Design and simulation of matching section for 6D cooling channel

V. Balbekov, Fermilab

March 18, 2014

Introduction

6D cooling channel between charge separator and bunch merger is considered.

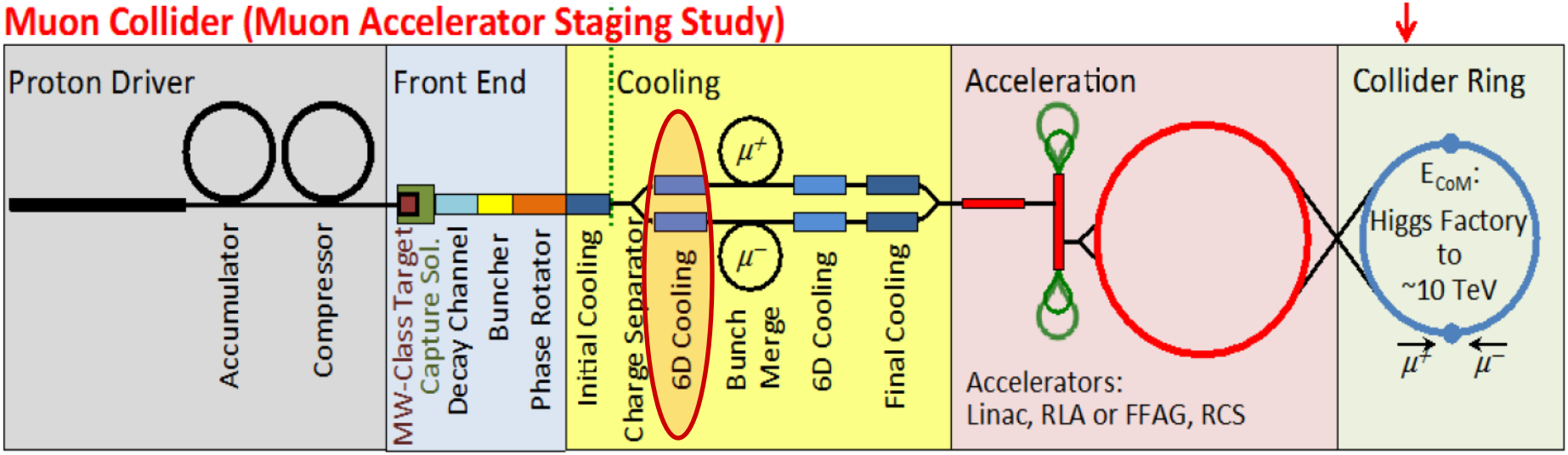


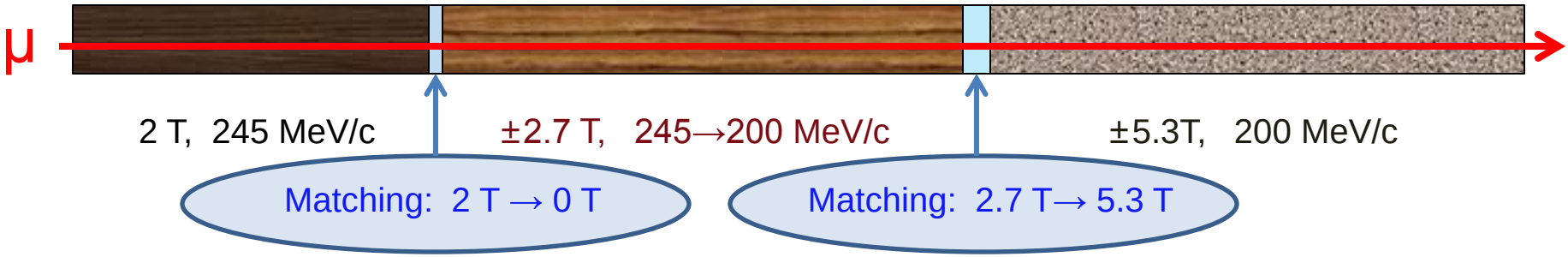
Figure 1. The muon collider overall block diagram.

- Source “Initial Baseline selection of 6D cooling scheme”
- Marked part is explored
- 21 bunch of one sign after phase rotator are taken as input for the cooler.
- The goal is to get the beam with transverse emittance < 2 mm and longitudinal emittance <5 mm/bunch.

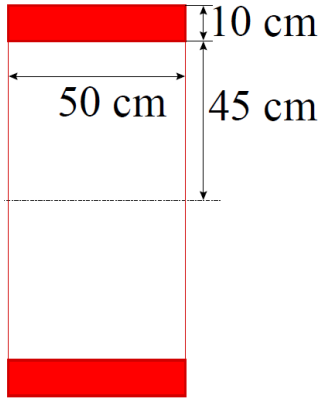
General view and properties

2 STAGES COOLER IS CONSIDERED (not at scale)

Rotator-separator 1st stage: 100 cells × 2 m 2nd cooler: 150 cells × 1.32 m



STANDARD COILS ARE APPLIED THROUGHOUT



Length 50 cm

Inner radius 45 cm

Thickness 10 cm

Different current

STANDARD RF:

325 MHz / 21.6 MV/m

Cavity length 24 cm

Groups: 2 or 3 cavities

LH_2 ABSORBERS ?

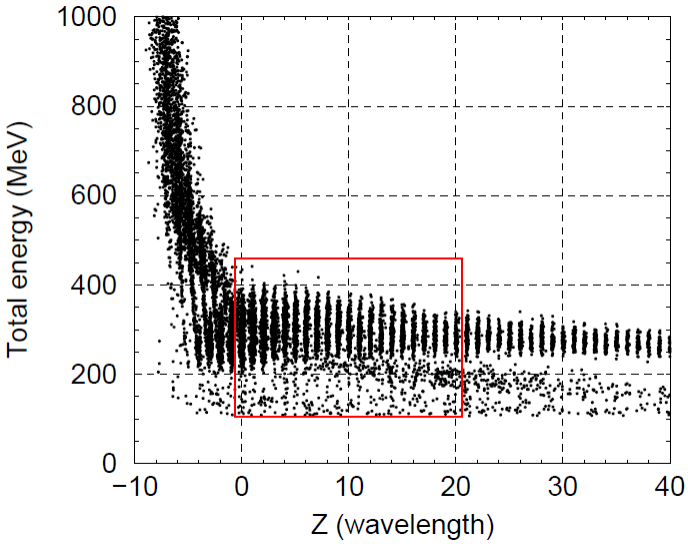
Rotator beam, longitudinal distribution

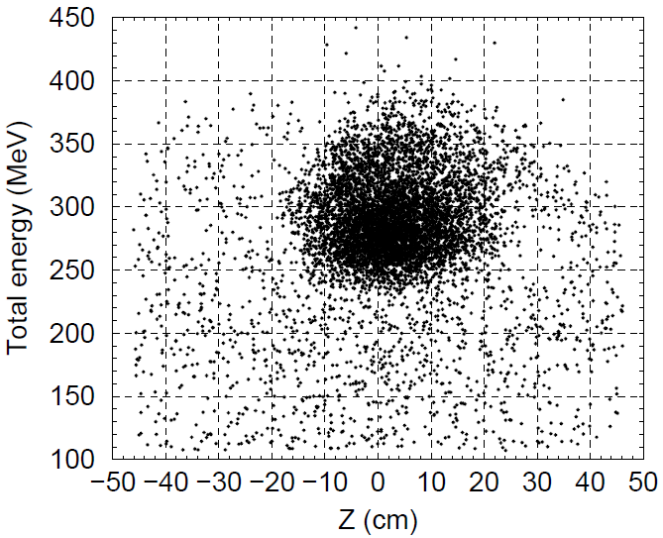
Output rotator beam consists of ~ 100 bunches and has huge energy spread.

However, only 21 bunches are assumed to be used in next stages: merge, acceleration, etc.

They are marked by red and shown separately in the left plot, and gathered in one superbunch in the right plot

Emittance of this super-bunch is about 4 cm.





It is seen that a lot of the particles are actually located out of stability region (e.g. E<200 MeV) so they cannot be captured for the cooling.

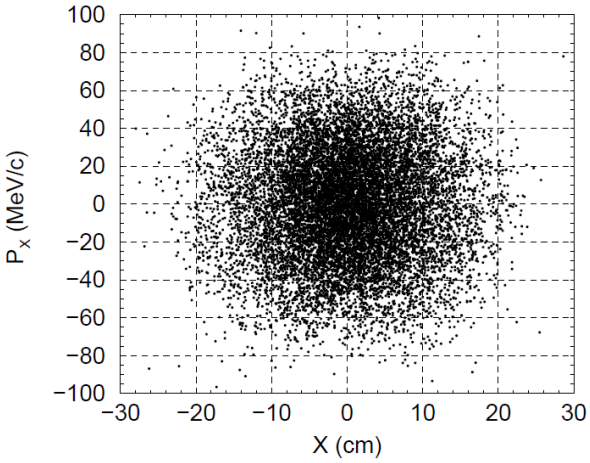
Therefore, essential loss of particles and decrease of the bunch longitudinal emittance are expected in very early stages of the cooling.

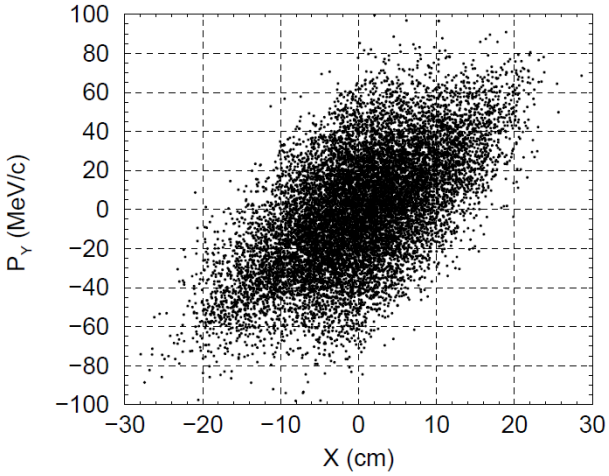
Rotator beam, transverse distribution

Solenoid field is 2 T inside the rotator.

Average mechanical angular momentum of the beam is high in the channel resulting strong $X\text{-}P_y$ and $Y\text{-}P_x$ correlation.

2 projection of the phase space of the bean in the solenoid are plotted

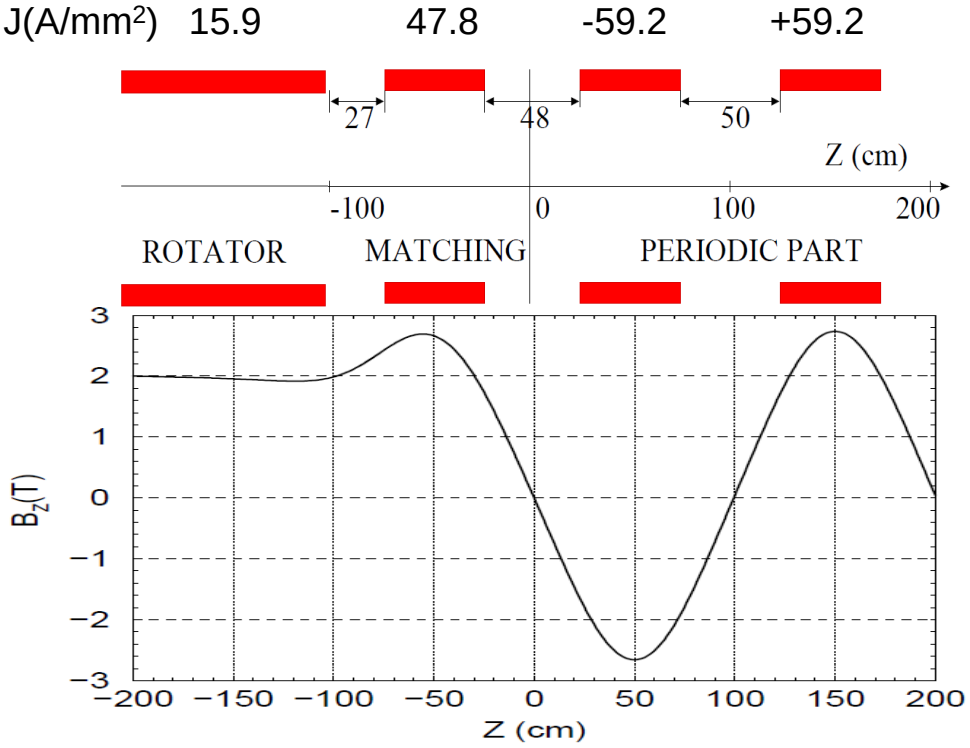




However, the canonical angular momentum of the beam is not so large, and a modest correlation remains after the beam leaves the field (it will be illustrated later).

Transverse emittance of the beam $([D_4]^{1/4})$ is about 1.7 cm.

Matching of the rotator and 1st stage



Part of the channel is sketched here (coils and axial field)

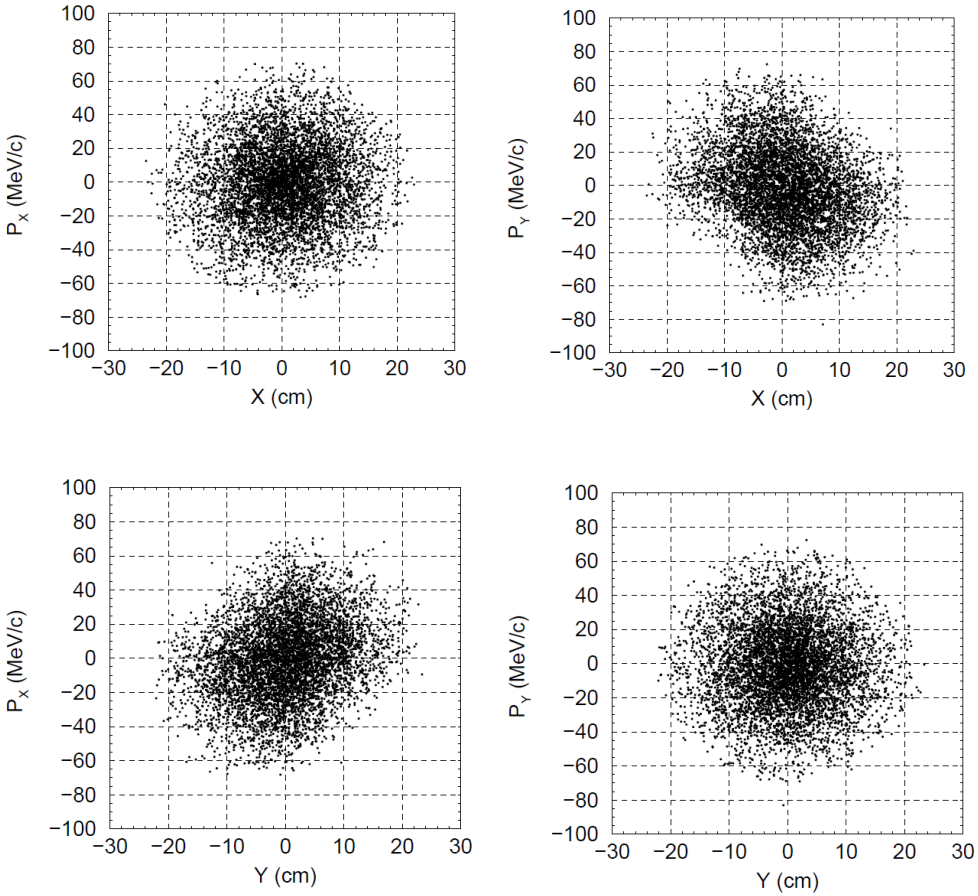
- 2 T field of the rotator is not structured (no coils, fringe, etc.).
- The structure should be thought out to match the rotator with 1st cooling channel including alternate solenoids.
- A facilitation is that their beta-functions are close in magnitude: 81 cm and 80 cm
- Jointed channel is constructed of the standard coils (see p.3)
- Current density is

47.8 A/mm² in the matching coil
59.2 A/mm² in the periodic part

- Maximal field in the coil is 4.57 T
- Coil tilt is 40 mrad in the periodic channel. Matching coil is not tilted.

Transverse phase space after the matching

Transverse phase space in the beginning of the periodic channel (Z=0, $B_z = 0$)



Average mechanical angular momentum is rather close to the canonical one

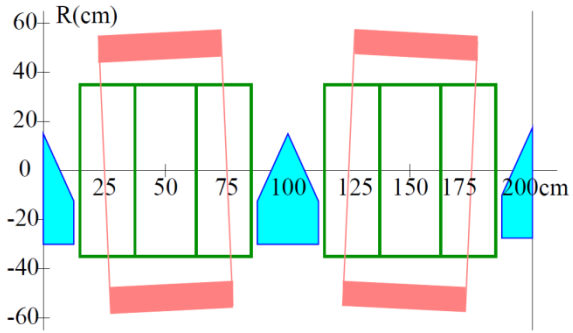
Therefore, X-P_y and Y-P_x correlations are unimportant for emittance calculation:

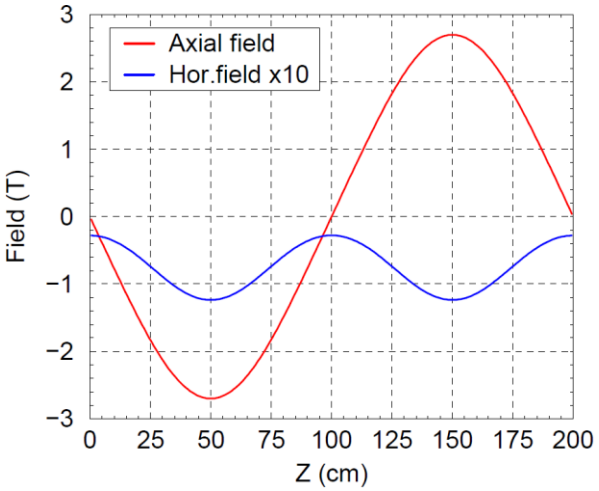
$\sigma_X \sigma_{Px} = 1.70$ cm

$\sigma_Y \sigma_{Py} = 1.72$ cm

$(D_4)^{1/4} = 1.66$ cm

1st stage of the cooler





The cell length is 200 cm

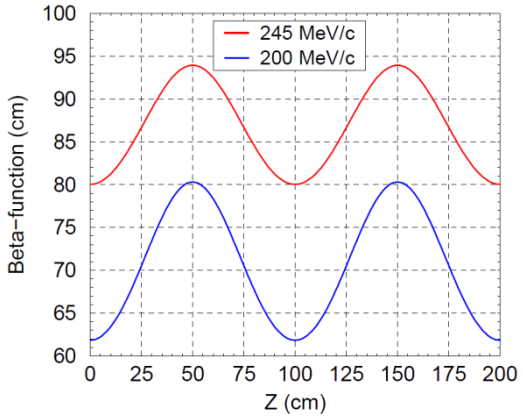
Current density is ±59.2 A/mm^2

Maximal field in the coil is 3.7 T

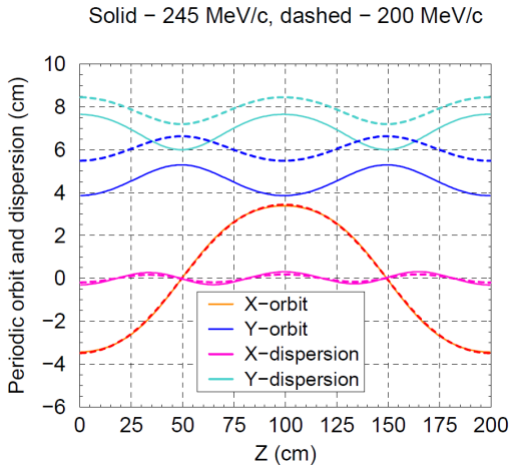
The coil tilt is ±40 mrad

Angle of the LH_2 absorber is 50^o

Distance from axis to the absorber edge is 15 cm



Beta-function at
200 MeV/c and 245 MeV/c

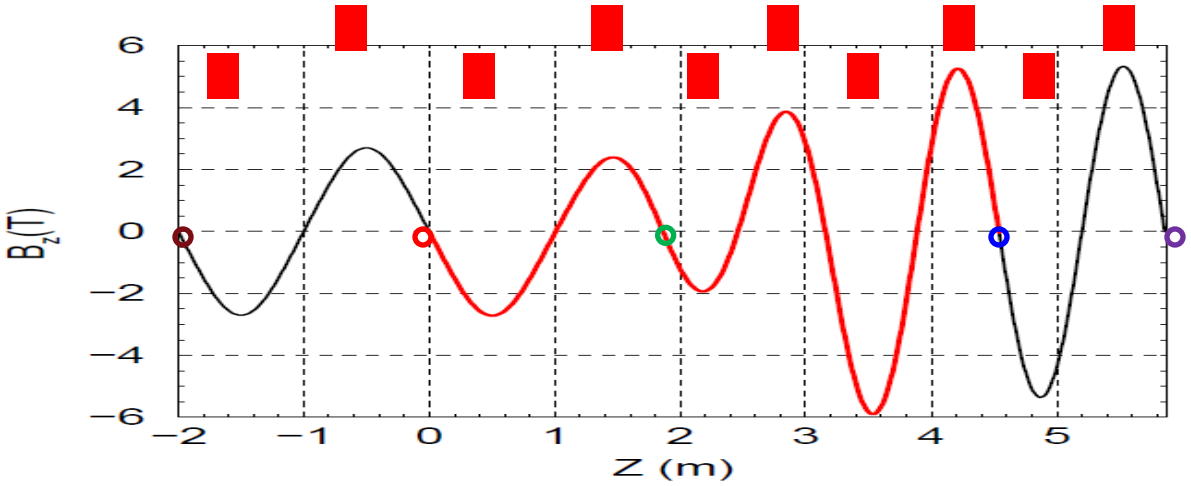


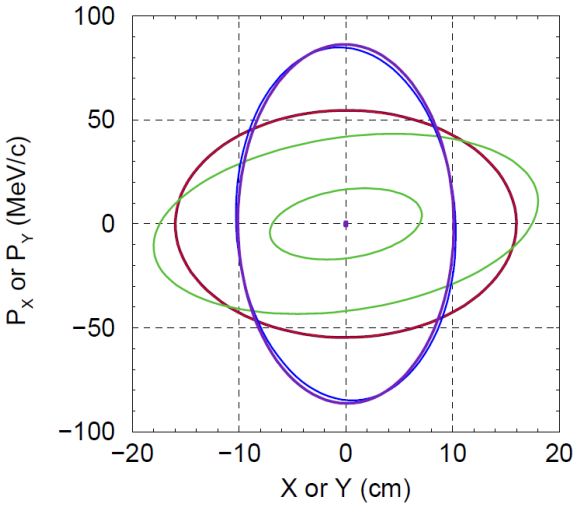
Periodic orbit and dispersion
at 200 MeV/c and 245 MeV/c.
Horizontal orbit and dispersion
almost do not depend on
momentum.

Matching of 1st and 2nd stages of the cooler

J = -59.2, 59.2, -59.2, 59.7, -71.6, 124, -175, 175, -175, 175 A/mm^2

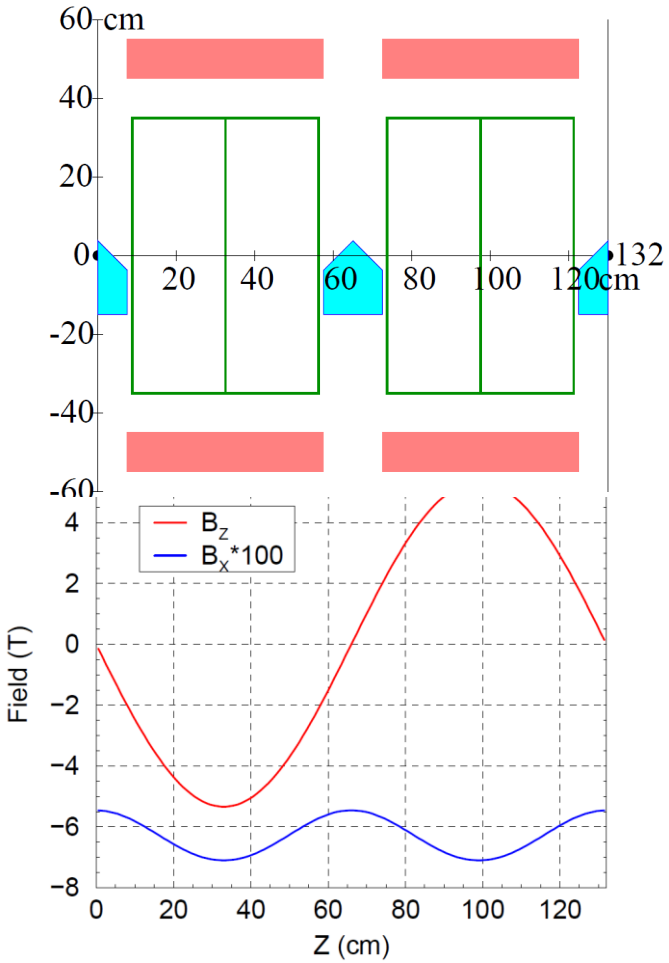
Z = -1.5 , -0.5 , 0.5 , 1.5, 2.23, 2.83, 3.55,4.21,4.87, 5.53 m





- The goal is to match beta-functions avoiding X-Y coupling at the absorbers ($\int Bdz = 0+$
- Standard coils are used throughout being suited to location and required field
- The coils are not tilted in the matching part (red)
- Phase ellipses in marked points are plotted. Outer X-P_X , inner Y-Py ellipses.

2nd stage of the cooler



The cell length is 132 cm

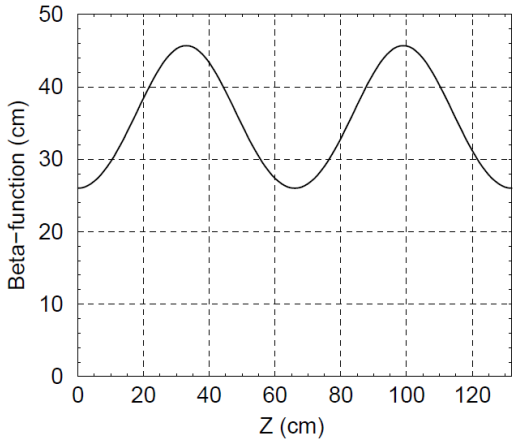
Current density is ±175 A/mm^2

Maximal field in the coil is 12 T

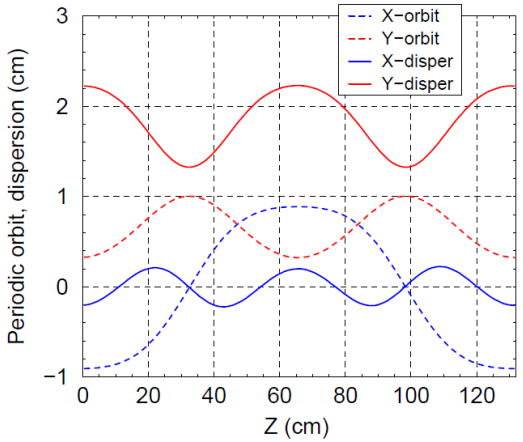
The coil tilt is ±7.5 mrad

Angle of the LH_2 absorber is 97^o

Distance from axis to the absorber edge is 4 cm

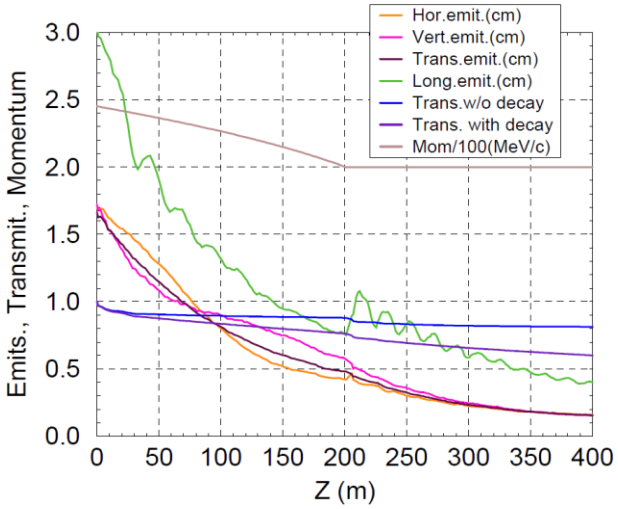


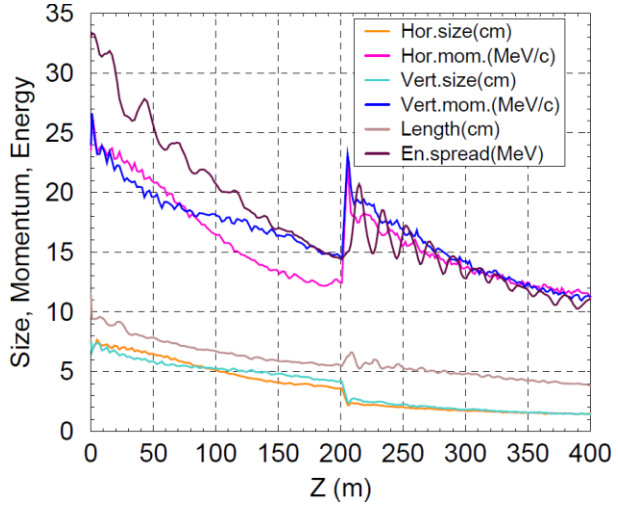
Beta-function vs coordinate



Periodic orbit and dispersion

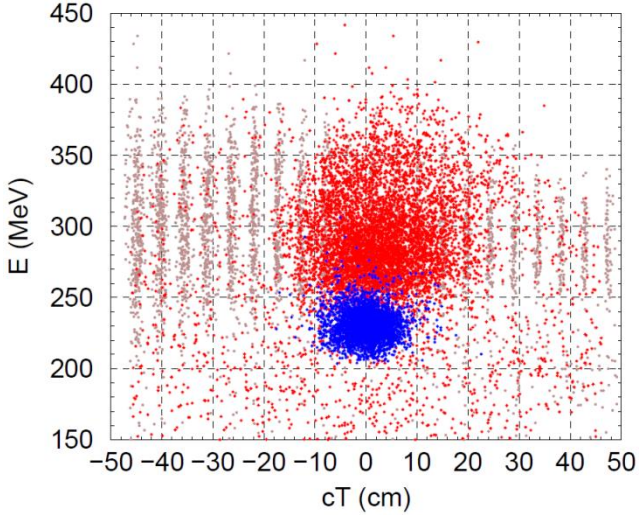
Cooling without windows





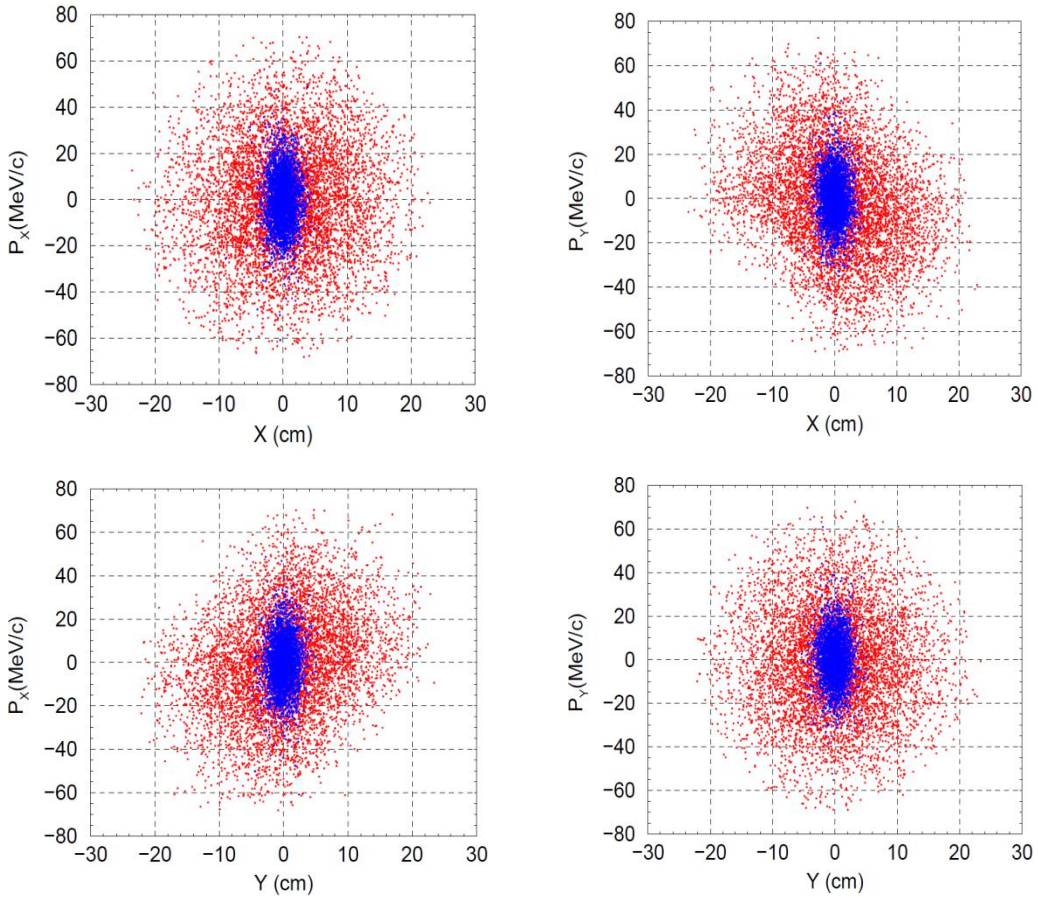
With 400 m cooling channel:
Trans. emittance 16.6 mm → 1.52 mm
Long emittance 30-40 mm → 3.8 mm
Transmission 81% w/o decay, 60% with decay

Longitudinal expansion of bunches just after the matching is the main problem resulting in irreversible emittance increase of about 30-40%.



Jump of transverse momentum plus nonlinear transverse-longitudinal coupling cause the effect which suppression failed still.

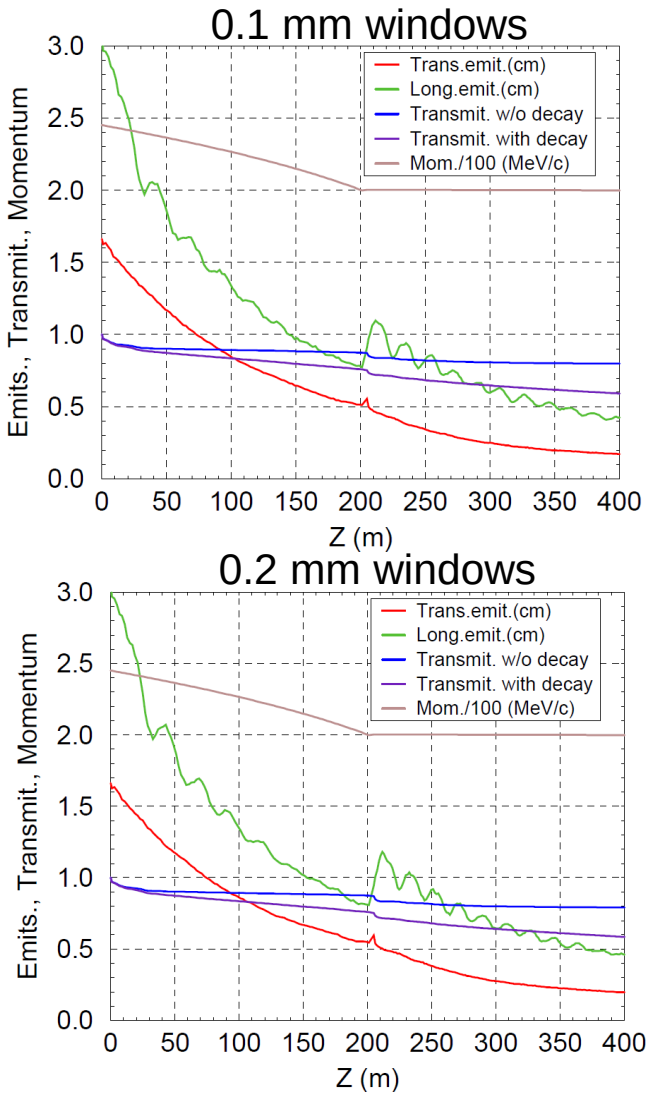
Transverse phase space



All projections of transverse phase space are shown before and after the cooling at the points where $B_z = 0$.

Finale 4D ellipsoid is canonical being free of X-Y coupling.

Cooling with Be windows (no Al)



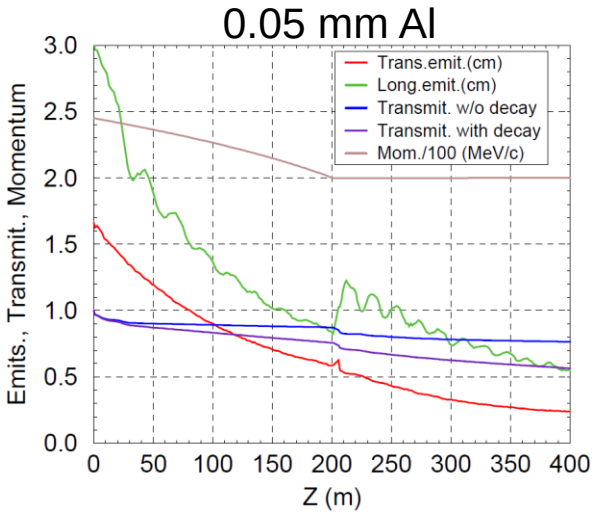
Effect of Be windows of constant thickness is illustrated by plots and table

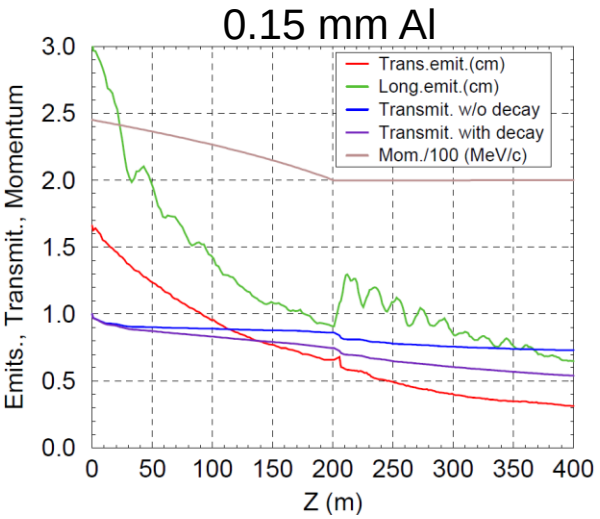
h(mm)	ε_t(mm)	ε_z(mm)	Transmit(%)
0.0	1.5	3.8	81/60
0.1	1.7	4.1	80/59
0.2	2.0	4.5	79/58

The emittances increase by factor 1.13-1.33 with Be windows 0.1-0.2 mm.

Cooling with different Al windows (Be 0.2 mm)

Cooling channel with 0.2 mm Be windows and different Al windows is considered.

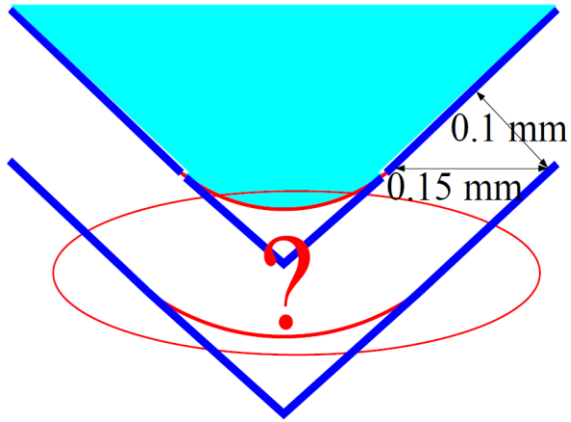




ε_t = 3.1 mm

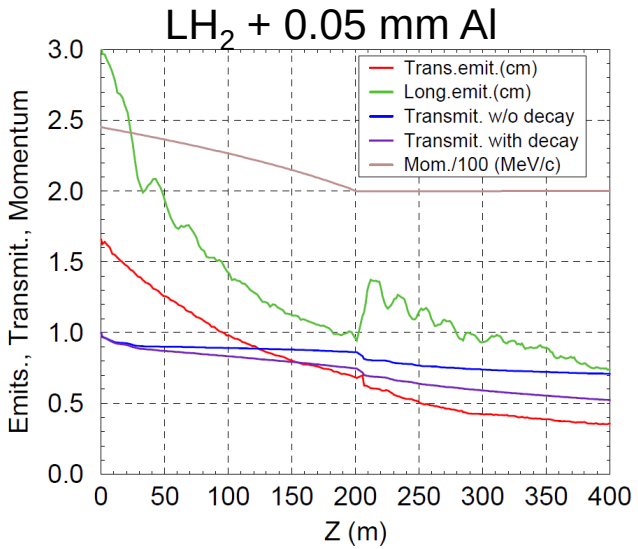
Unfavorable effect of Al is very significant, in particular, because of large slope of the film in wedges.

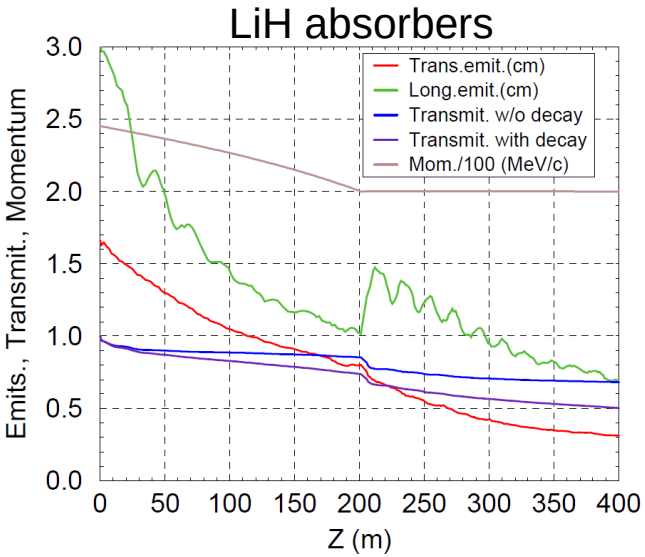
With the wedge angle 97° in 2nd stage, effective thickness of Al film exceeds the nominal value by factor 1.5



What is a realistic design of the edge?

Comparison LH_2+Al windows and LiH





Cooling with 0.2 mm Be windows and different Al windows are compared in the table.

The same channel with LiH absorber is presented as well

h(mm)	ε_t(mm)	ε_z(mm)	Transmit(%)
0.00	2.0	4.5	79 / 58
0.05	2.4	5.6	76 / 56
0.10	2.7	6.1	75 / 55
0.15	3.1	6.3	73 / 54
0.20	3.5	7.3	70 / 52
LiH:	3.1	6.9	69 / 51

The cooler with LiH absorbers has better performance than similar cooler with LH2 absorbers and Al windows of thickness >~0.15 mm.

Conclusion

- 2 stages 6D cooler of length 400 m assembled from standard parts is considered.
- Output beam of the rotator is used as the input of the cooler
- Without Be-Al windows, the cooler produces beam with transverse emittance 1.5 mm, average longitudunal emittance 4 mm per bunch, and transmission 81/60% without/with decay.
- The emittances increase by 15 -30% with Be windows 0.1-0.2 mm.
- Al windows of thickness 0.10-0.15 mm leads to an additional increase of the emittances by factor 1.35-1.55.
- Performances of the channel with liquid hydrogen absorbers and Al windows of thickness > 0.15 mm look worse than similar channel with LiH absorbers.