Rectilinear Cooling Study at IMP

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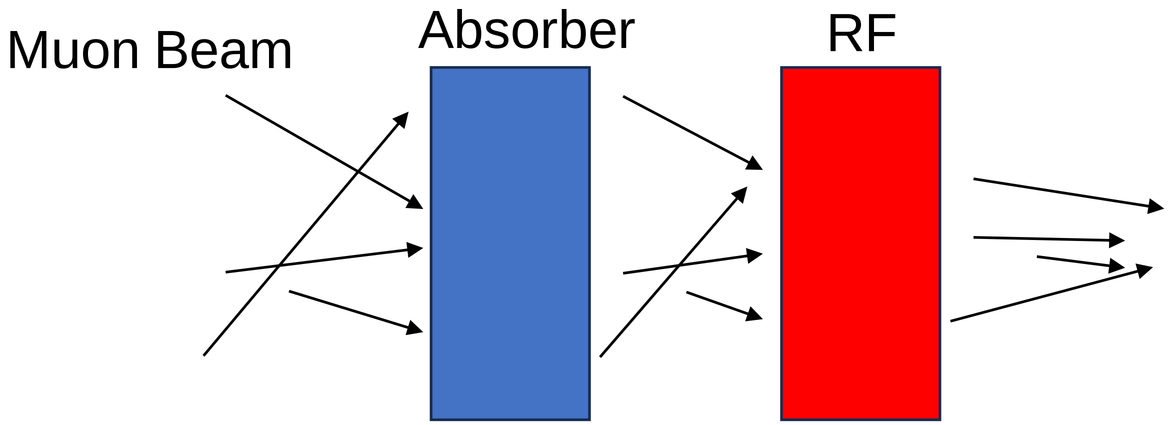
Thanks to Chris Rogers, Scott Berg & Elena Fol.

Outline

- Reminder of ionization cooling concept
- New simulation results on 6D rectilinear cooling
- Simulation results on high-pressure H_2 gas filled rectilinear channel
- Another possible lattice with large angular dispersion

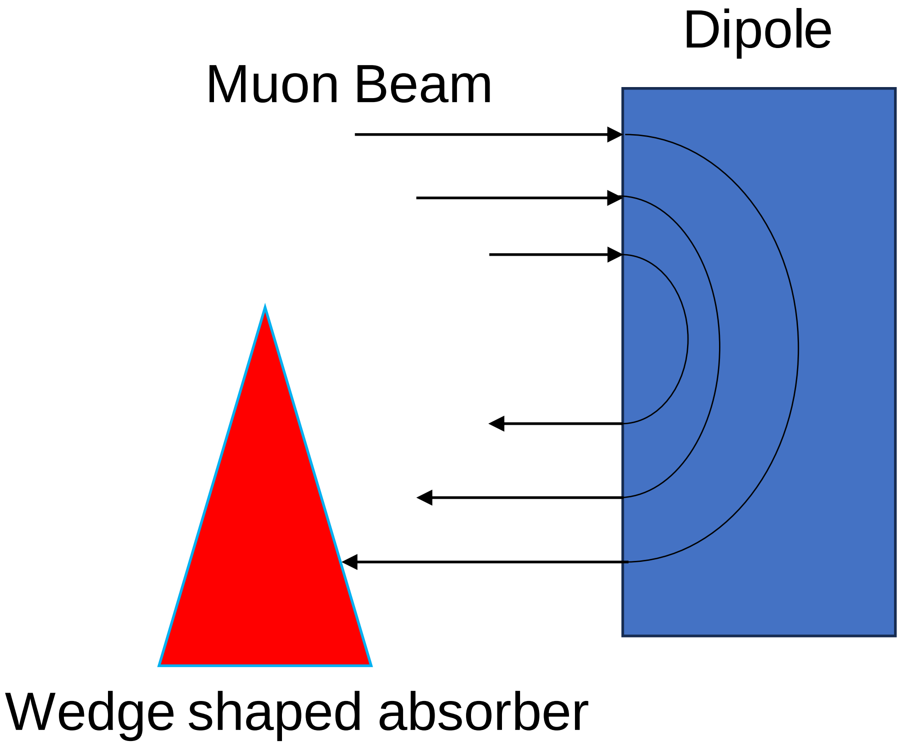
Reminder of 4D Ionization Cooling



- 4D cooling process:
  - Muon beam loses momentum in all directions at absorber
  - Muons beam gets momentum compensation only in longitudinal direction
  - Muons beam is more parallel

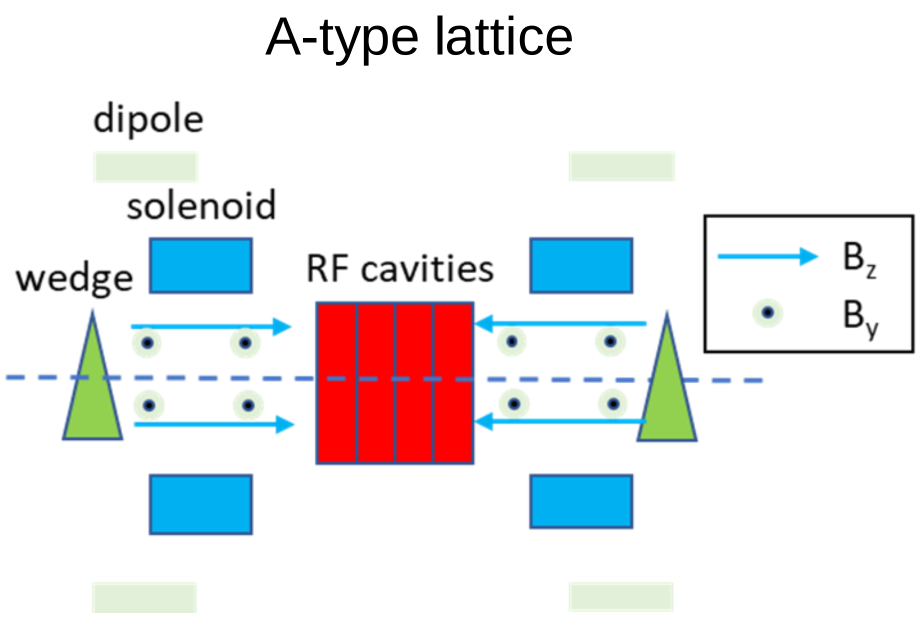
- Random multiple scattering in absorber decreases cooling effect:
  - Mitigate with strong focusing
  - Mitigate with absorber material of low-Z

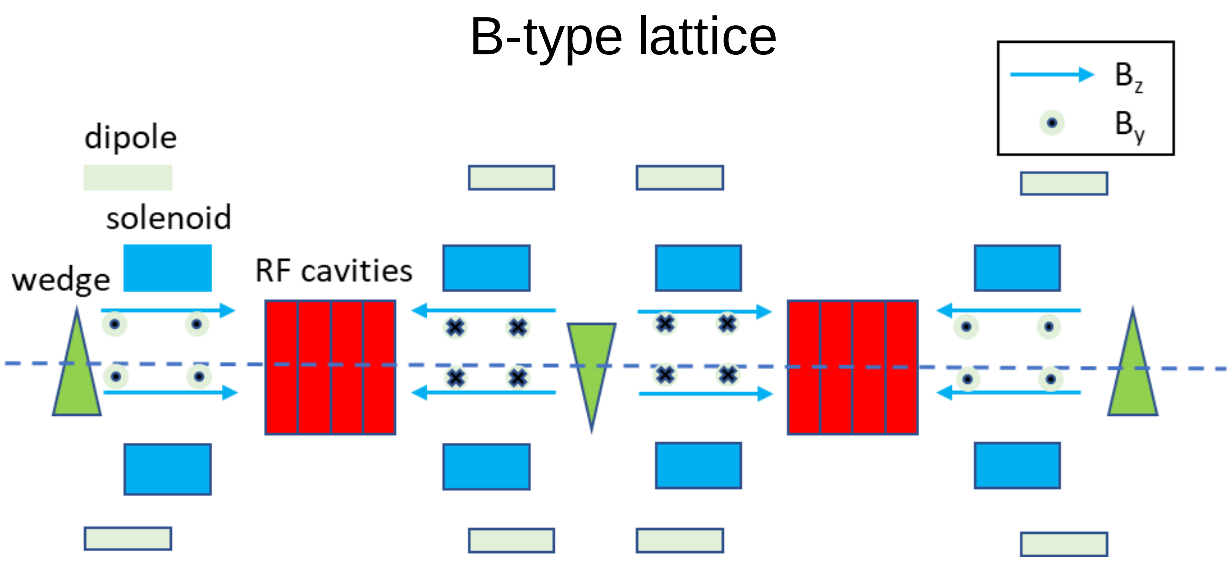
Reminder of 6D Ionization Cooling



- Dipole is used to spread the beam transversely so that particles with higher momentum are on the outer side.
- Longitudinal emittance reduces because particles with higher momentum go through thicker part of the absorber and lose more energy.
- Trade-off between longitudinal cooling and transverse heating.

Rectilinear Cooling Lattice

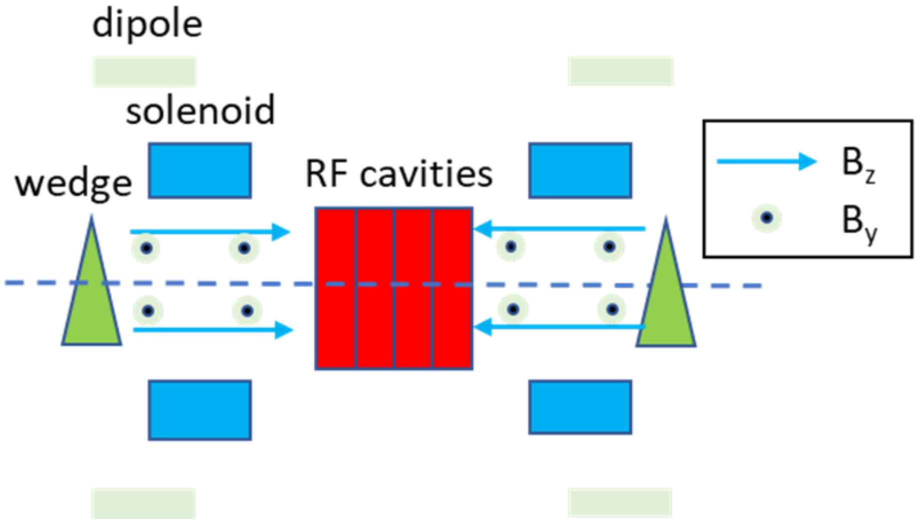




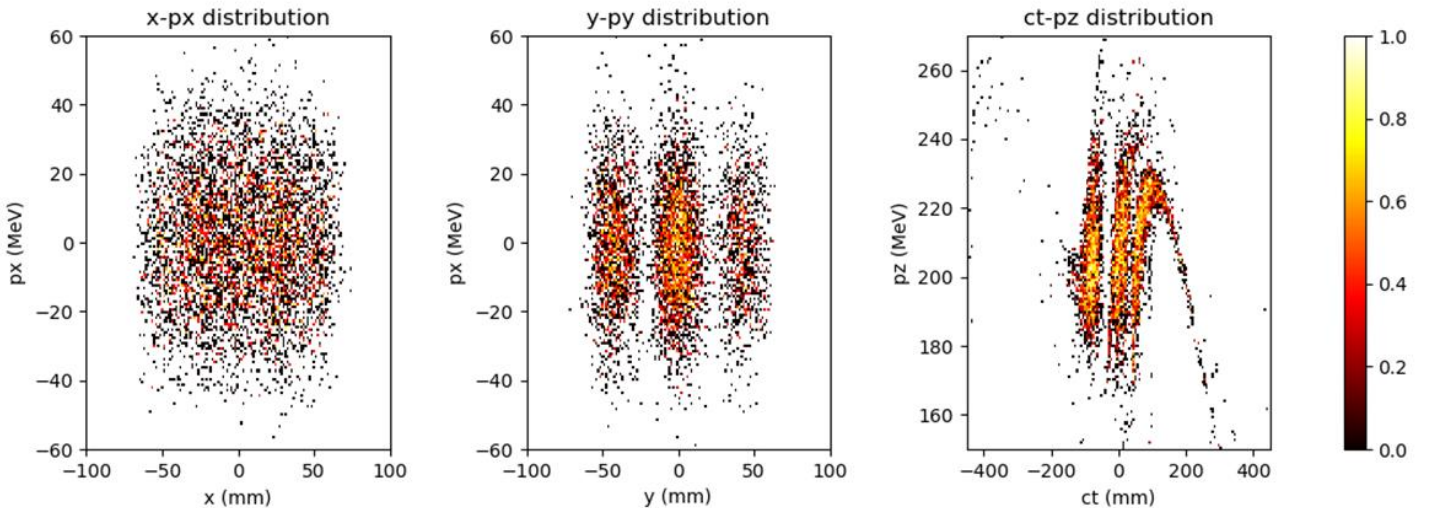
The whole channel is put in a straight line. The solenoid field focuses muons tightly in the wedge absorber. The dipole field provides dispersion for longitudinal cooling. The aim is to reduce the transverse and longitudinal emittance simultaneously.

New Simulation Results Using A-type Lattice

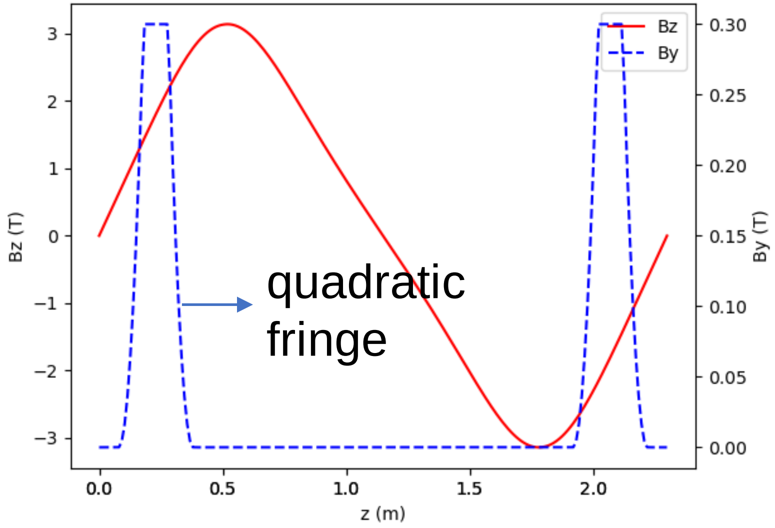
A-type lattice



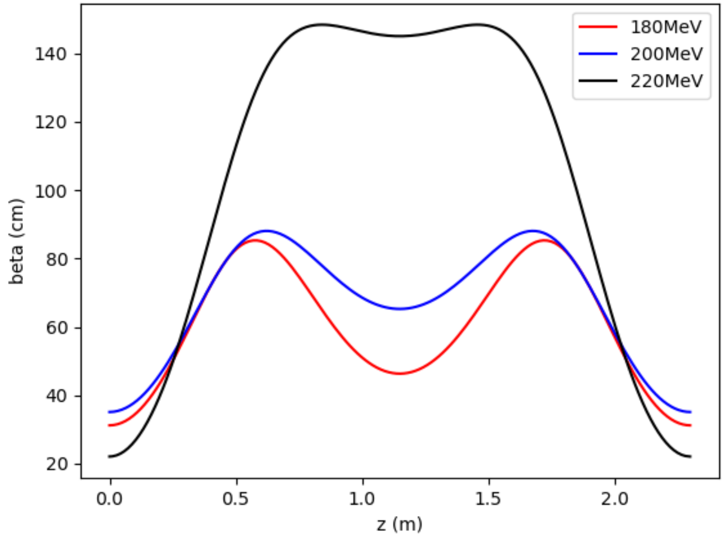
Input beam (after bunch merging)



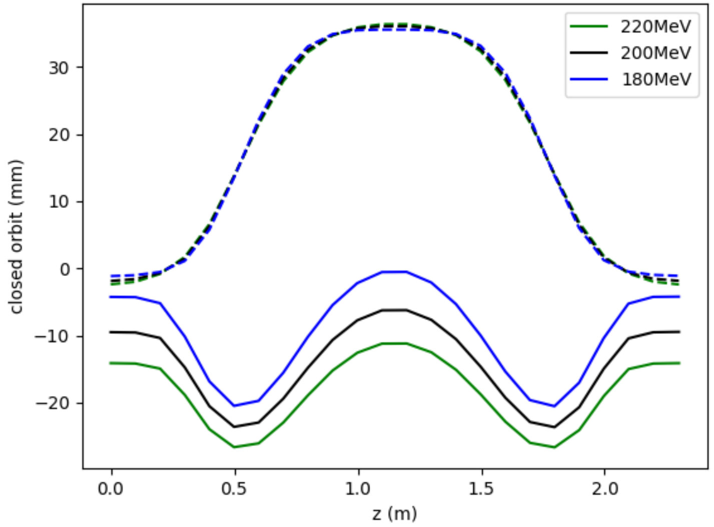
On-axis field(stage1)



Beta value(stage1)



Closed orbit(stage1)

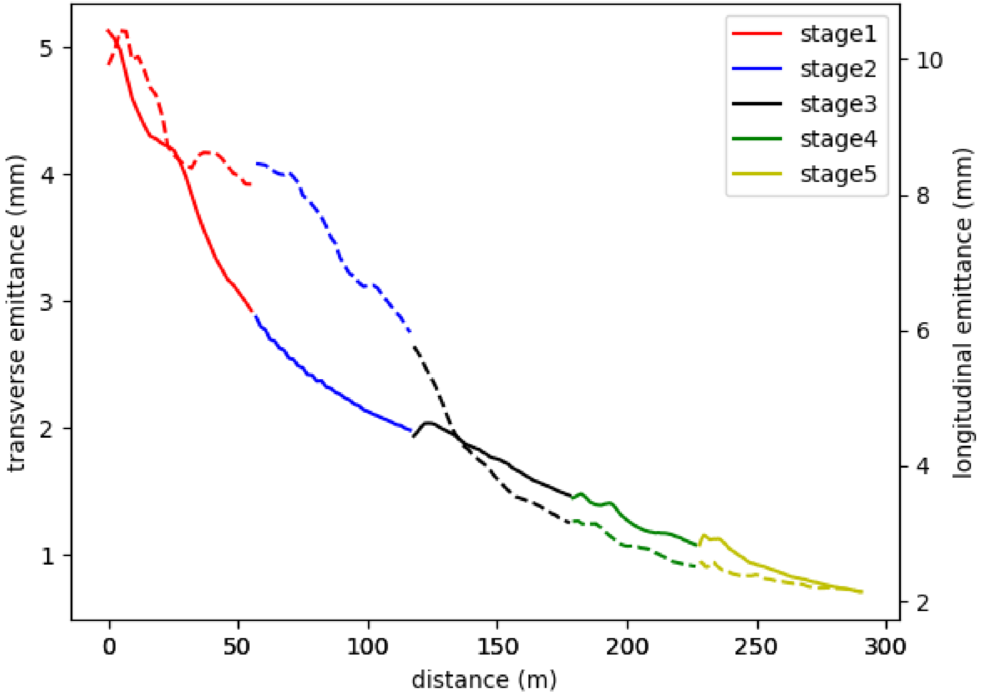


New Simulation Results Using A-type Lattice

	Stage 1	Stage 2	Stage 3	Stage 4	Stage5
cell length	2.3 m	1.8 m	1.4 m	1.1 m	0.8 m
$B_{z,max}$	3.1 T	4.1 T	4.8 T	6.2 T	8.8 T
β	35 cm	30 cm	20 cm	15 cm	10 cm
B_y	0.3 T	0.375 T	0.425 T	0.45 T	0.35 T
dispersion	5 cm	5 cm	4.5 cm	2.5 cm	1.8 cm
wedge material	liquid hydrogen				
wedge length	37 cm	32 cm	24 cm	20 cm	12 cm
wedge angle	110°	120°	115°	110°	120°
RF frequency	325 MHz				650 MHz
RF #	6			4	
RF length	22 cm	17.7 cm	12 cm	14.6 cm	11.6 cm
RF gradient	22 MV/m	21.4 MV/m	24.3 MV/m	22.9 MV/m	21.1 MV/m

New Simulation Results Using A-type Lattice

Performance of cooling channel



	$\varepsilon_{\perp}$(mm)	$\varepsilon_{\parallel}$(mm)	ε_{6D}(mm^3)	Tr(%)
initial	5.13	9.91	260	
Stage 1	2.92	8.16	71.6	87.1
Stage 2	1.99	5.97	24	91.2
Stage 3	1.47	3.16	7.12	88
Stage 4	1.08	2.52	3.11	92.2
Stage 5	0.712	2.14	1.14	89.2

Stage	$\varepsilon_T^{\rm sim}$ [mm]	$\varepsilon_L^{\rm sim}$ [mm]	$P_z^{\rm sim}$ [MeV/c]	T [%]
Begin	17.00	46.00	255	
A1	6.28	14.48	238	70.6
A2	3.40	4.64	229	87.5
A3	2.07	2.60	220	88.8
A4	1.48	2.35	215	94.6
Begin	5.10	10.04	209	
B1	3.76	7.76	210	89.7
B2	2.40	6.10	208	90.6
B3	1.55	4.28	207	89.2
B4	1.10	3.40	207	89.7
B5	0.68	2.97	204	87.5
B6	0.50	2.16	202	88.0
B7	0.38	1.93	200	89.6
B8	0.28	1.57	200	89.0

To reach the same 6D emittance(1.14 mm^3), distance is reduced by ~60 m and transmission is increased by ~5% compared with the result of Stratakis lattice.

D. Stratakis and R. B. Palmer, Rectilinear six-dimensional ionization cooling channel for a muon collider: A theoretical and numerical study, Phys. Rev. ST Accel. Beams 18 (2015)

RF Breakdown Issue

➢ Limitation on RF gradient

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 072001 (2005)

Effects of high solenoidal magnetic fields on rf accelerating cavities

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(Received 18 April 2005; published 6 July 2005; corrected 7 September 2005)

We have measured the effects of high (0–4.5 T) magnetic fields on the operating conditions of 805 MHz accelerating cavities, and discovered that the maximum accelerating gradient drops as a function of the axial magnetic field. While the maximum gradient of any cavity is governed by a number of factors including conditioning, surface topology and materials, we argue that $\mathbf{J} \times \mathbf{B}$ forces within the emitters are the mechanism for enhanced breakdown in magnetic fields. The pattern of emitters changes over time and we show an example of a bright emitter which disappears during a breakdown event. We also present unique measurements of the distribution of enhancement factors, β, of secondary emitters produced in breakdown events during conditioning. We believe these secondary emitters can also be breakdown triggers, and the secondary emitter spectrum helps to determine the maximum operating field.

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Measurements at the Mucool Test Area (MTA) of Fermilab have shown that the achievable accelerating gradients for an 805 MHz vacuum pillbox cavity decreased from 40–60 MV/m to less than 20 MV/m in a 3 T solenoidal field.

➢ Solution on RF breakdown

PRL **111,** 184802 (2013) PHYSICAL REVIEW LETTERS week ending 1 NOVEMBER 2013

Pressurized H_2 rf Cavities in Ionizing Beams and Magnetic Fields

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(Received 12 July 2013; published 29 October 2013)

A major technological challenge in building a muon cooling channel is operating rf cavities in multitesla external magnetic fields. We report the first proof-of-principle experiment of a high pressure gas-filled rf cavity for use with intense ionizing beams and strong external magnetic fields. rf power consumption by beam-induced plasma is investigated with hydrogen and deuterium gases with pressures between 20 and 100 atm and peak rf gradients between 5 and 50 MV/m. The low pressure case agrees well with an analytical model based on electron and ion mobilities. Varying concentrations of oxygen gas are investigated to remove free electrons from the cavity and reduce the rf power consumption. Measurements of the electron attachment time to oxygen and rate of ion-ion recombination are also made. Additionally, we demonstrate the operation of the gas-filled rf cavity in a solenoidal field of up to 3 T, finding no major magnetic field dependence. All these results indicate that a high pressure gas-filled cavity is a viable technology for muon ionization cooling.

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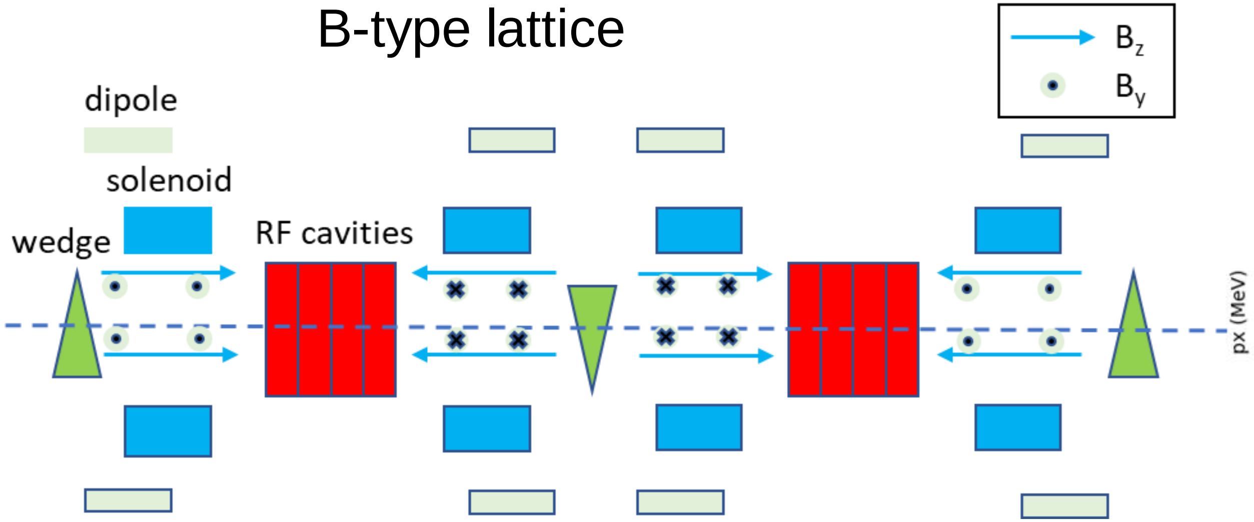
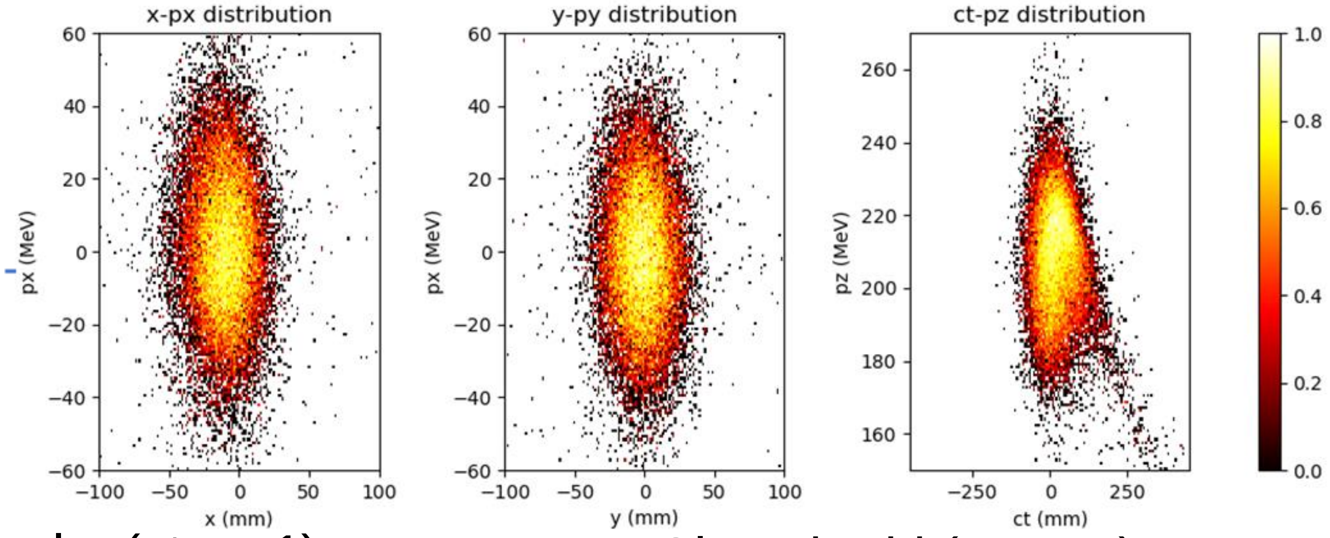
A breakdown gradient of 65.5MV/m could be achieved in a 3 T magnetic field with 70 atm hydrogen gas.

Simulation Results on High-pressure Channel

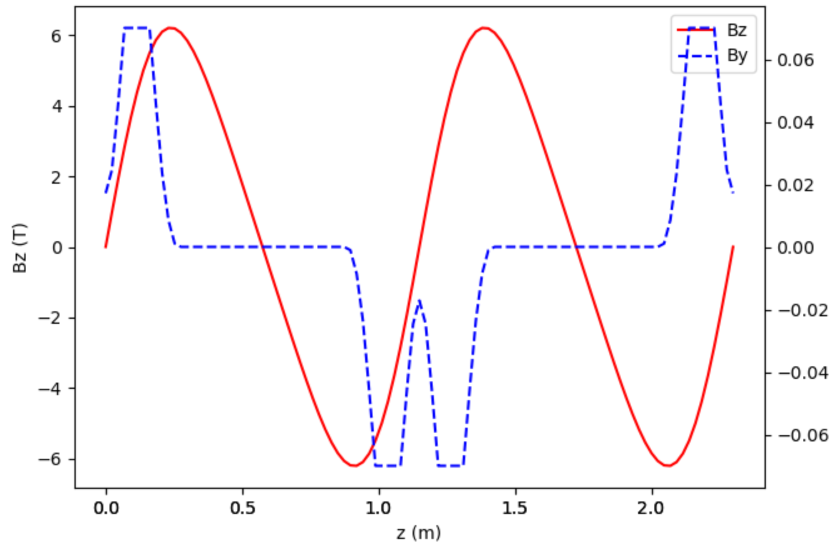
B-type lattice



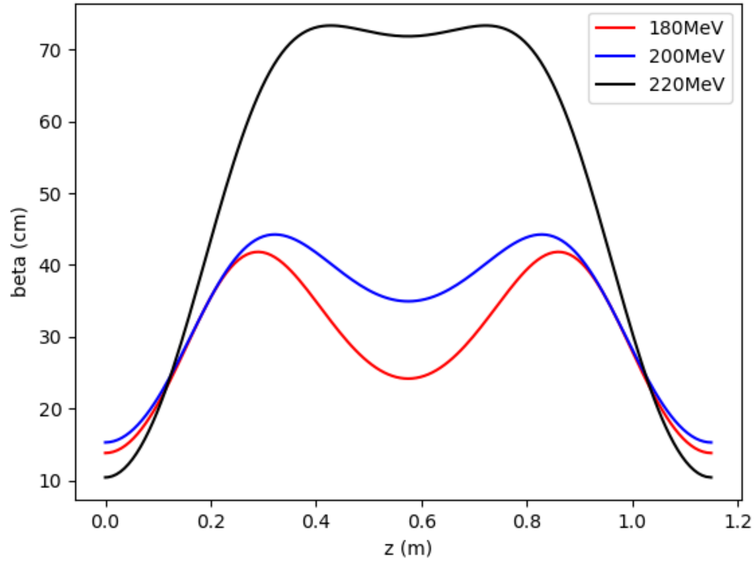
Input beam(correlated Gaussian distribution)



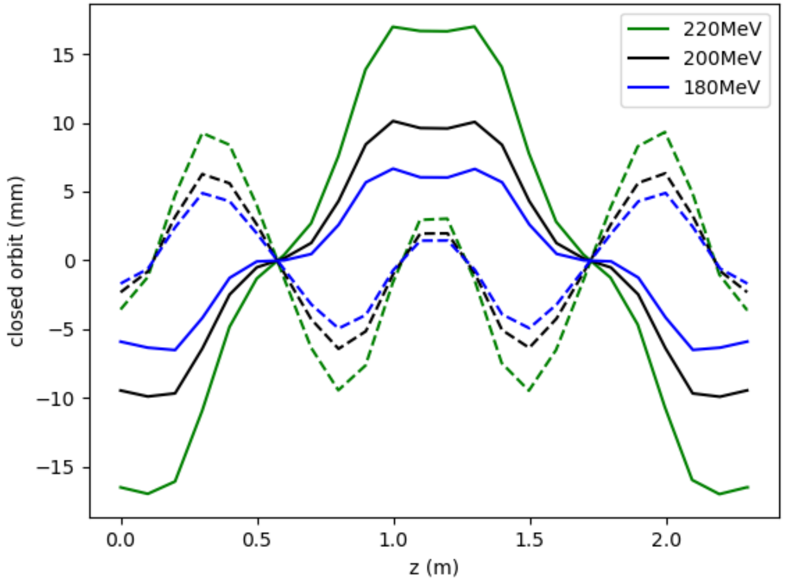
On-axis field(stage1)



Beta value(stage1)



Closed orbit(stage1)



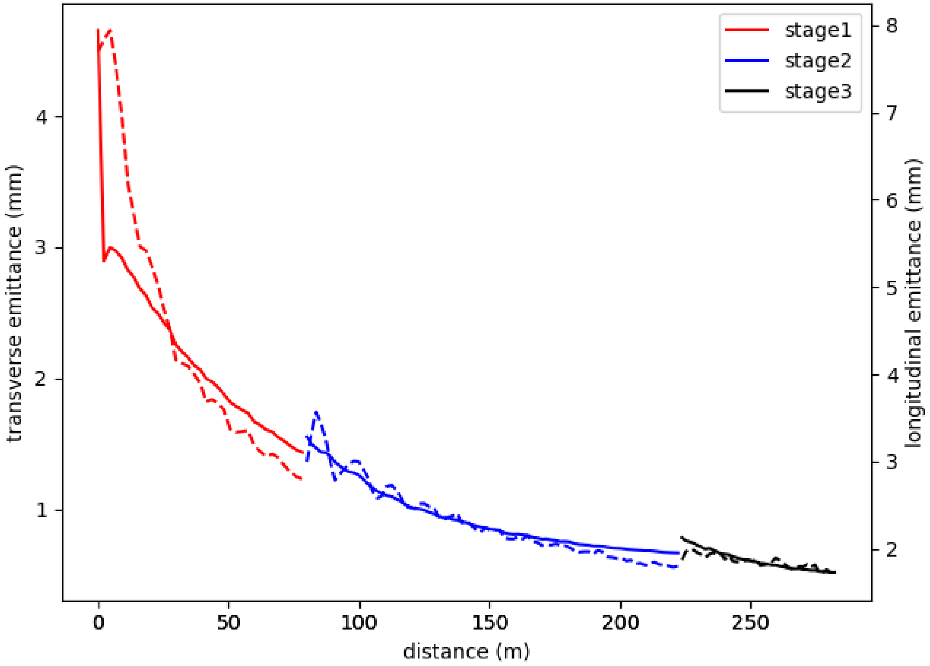
Simulation Results on High-pressure Channel

	Stage 1	Stage 2	Stage 3	Stage 4
pressure	35 atm			
cell length	2.3 m	1.8 m	1.5 m	1.5 m
$B_{z,max}$	6.2 T	8.8 T	12.1 T	13.1 T
β	16 cm	10 cm	5 cm	4 cm
B_y	0.07 T	0.12 T	0.2 T	0.18 T
dispersion	-4 cm	-3.5 cm	-2 cm	-1.3 cm
wedge material	liquid hydrogen			
wedge length	15 cm	11 cm	11 cm	9 cm
wedge angle	116°	100°	120°	120°
RF frequency	704 MHz			
RF #	4			
RF length	11.5 cm	12.8 cm	8.7 cm	8.5 cm
RF gradient	39.6 MV/m	30.6 MV/m	44.4 MV/m	34.2 MV/m

Simulation Results on High-pressure Channel

➢ Cooling performance (**Need optimization**!)

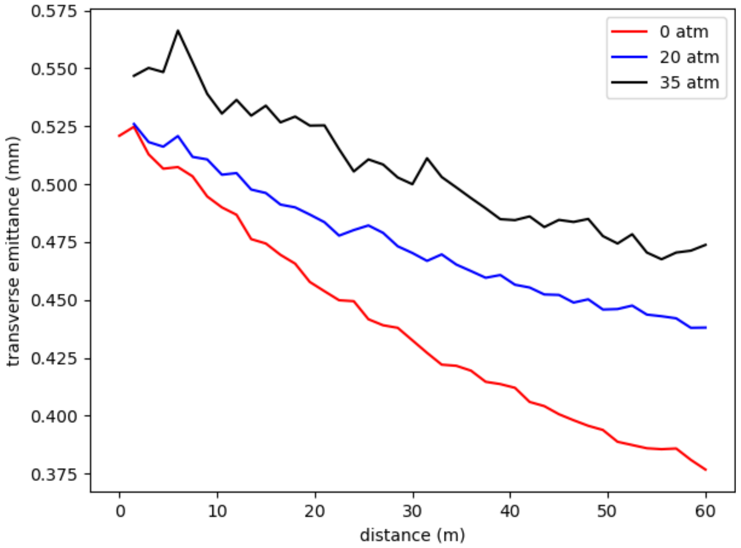
Stage 1 to Stage 3 (35 atm)

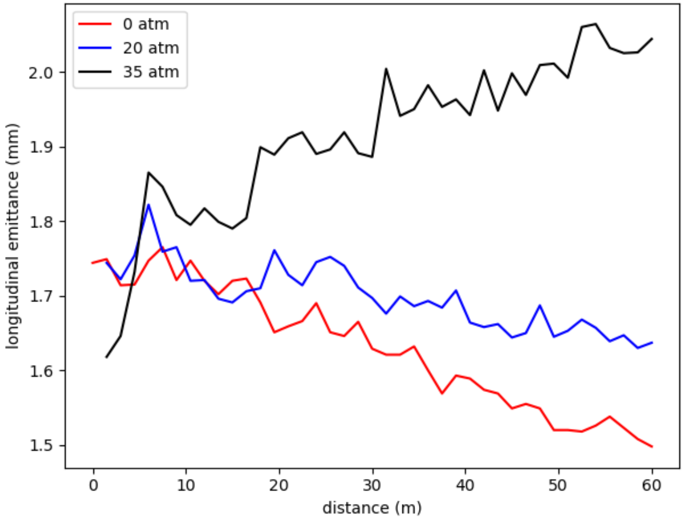


Transverse emittance: 4.65 to 0.52 mm
Longitudinal emittance: 7.7 to 1.74 mm

No significant difference from vacuum case.

Stage 4



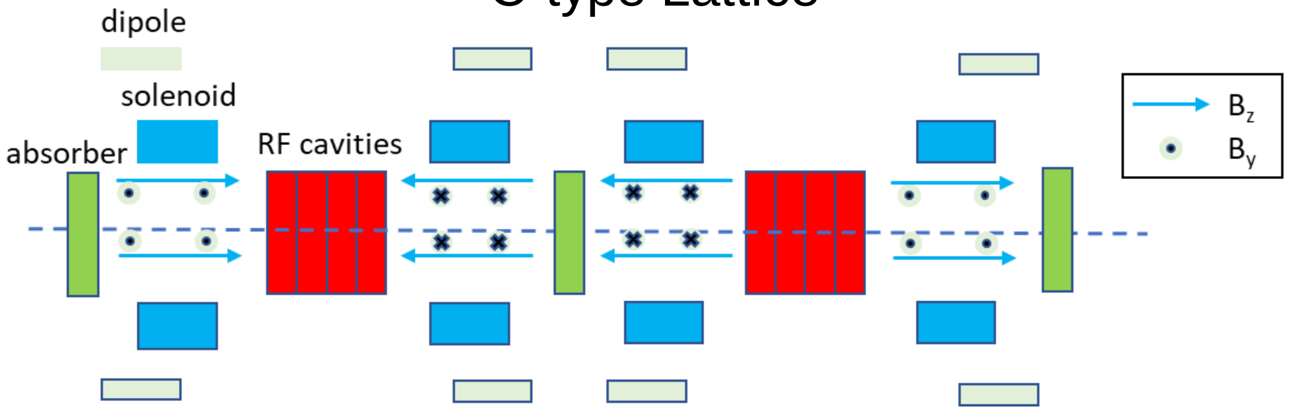


- 0 atm : Transverse emittance: 0.52 to 0.37 mm
  Longitudinal emittance: 1.74 to 1.5 mm
- 20 atm : Transverse emittance: 0.52 to 0.44 mm
  Longitudinal emittance: 1.74 to 1.6 mm
- 35 atm : Transverse emittance: 0.52 to 0.47 mm
  Longitudinal emittance: 1.74 to 2 mm

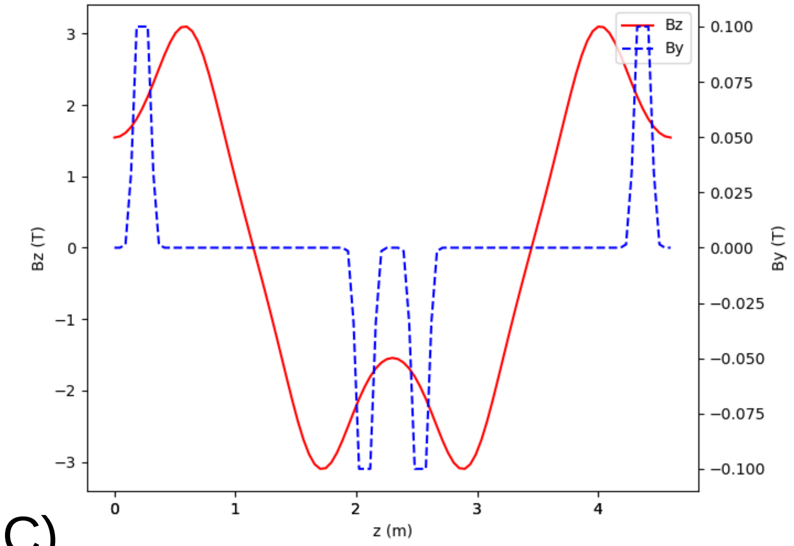
Significant difference from vacuum case.

Another Possible Lattice

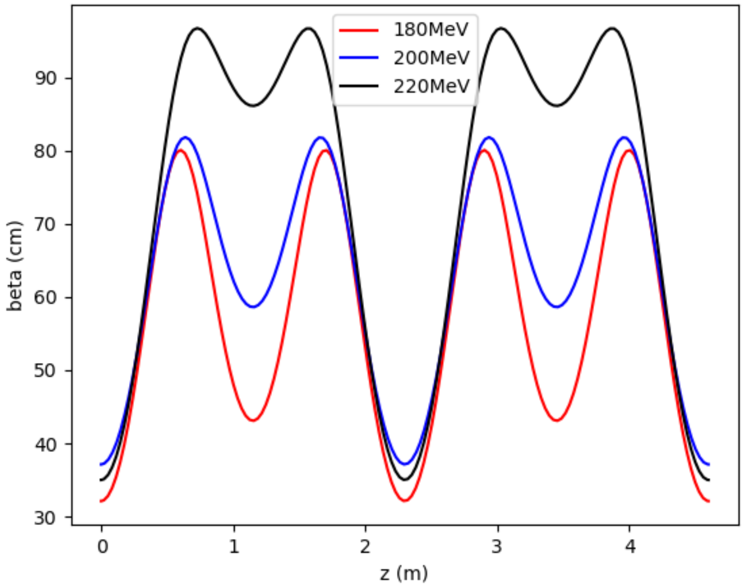
C-type Lattice



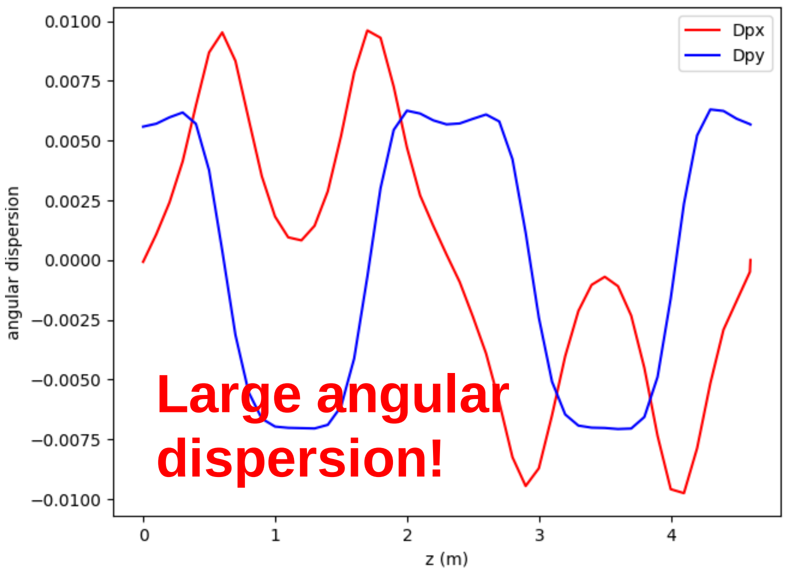
On-axis field



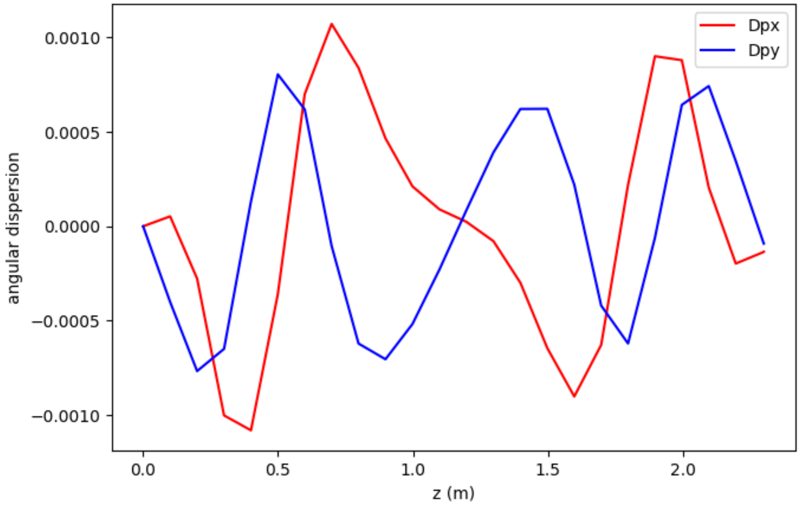
Beta value



Angular dispersion (Lattice C)

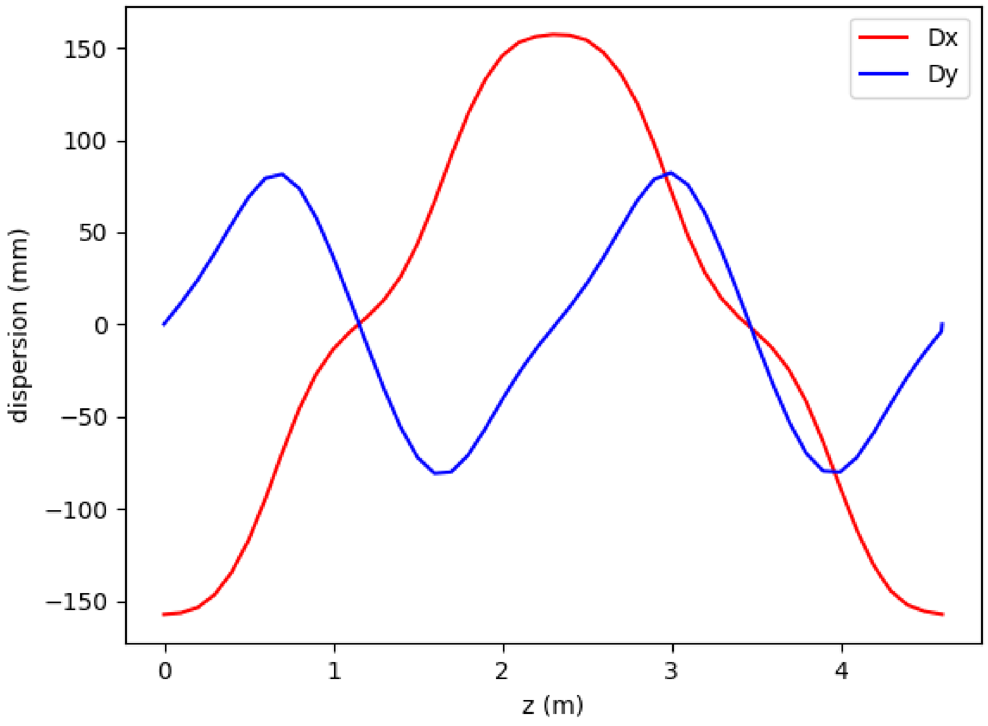


Angular dispersion (Lattice A)

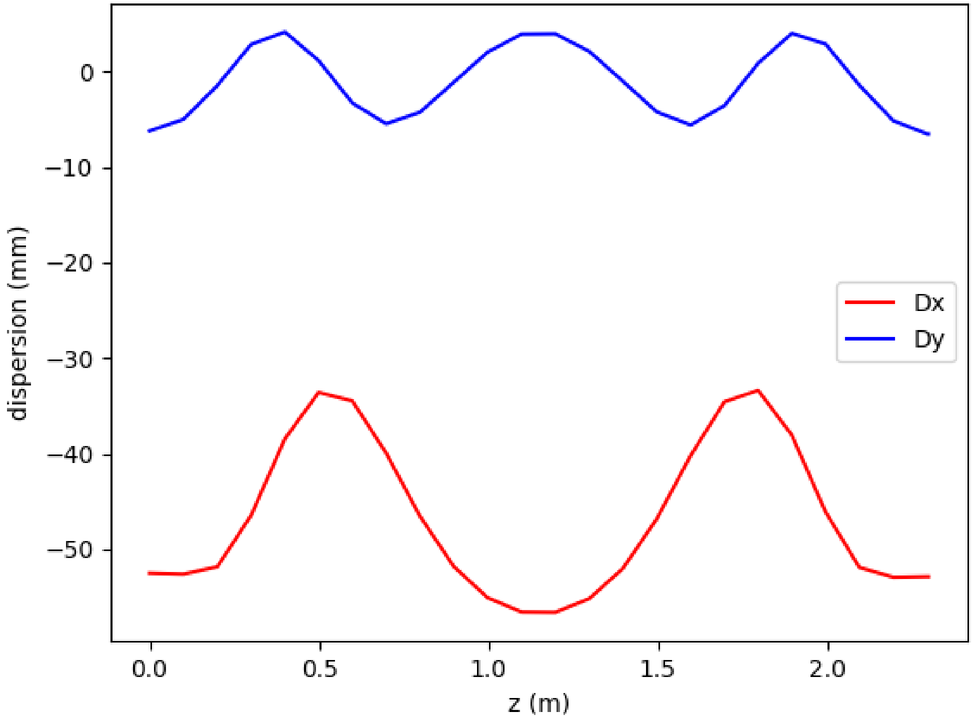


Another Possible Lattice

Dispersion (Lattice C)



Dispersion (Lattice A)



Lattice C also has large dispersion which may be bad for the transverse cooling and transmission. Need more simulation work!

Conclusions and Next Steps

➢Conclusions:

- New rectilinear lattice parameters have been found resulting in the reduction of the channel length.
- High-pressure hydrogen gas may have adverse effect on the cooling performance. (Preliminary result. Need more optimization!)

➢Next steps:

- Extend the cooling channel to more stages.
- Check the cooling performance of the lattice with high angular dispersion.
- Do simulation with collective effects in G4Beamline. (e.g., space charge and short-range wakefield)

Thanks for your attention.

Any comment or suggestion is welcome!