中国科学院大学
University of Chinese Academy of Sciences

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Update on Rectilinear Cooling Channel Work at IMP

Zhu Ruihu(朱瑞虎)
Institute of Modern Physics, Chinese Academy of Sciences
University of Chinese Academy of Sciences

Muon Cooling Working Group Meeting, 2023.02.23

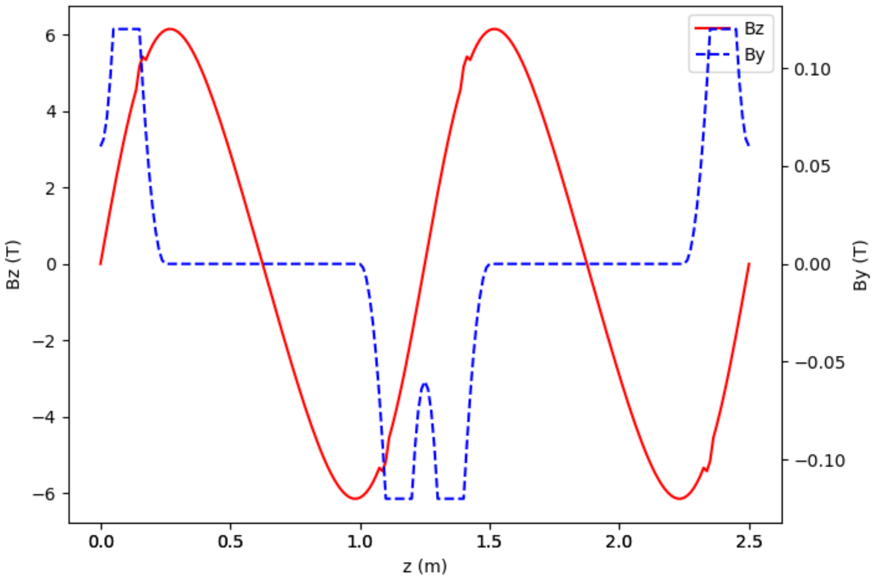
Outline

- Cooling performance with fringe field of dipole
- Cooling performance with window of wedge and RF cavity
- General Lorentz transformation expression for space charge effect module in G4Beamline

Fringe field of dipole

- Use quadratic function for fringe field

```
fieldexpr fringe_left1 length=2*$fringe_length width=1000 height=1000 By=if(z<0,0,$dipole/($fringe_length)^2*z^2)
fieldexpr fringe_right1 length=2*$fringe_length width=1000 height=1000 By=if(z>=0,0,$dipole/($fringe_length)^2*z^2)
fieldexpr fringe_left2 length=2*$fringe_length width=1000 height=1000 By=if(z<0,0,-$dipole/($fringe_length)^2*z^2)
fieldexpr fringe_right2 length=2*$fringe_length width=1000 height=1000 By=if(z>=0,0,-$dipole/($fringe_length)^2*z^2)
```



field of stage1

- Should use Enge function:

$$s = fringeFactor * \frac{(z - z_{edge})}{aperture}$$

$$if(s < -4)\ Enge(s) = 1$$

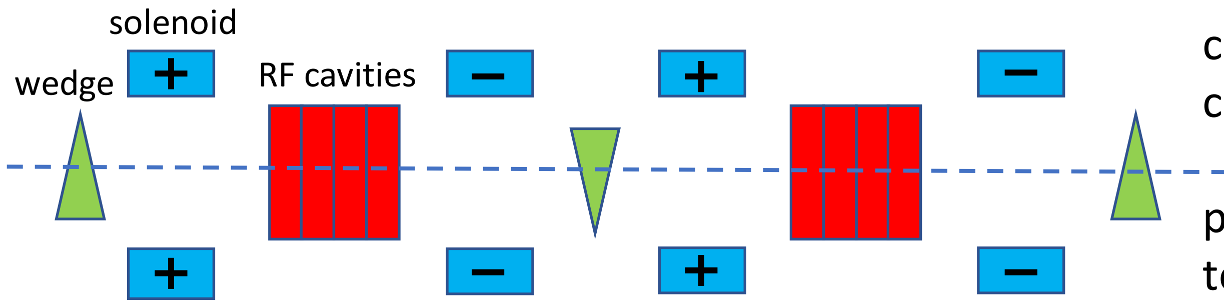
$$if(s > 4)\ Enge(s) = 0$$

$$Enge(s) = 1/(1 + \exp(a_1 + a_2 s + a_3 s^2 + a_4 s^3 + a_5 s^4 + a_6 s^5))$$

- However, the default values for a1~a6 in G4Beamline cause very small off-z-axis By field.

(Maybe it's because the default values are for the long dipole (1m~2m), but the dipole in my simulation is only 10 cm long with half-height of 50 cm)

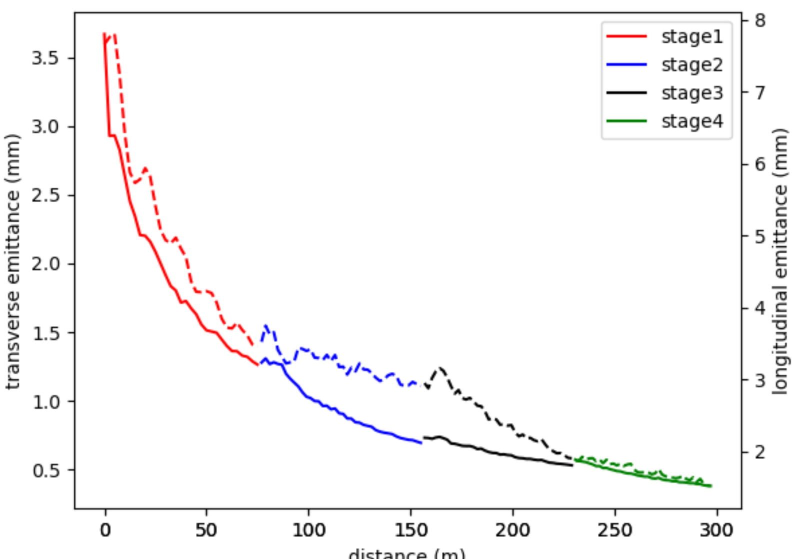
Cooling lattice with fringe field (no window)



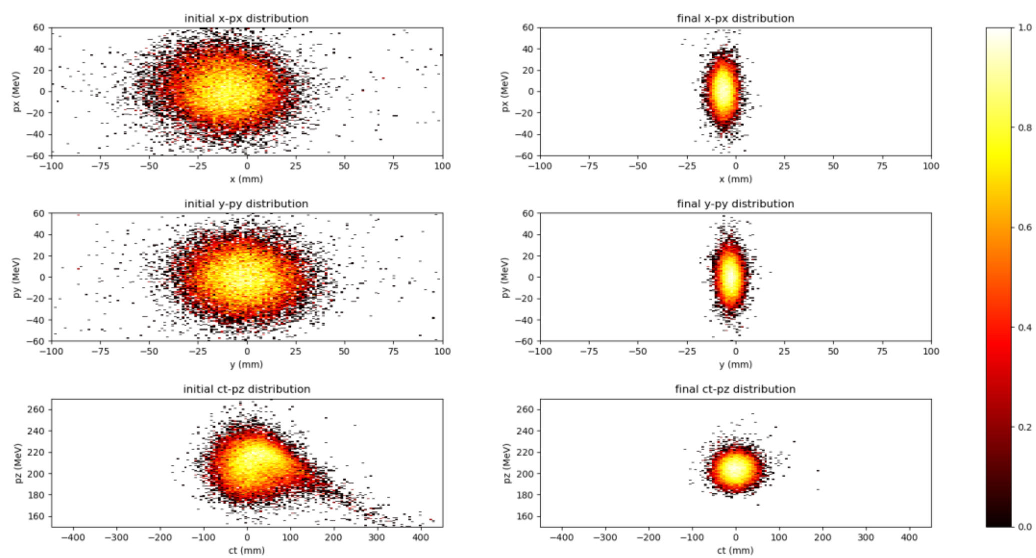
closely follow Chris's cooling cell structure

place dipole in wedge region to create dispersion

cooling performance(4 stages)



initial and final particles distribution



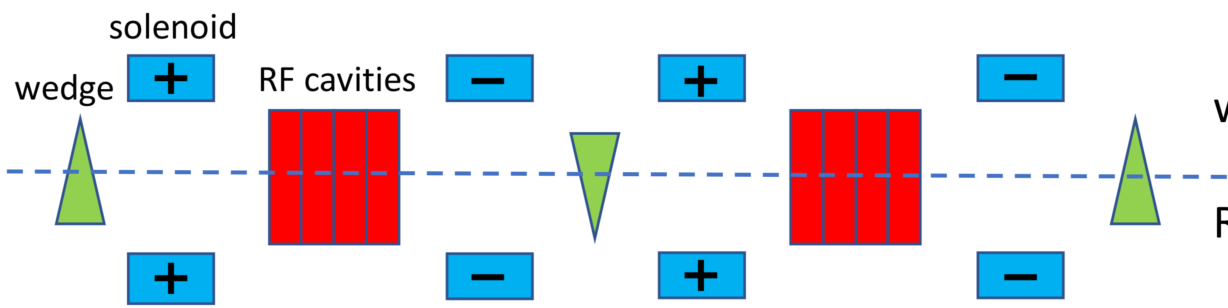
- transverse emittance: 3.67 mm to 0.38 mm
- longitudinal emittance: 7.67 mm to 1.52 mm
- 6D emittance: 105 mm^3 to 0.223 mm^3
- transmission(including decay): 80.8%(stage1) 92%(stage2) 88.5%(stage3) 91.3%(stage4) 60%(overall)

Cooling lattice with fringe field (no window)

	Stage 1	Stage 2	Stage 3	Stage 4
cell length	2.5 m	2 m	1.85 m	1.7 m
$B_{z,max}$	6.3 T	7.5 T	9.3 T	11.2 T
β	18 cm	12 cm	8 cm	5 cm
momentum acceptance	160~240 MeV	170~230 MeV	170~230 MeV	170~230 MeV
B_y	0.12 T	0.14 T	0.2 T	0.2 T
dispersion	-6 cm	-5 cm	-4 cm	-2.5 cm
wedge length	20 cm	14cm	12 cm	10 cm
wedge angle	67°	57°	100°	110°
RF frequency	675 MHz	675 MHz	675 MHz	675 MHz
RF #	4	4	4	4
RF length	15.8 cm	13.1 cm	14.3 cm	10.3 cm
RF gradient	31.45 MV/m	26.47 MV/m	24.62 MV/m	23.36 MV/m

Carefully designed so that RF gradient decreases as Bz increases.

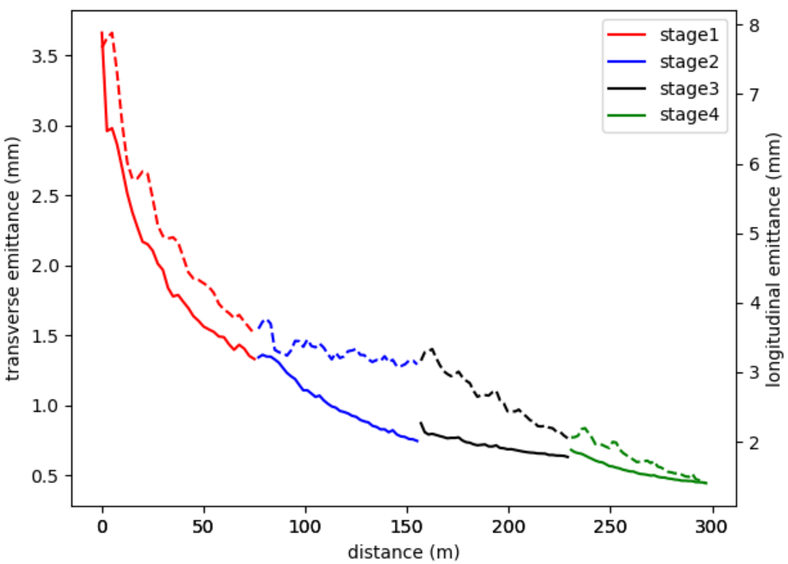
Cooling lattice with fringe field (with window)



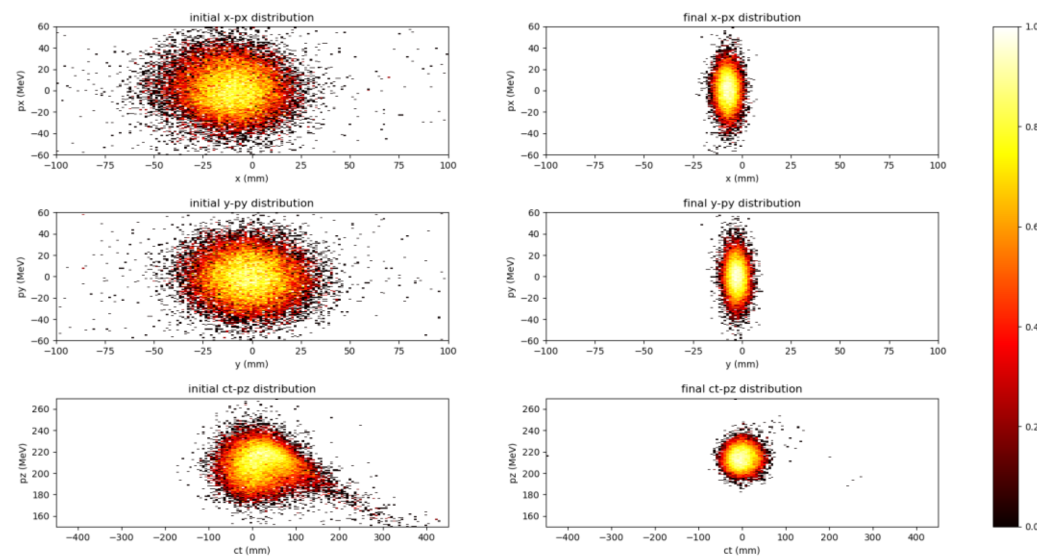
wedge window: Be, 100µm

RF cavity window: Be, 50µm

cooling performance(4 stages)



initial and final particles distribution



- transverse emittance: 3.67 mm to 0.45 mm
- longitudinal emittance: 7.67 mm to 1.41 mm
- 6D emittance: 105 mm^3 to 0.293 mm^3
- transmission(including decay): 79.6%(stage1) 90.3%(stage2) 87%(stage3) 90.8%(stage4) 56.8%(overall)

Cooling lattice with fringe field (with window)

	Stage 1	Stage 2	Stage 3	Stage 4
cell length	2.5 m	2 m	1.85 m	1.7 m
$B_{z,max}$	6.3 T	7.5 T	9.3 T	11.2 T
β	18 cm	12 cm	8 cm	5 cm
momentum acceptance	160~240 MeV	170~230 MeV	170~230 MeV	170~230 MeV
B_y	0.12 T	0.14 T	0.2 T	0.2 T
dispersion	-6 cm	-5 cm	-4 cm	-2.5 cm
wedge length	20 cm	14 cm	12.5 cm	10 cm
wedge angle	67°	67°	103°	110°
RF frequency	675 MHz	675 MHz	675 MHz	675 MHz
RF #	4	4	4	4
RF length	17.8 cm	12.7 cm	14.5 cm	10.5 cm
RF gradient	30.2 MV/m	27.5 MV/m	24.2 MV/m	23.8 MV/m

Carefully designed so that RF gradient decreases as Bz increases.

Space charge modeling in G4Beamline

- General expression for Lorentz transformation of electromagnetic field

$$\mathbf{E}' = \gamma \mathbf{E} - \frac{\gamma^2}{c^2(\gamma+1)}(\mathbf{E}\cdot\boldsymbol{v})\boldsymbol{v} + \gamma(\boldsymbol{v}\times\mathbf{B})$$

$$\mathbf{B}' = \gamma \mathbf{B} - \frac{\gamma^2}{c^2(\gamma+1)}(\mathbf{B}\cdot\boldsymbol{v})\boldsymbol{v} - \frac{\gamma}{c^2}(\boldsymbol{v}\times\mathbf{E})$$

Shown in ''Introduction to Electrodynamics'' by David J.Griffiths, 3rd Edition 1999

- I will implement this formula in G4Beamline and see if space charge has huge effects on beam cooling process.

Conclusion and Plan

- Successfully cool the matched beam in a 4-stage channel with transmission of 60% without windows and 57% with windows. Be windows have very limited effects on beam cooling results.

(without windows: transverse: 3.67 mm to 0.38 mm, longitudinal: 7.67 mm to 1.52 mm
with windows: transverse: 3.67 mm to 0.45 mm, longitudinal: 7.67 mm to 1.41 mm)

- Modify the current space charge module and add wakefield module in G4Beamline source code to model collective effects in cooling process.

Thanks for your attention!
Any comment or suggestion is welcome!