Adiabatic rectilinear 6D cooling channel

(after phase rotator choice)

V. Balbekov, Fermilab

6D vacuum RF workshop 05/13/2014

Outline

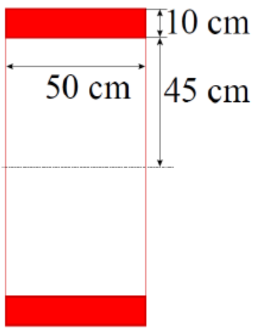
- Motivation
- Matching by adiabatic change of beta function
- 2-stages channel with adiabatically matched beta
- Shorter 1-stage channel with adiabatically varying parameters
- LH_2 or LiH?
- Gas filled rectilinear 6D channel

After-Rotator cooling channel: schematic (Mart 2014 design)

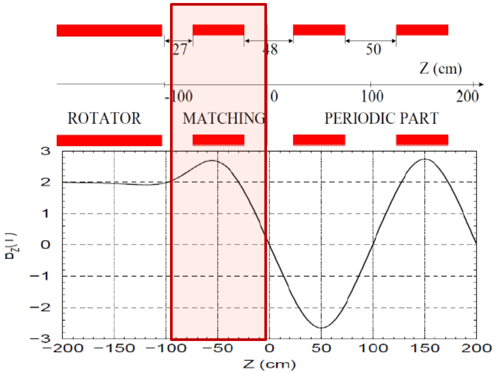
Rotator:
2 Tesla uniform field,
245 MeV/c beam,
80 cm beta-function

First stage:
100×200 cm cells, beam mom.
245 MeV/c → 200 MeV/c,
beta-function 80 cm → 62 cm

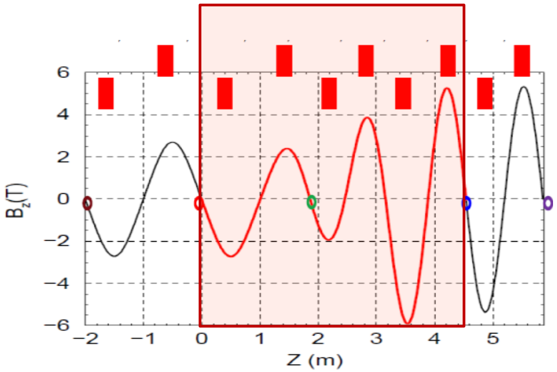
Second stage:
150×132 cm cells,
beam mom. 200 MeV/c,
beta-function 26 cm



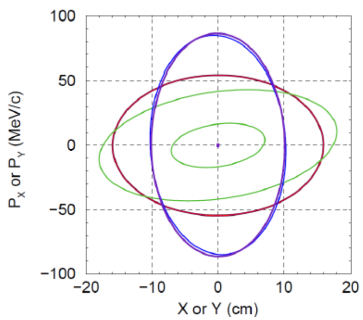
Standard coil to be used



1st matching: beta 80 cm → 80 cm.
Single special coil is used



2nd matching: beta 62 cm → 26 cm.
6 special coils are used.

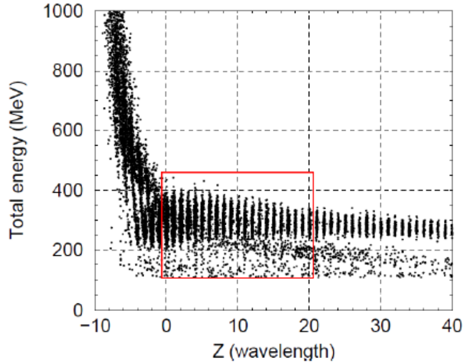


Transformation of phase ellipses X-P_X and Y-P_Y

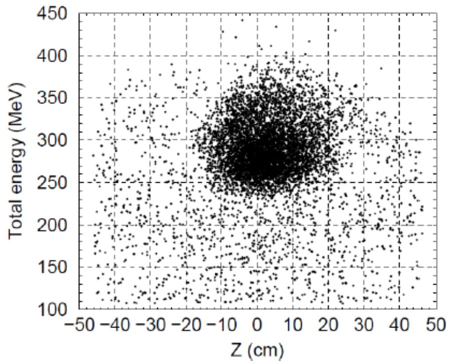
235 MHz / 21.6 MV/m pillbox cavities are used everywhere

After-Rotator beam distribution

Longitudinal phase space after rotator. Red square: 21 bunch available for cooling.

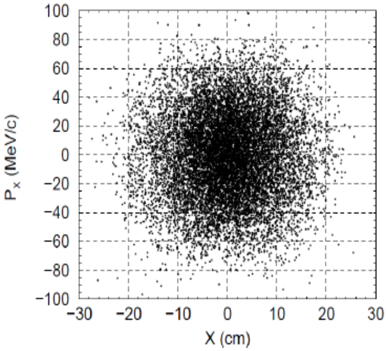


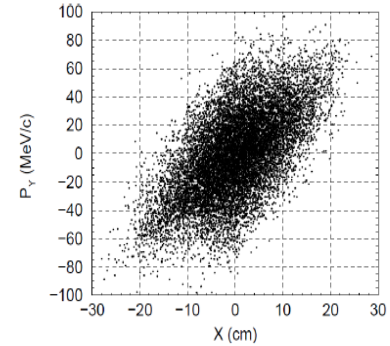
21 bunch are gathered together. The particles with E < ~225 MeV are actually out of stability region



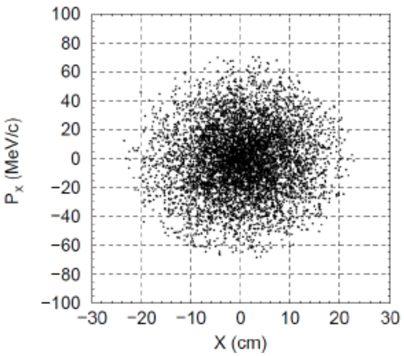
Z = ct in these plots

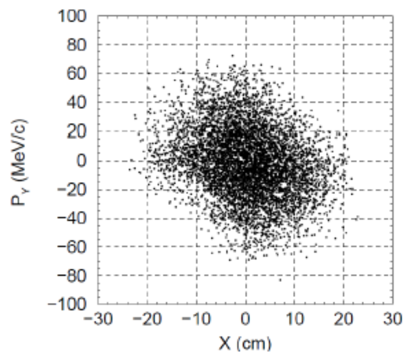
Transverse phase space in the rotator before the matching (uniform field 2 T)



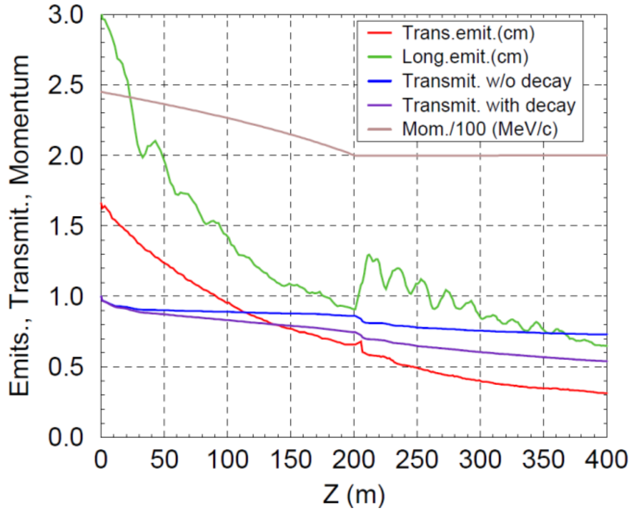


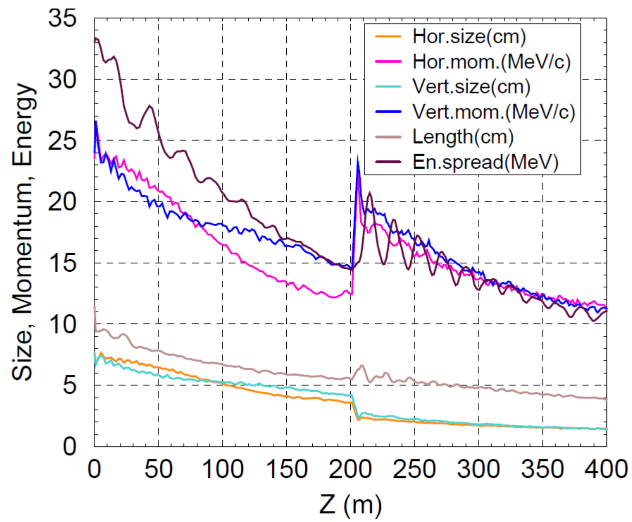
Transverse phase space after the matching (the point with $B_Z = 0$ which actually is the beginning of periodic channel).





After-Rotator channel: cooling example (Mart 2014 simulation)





Cooling with LH_2 absorber, 0.1 mm Al windows and 0.2 mm Be windows. Top – beam emittance, bottom – size.

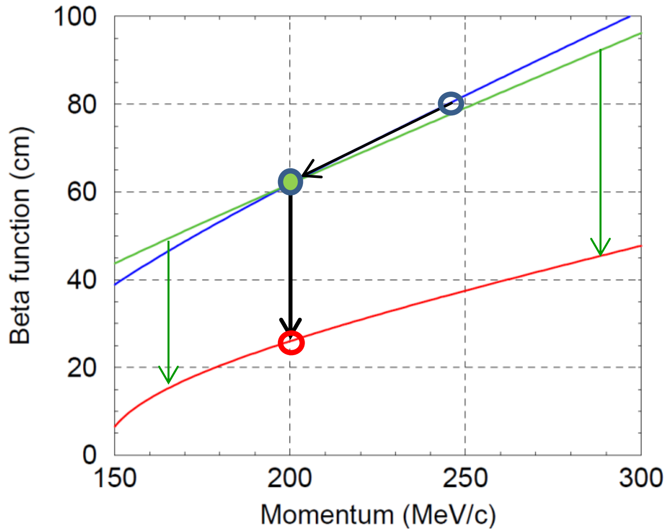
Abrupt decrease of beta-function in the matching section (62 cm to 26 cm) results in very fast growth of transverse momentum spread.

It is accompanied by decrease of longitudinal velocity of particles which would require the energy increase for the compensation.

Because energy cannot be change so fast, longitudinal mismatching and emittance growth seems to be inevitable.

Abrupt change of beta function results in growth of longitudinal emittance.
Probably, the only radical solution of the problem is adiabatically slow transformation of the beta.

Adiabatic matching of the 2-stages channel (the idea)



Beta-function in absorber against momentum

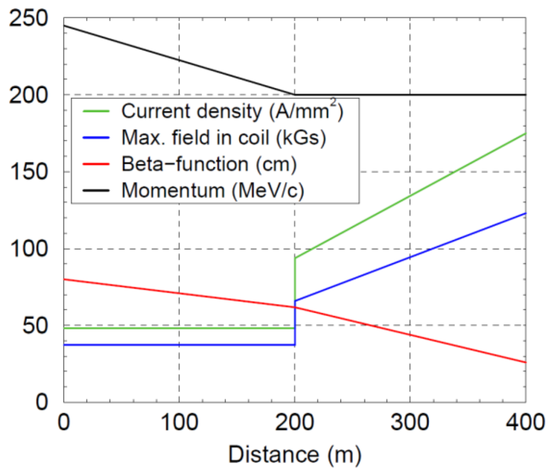
Blue line – 200 cm cell, solenoid field is 2.7 / 4.6 T.

The beam decelerated from 245 to 200 MeV/c.
Beta function decreases from 80 to 62 cm.
Then the beam is transferred to 2nd stage (132 cm cells)

In the beginning of 2nd stage solenoid field is 2.8 T / 6.6 T, beta function almost the same as in 1st stage

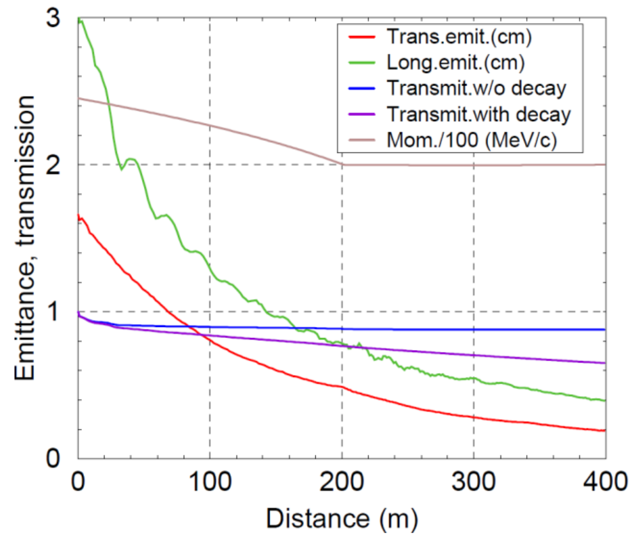
Current density and field gradually increase from beginning to end of 2nd stage.

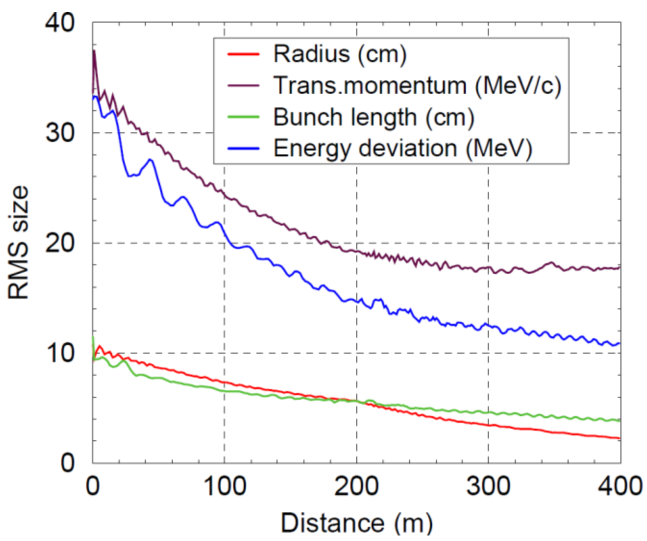
Red line – the stage end: solenoid field is 5.3 /12.3 T. Beam momentum 200 MeV/c, beta function 26 cm.



Designed 200 cm and 132 cm cells with coils 50 cm length and 45 cm radius can be used for adiabatically matched after-phase-rotator cooling channel

Example of cooling with adiabatic matching (not optimized)





Presented channel includes 100 cells of length 2 m and 150 cells of 1.32 m (200+200 m).

Magnetic field is constant is 1st stage and increases linearly from the beginning to the end of 2nd stage.

Reference momentum decreases in 1st stage.

The channel is not optimized
and windows are not included yet.

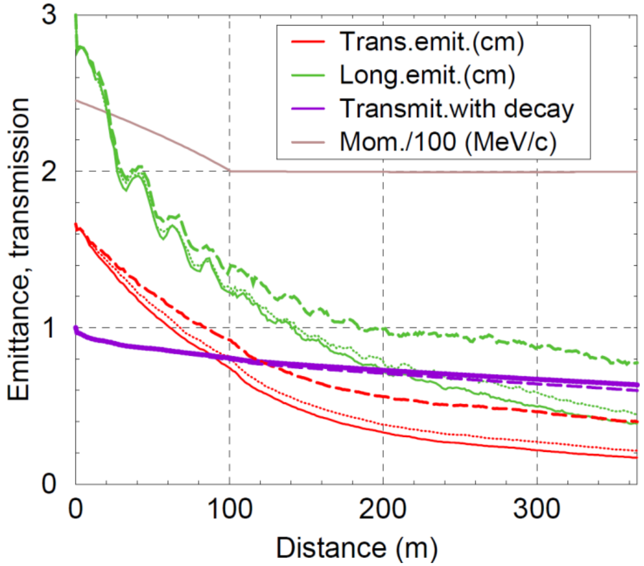
Top – beam emittance, momentum and transmission, bottom – beam size.

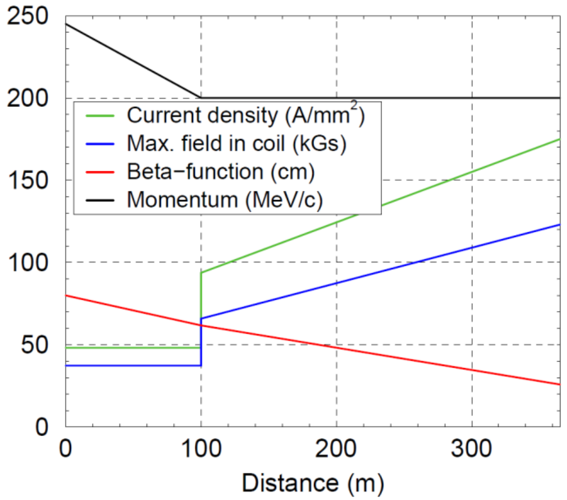
Both transverse and longitudinal emittance and size are smooth shaped curves attesting the matching is perfect.

Non-decay particle loss are observed only in beginning of the channel where it is very expectable.

The adiabatic matching works though should be optimized (in particular, with windows).

Optimization with windows





Presented channel includes 50 cells of length 2 m and 200 cells of 1.32 m (100+264 m).

Magnetic field is constant is 1st stage and increases linearly from the beginning to the end of 2nd stage.

Reference momentum decreases in 1st stage.

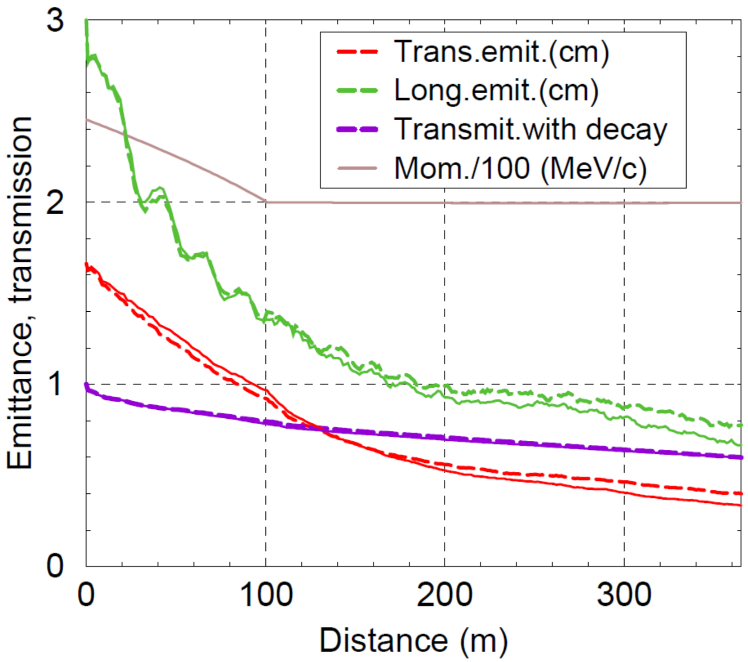
Three cases are presented in the top plot:

(A) solid lines – no windows,
(B) dotted lines – 0.2 mm Be windows, no Al walls
(C) dashed lines – 0.2 mm Be and 0.2 mm Al walls

	A	B	C
Trans. emit. (mm)	1.7	2.1	4.0
Long. emit. (mm)	3.9	4.5	7.8
Transmission (%)	64	64	60

Al windows produce maximal adverse effect. Inclination of the wedge walls is important factor increasing effective Al thickness by factor ~1.5

Comparison of LH_2+Al and LiH absorbers



<u>The same channel as before:</u>

- 1st stage 50×2 m cells, 2nd one 200×1.32 m cells
- Reference momentum decreases in 1st stage.
- Magnetic field is constant is 1st stage and increases linearly in 2nd one.

<u>Two cases are compared</u>:

- Dashed lines -- LH_2 absorbers with 0.2 mm Al walls and 0.2 mm Be windows;
- Solid – LiH absorbers and 0.2 mm Be windows

LiH absorbers are better than LH_2 absorbers with thick Al walls.
Slope and thickness of the walls is a problem of wedge absorber.
Heating by muon beam is an open question.

Higher cooling rate: restrictions by absorber thickness

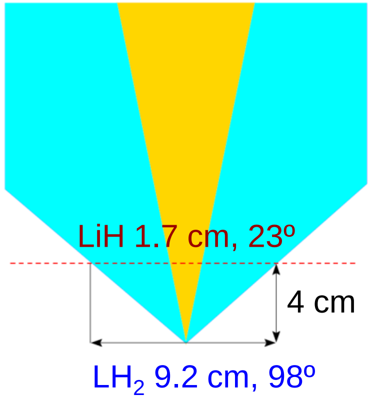
Synchronous phase is about 18º in the examples that is energy gain is about 30% of the RF gradient (6.5 / 21.6 MV/m).

Small phase is useful in the beginning of the channel to maximize its longitudinal acceptance but it could be increased at the end.

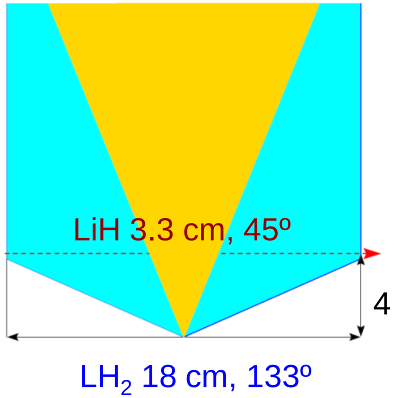
However, there is a serious obstacle because thicker absorbers are required for higher acceleration / deceleration rate.

It would be a big problem with LH_2 absorbers but rather easy with LiH ones which can be wedged or flat-laminated.

> LiH absorbers offer a possibility to take the full advantage of RF system for cooling rate, and to reach required emittance with shorter / cheaper cooling channel

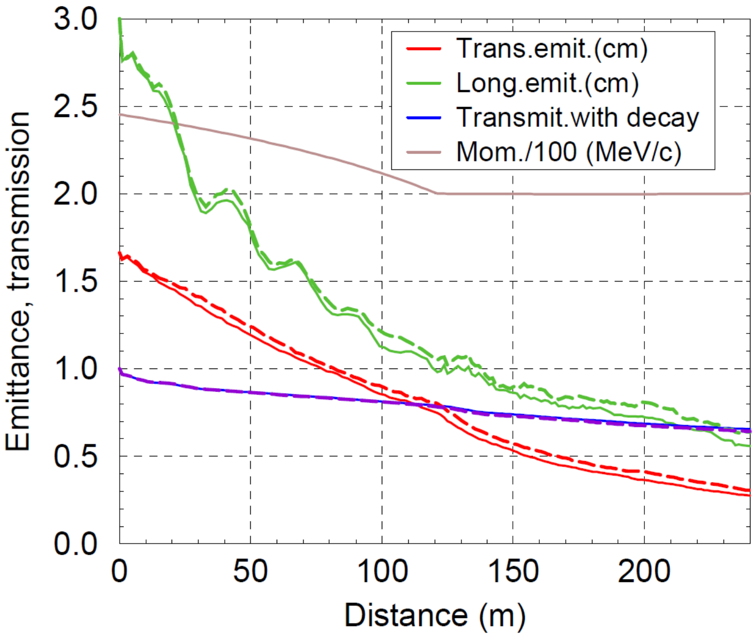


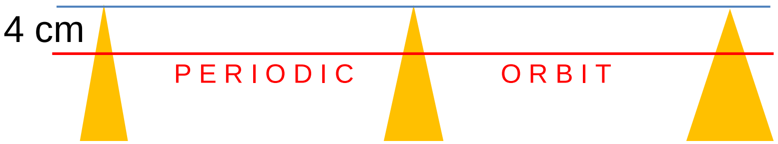
Absorbers for synchronous phase 18º.
LH_2 – thickness 9.2 cm in axis, angle 98º.
LiH – 1.66 cm and 23º.



Absorbers for synchronous phase 37º.
LH_2 – thickness 18 cm in axis, angle 133º.
LiH – 3.3 cm and 45º.

Shorter two-stages channel with variable LiH absorbers





The channel includes 60 × 2 m cells,
and 91 × 1.32 m cells (120+120 m).

Axial field has a constant amplitude of 2.7 T in 1st stage and increasing amplitude from 2.8 T to 5.3 T in 2nd stage.

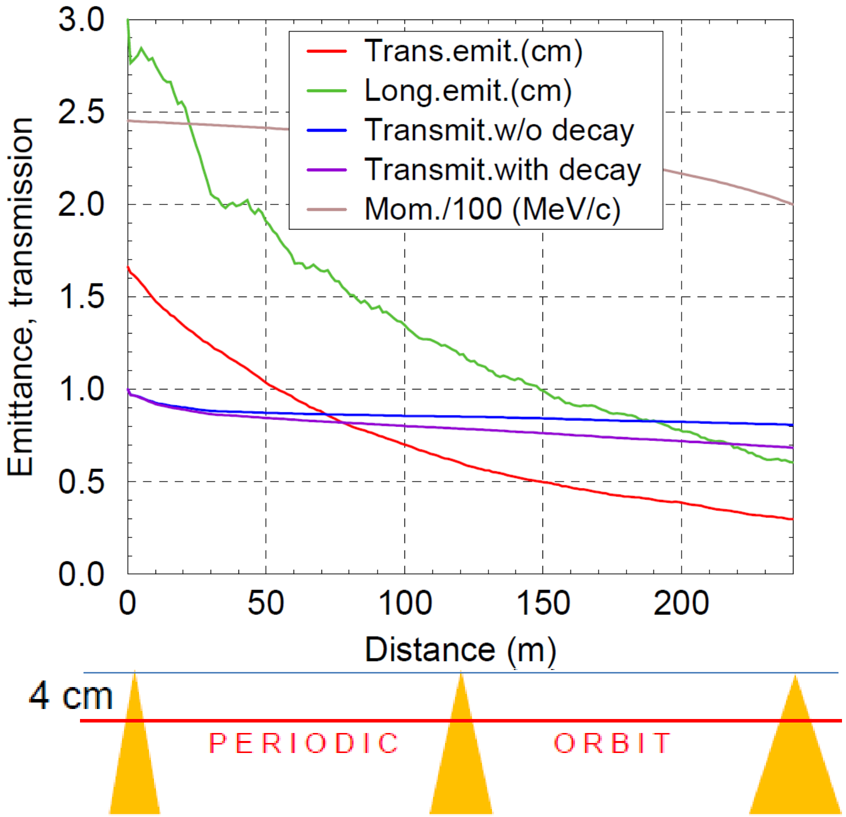
Synchronous phase linearly increases from 18º to 37º in the length of 240 m.

Absorber edges are located in 4 cm on the orbit, so corresponding opening angles are 23º at the beginning and 44º at the end.

Solid lines – no Be windows,
Dashed lines – 0.2 mm Be windows

This LiH channel provides the same emittances as similar LH_2 channel with Al windows of thickness 0.15 mm.
The channel is shorter: 240 m against 400 m
and transmission is better: 65% against 54%

One-stage channel with variable LiH absorbers



One-stage cooling channel with short cells and variable field/momentum ratio can provide rather large initial acceptance

Presented channel consists of 181 cells of length 1.32 m.

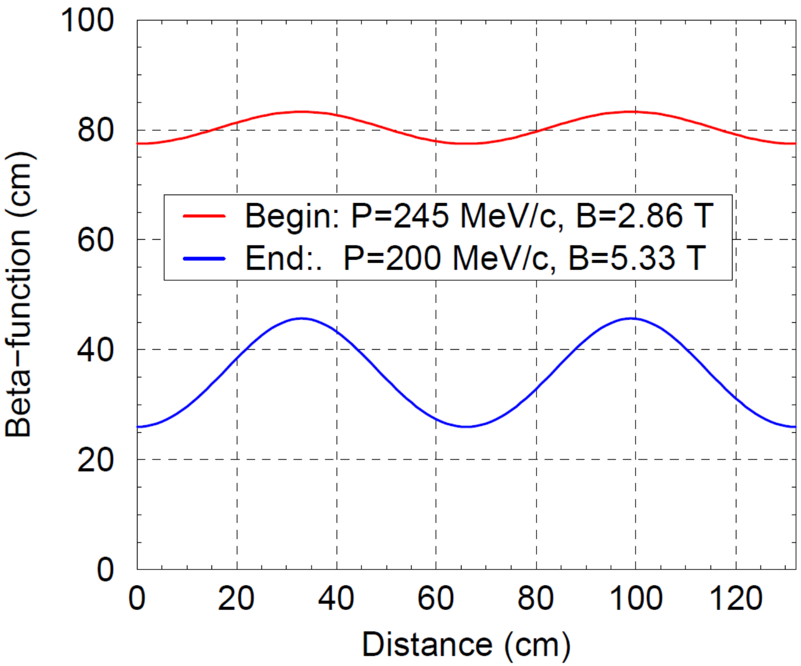
Momentum, field and acceleration gradient change linearly from the channel beginning to its end.

As a result, beta function decreases from 76 cm at the beginning to 26 cm at the end

Other characteristics are retained:
the same LiH absorbers, 0.2 mm Be windows, increasing synchronous phase 18º → 37º.

The one-stage cooler has even better performance than 2-stages one. In particular, transmission increased from 65% to 69% (decay on). True, it requires more solenoids: 362 instead of 302 in the case (longer cells are more economical).

Gas filled rectilinear 6D cooler – the idea



Modulation of beta-function is moderate in considered channel:
±4% in the beginning, and ±26% in the end.

It means that the cooling is not very much sensitive to the absorber positions, so that a uniform distribution of ionization energy loss looks rather reasonably

gas filled channel!

Of course, wedge absorbers should be retained (probably reduced) for emittance exchange.

Using of gas filled channel with tilted solenoids looks prospectively for a modest cooling, e.g. after phase rotator or as a first stage after merge. Distribution of ionization energy loss between the gas and wedge absorbers in ratio 50/50 seems to be reasonable.

Gas filled rectilinear 6D cooler – an example

Presented cooling channel consists of 181 cells of length 1.32 m which are filled by gaseous hydrogen

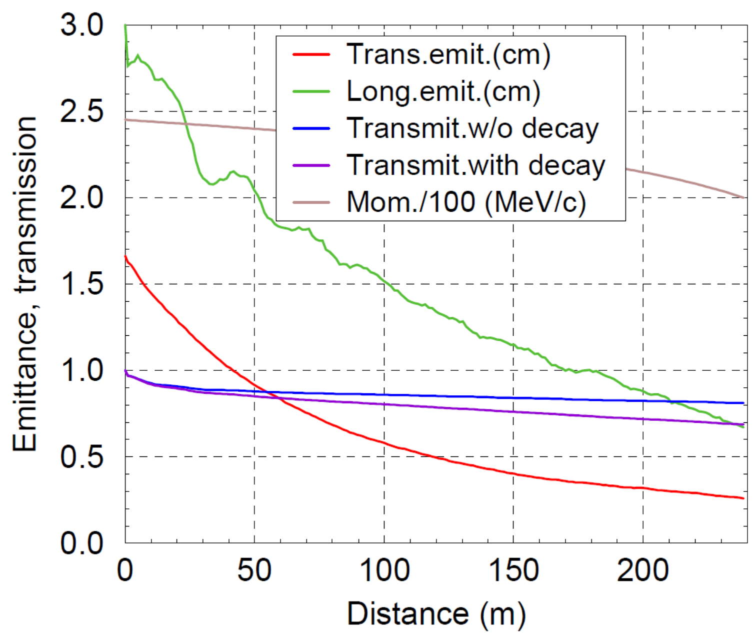
The gas pressure is 29 bar at temperature 273K that is 8.2 bar at 77K (LN_2).

Thickness of LiH wedge absorbers increases from 4 mm at the beginning to 12 mm at the end.

With fixed edge-axis distance 30 mm, the absorbers opening angle is 7.8°--23°.

Synchronous phase increases from 18º to 37º

Be windows 0.2 mm are applied.



	LH_2+Al 0.1/0.2 mm	LiH	LiH+GAS
Trans. emit. (mm)	3.1 / 4.0	3.0	2.6
Long. emit. (mm)	6.1 / 7.8	6.1	6.7
Transmission (%)	62 / 60	68	69

Table: Comparison of channels with wedge absorbers: LH_2+Al (365 m long); LiH; LiH+H_2 gas

LH_2+Al could be competitive only with walls ≤0.1mm
(in any case, being longer and providing less transmission)

H_2 filled channel with added LiH wedge absorbers looks promising but needs an optimization including front-end lids. Breakdown and plasma effects are open problems.

Conclusion

- Both transverse and longitudinal matching can be accomplished by adiabatically slow change of beta function, even with multistage FOFO channel.
- In the after-rotator cooling channel, Be windows of thickness 0.2 mm look acceptably increasing emittance by ~30%
- Aluminum walls seem to be more dangerous resulting emittance growth by factor ~2.3 at 0.2 mm thickness. Slope of walls of wedge absorber is an important factor which must be taken into account when the absorber shape is designed (cylindrical?)
- Similar or even better results can be obtained with LiH absorbers. However, they open up a possibility to take the full advantage of RF system by a graduate increase the absorber thickness (really impossible with LH_2 wedges) and synchronous phase

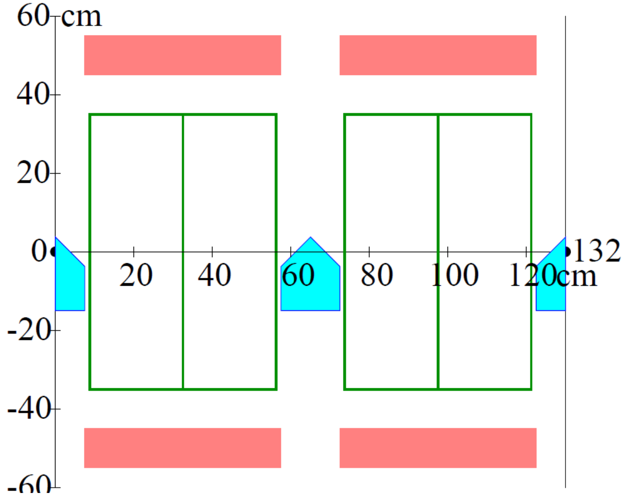
  LiH absorbers allows to decrease the channel length almost 2 times.

- Taking into account that the problem becomes harder at lower beta one can think that

  LH_2 wedge absorbers are unsuitable for 6D cooling at all.

- However, H_2 gas could be used in combination with LiH wedges to improve the channel performance at relatively low modulated beta function. The gas pressure is moderate but investigations of electric breakdown and plasma effects are needed.

Appendix: 132 cm cell (old design)



The cell length is 132 cm

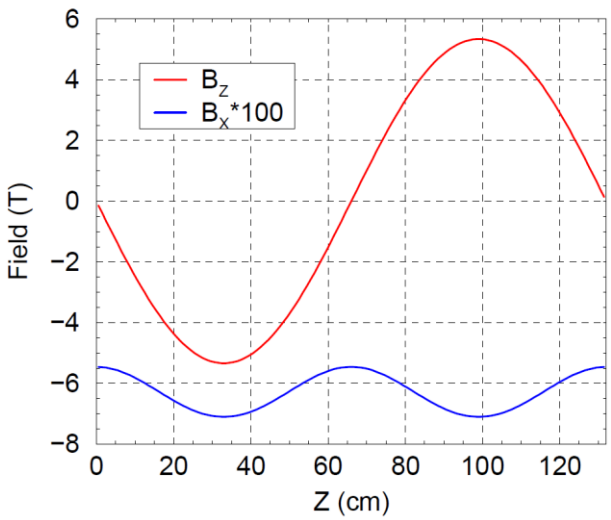
Current density is ±175 A/mm^2

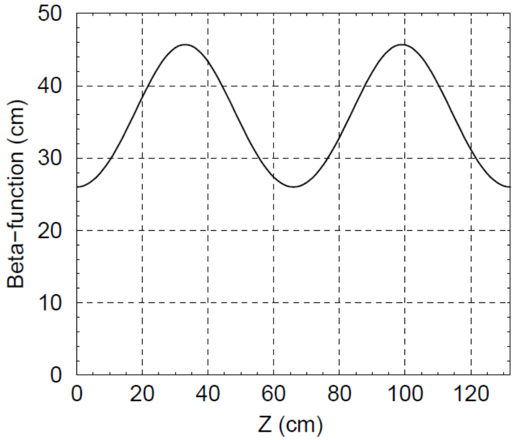
Maximal field in the coil is 12 T

The coil tilt is ±7.5 mrad

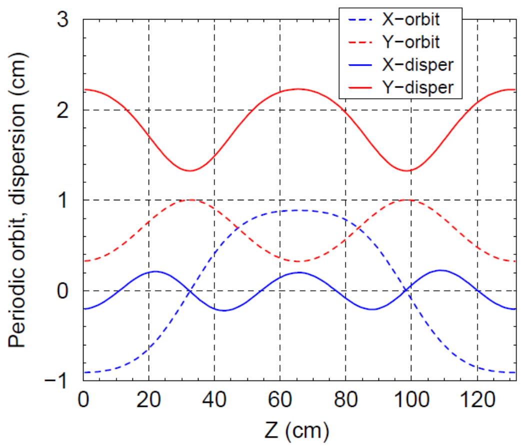
Angle of the LH_2 absorber is 97^o

Distance from axis to the absorber edge is 4 cm





Beta-function vs coordinate



Periodic orbit and dispersion