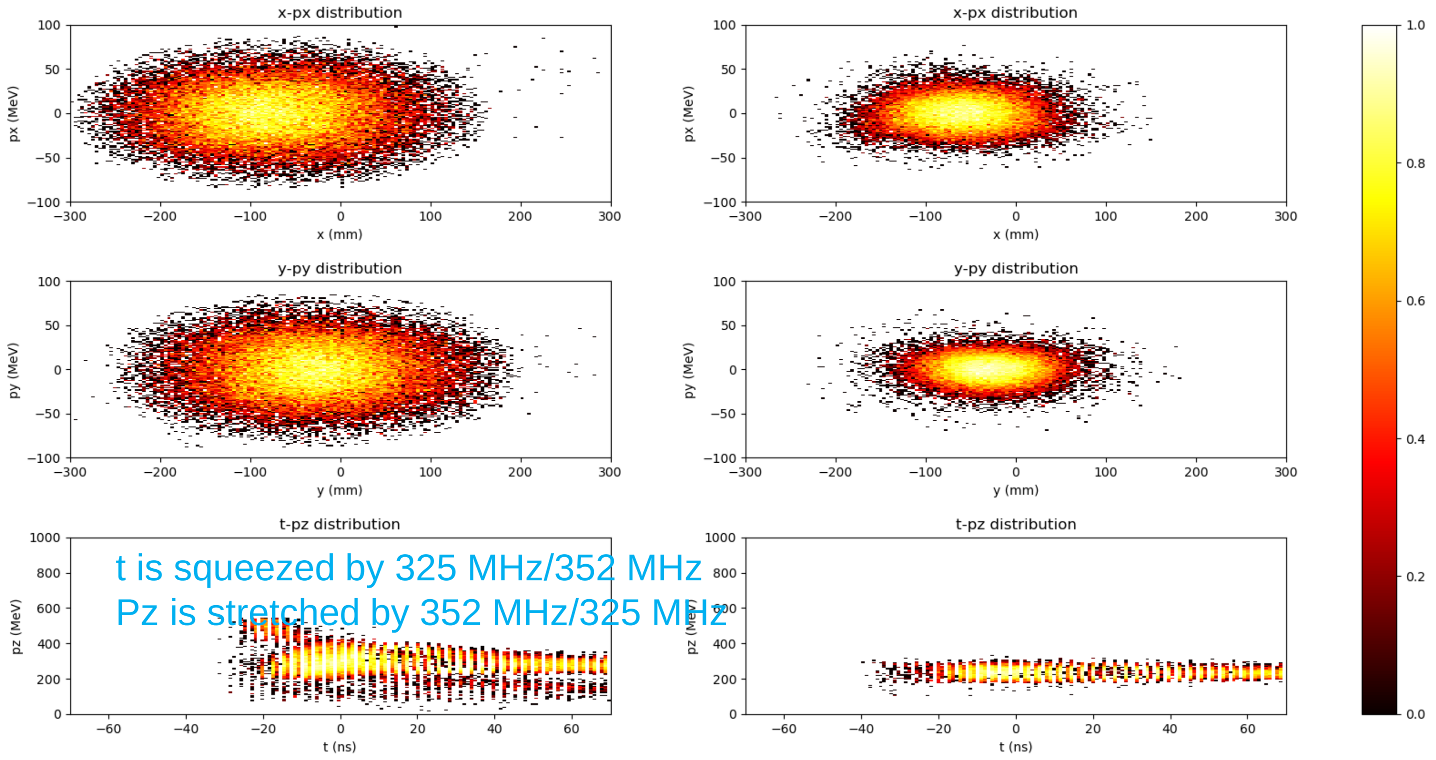


Cooling Stage 1 (before bunch merge)

Emittance reduction



Start End



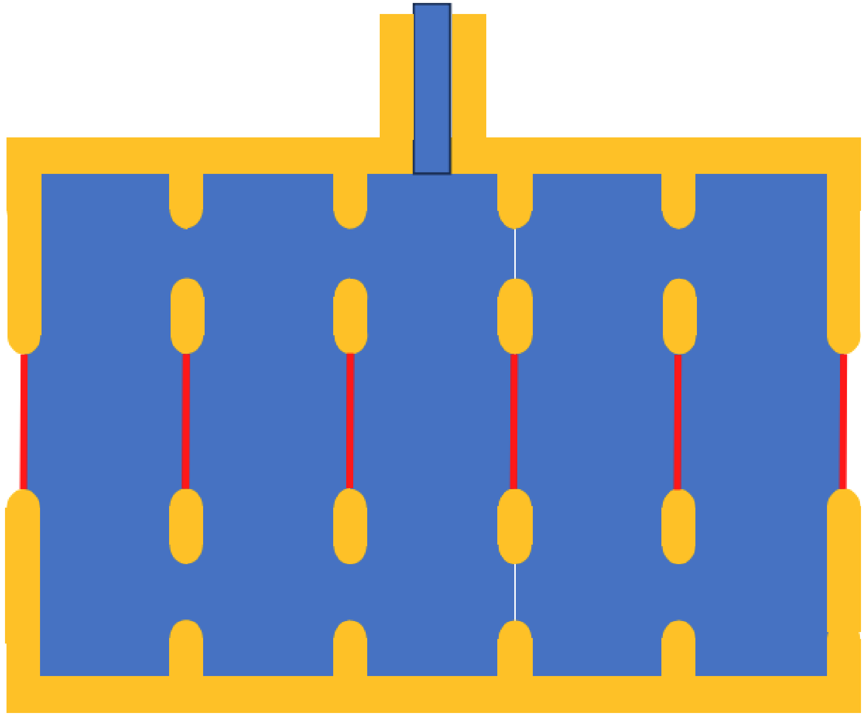
- Normalized transverse emittance: 17.1 to 6.49 mm
- Normalized longitudinal emittance: 45.7 to 13.4 mm
- Stage length: 101 m
- Transmission (including decay): 71.5%

π-mode RF

Conclusion II (Baseline proposal)

From Alexej's talk at the Cooling Cell workshop, [20240118_Multicell RF cavities for muon cooling.pdf (cern.ch)]

- In case, beam window can be used. **Magnetic coupled standing wave structure** provide solution with the most compact waveguide network
- Only **one RF coupler** and cryo-module feed-through is necessary to feed all the RF cells
- Number of **beam windows** is reduced from 2*Ncells to Ncells+1
- There are two disadvantages:
  - Higher (x Ncells) RF power per coupler
  - Lower transit time factor: from 0.83 (Chris's design) to 0.7 (pi-mode)
- …



352 MHz RF cavity length (200MeV): 19 cm (current) and 36.2 cm (π mode)
Will this affect the cooling performance a lot? Need to check!

Next Steps

- Continue the design for other stages (2, 3 and 4, even 5) before the bunch merge.
- Use the Maxwellian dipole fringe field in the cooling channel after the bunch merge and do the cooling simulations again.
- Try to use the lithium hydride wedge for the later stages. Try to use the π-mode RF cavities. Try to make the simulation design as realistic as possible.