Upgrade of 325 MHz muon cooling channel

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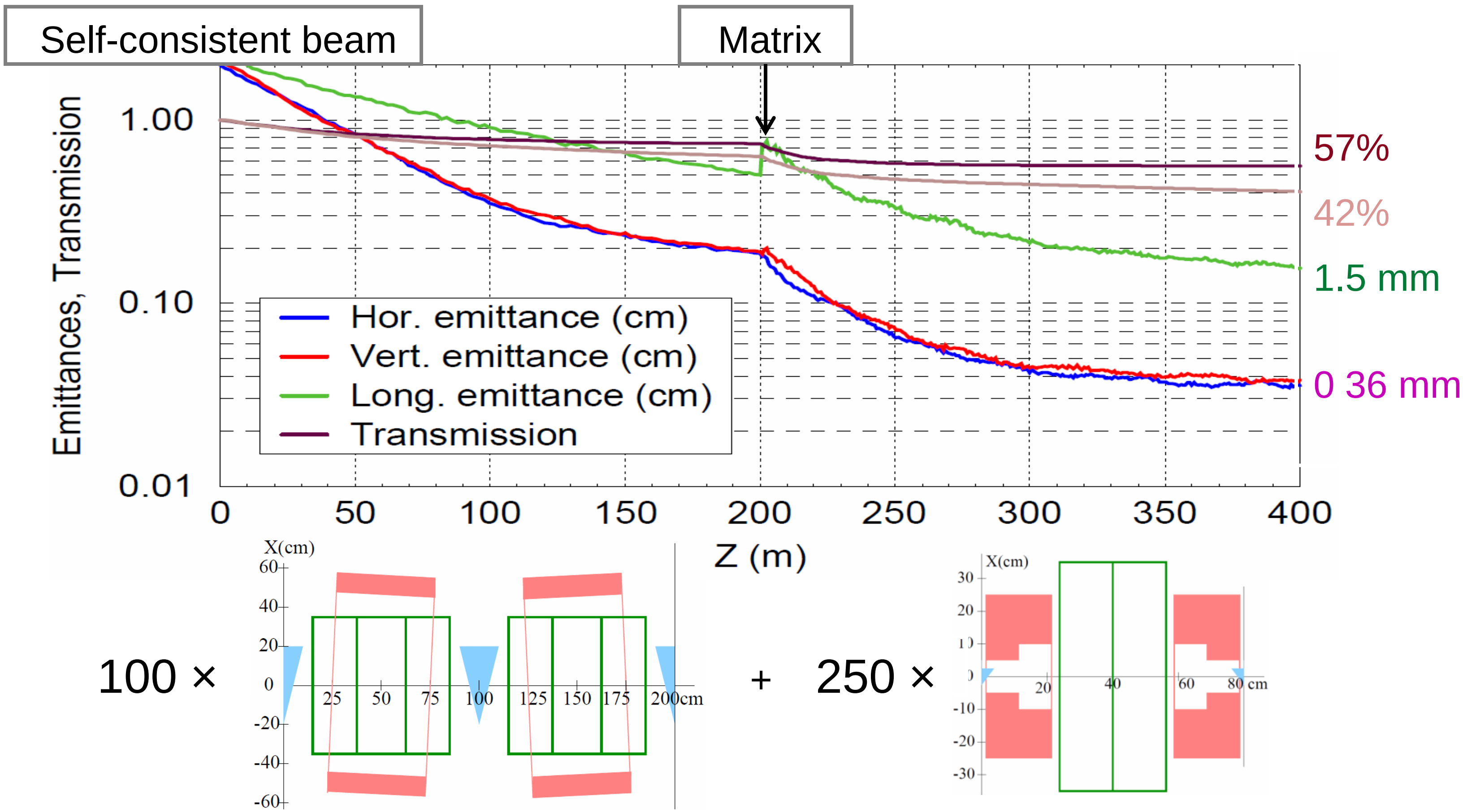
- 2 stages channel $\rightarrow$ 3 stages one
- Matching sections are included
- Transmission is increased
- Future trends are discussed

2 stages 325 MHz cooling channel (08/13/13 version)



GOAL OF THE UPGRADE IS:

1. To design a realistic matching section
2. To increase transmission as possible (is was ~75% per stage w/o decay)

Bench mark of the upgrade

325 MHz RF everywhere

- Higher frequency → shorter separatrix → shorter bunch → higher momentum spread.
- The last point falls into a contradiction with restricted momentum acceptance which is the main cause of the particle losses (it will be shown).
- Less radius of higher frequency cavities is immaterial factor if the cavities are not placed inside the solenoids.
- Higher accelerating gradient of higher RF requires longer absorbers (see below).

Lithium hydride absorbers in the last stage

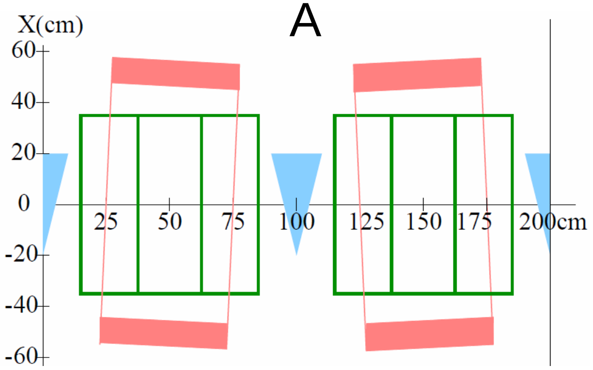
- Liquid hydrogen provides rather low decelerating gradient (~30 MeV/m at 200 MeV/c).
- Therefore, LH_2 wedge absorbers would be rather long (0.3 − 0.4 m).
- It is acceptable in earlier stages of the cooling with comparably high beta-functions but inadmissible in the last stage because average beta-function is large in a long absorber
- Additionally, very large opening wedge angle is require (formally 150º or more).

Required magnetic field could be reached with NbSn superconductor.

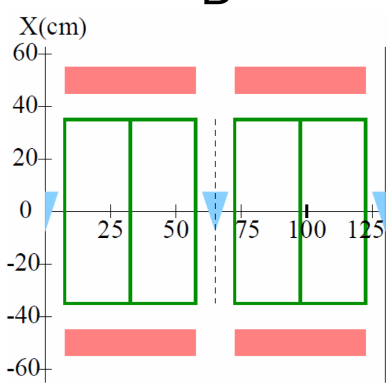
1^{st} stage is divided in 2 parts to decrease particle loss at injection

1A part− for maximal momentum acceptance; 1B − for minimal emittance

A



B

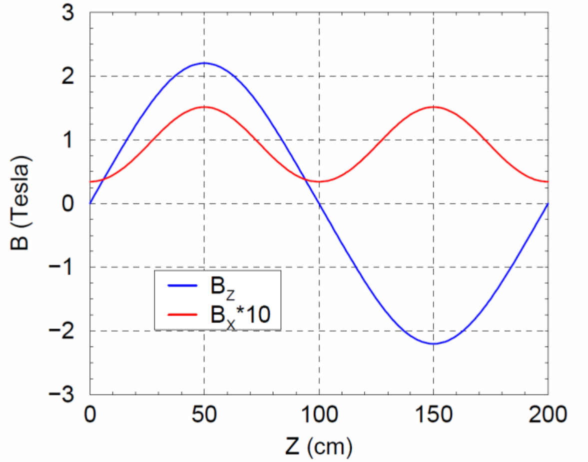


(15 mrad tilt is not shown)

Parameter	Units	A	B
Period length	cm	200	132
Coil length	cm	50	50
Coil inner radius	cm	45	45
Coil thickness	cm	10	10
Coil tilt	mrad	±60	±15
Current density	A/mm^2	48.3	175
Maximal field strength in coil	T	3.73	12.3
Reference momentum	MeV/c	200	200
Accelerating frequency	MHz	325	325
Accelerating gradient	MV/m	25	25
Synchronous phase	deg	23	23
LH_2 absorber center thickness	cm	21.8	14.5
Absorber opening angle	deg	40	88

Sub-stages 1A and 1B: field and beta-function

A



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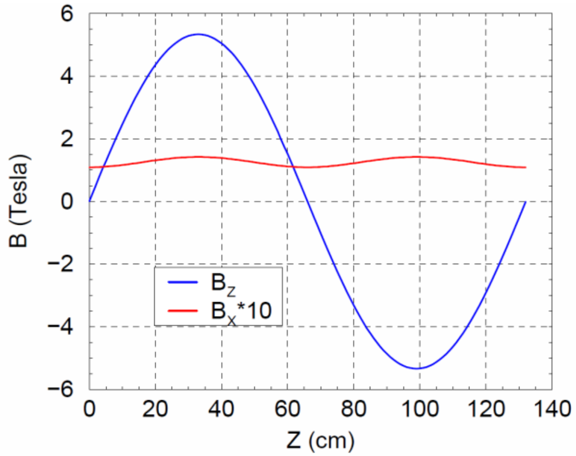
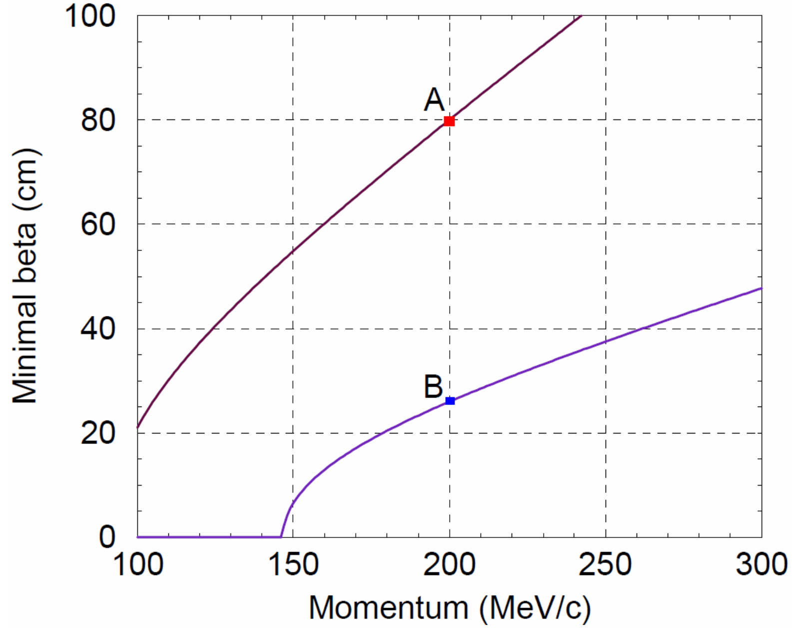




At P = 200 MeV/c:

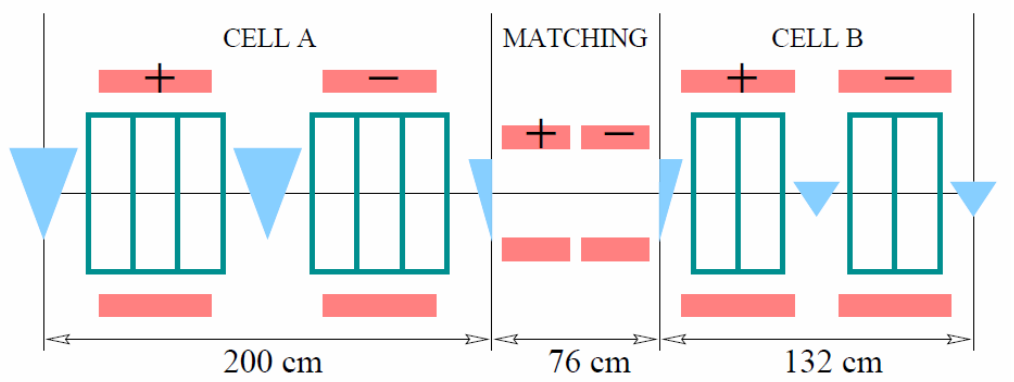
betatron phase advances are about

2π/3 (A)   and   4π/3 (B)

N.B. Uniform transverse field can be applied successfully

Matching of sub-stages 1A and 1B is effected by 90º FODO cell

Joining of the sub-stages

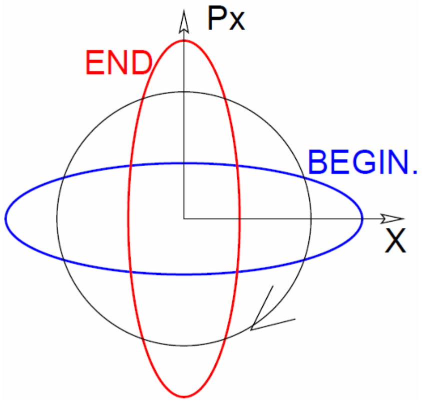


Matching section

Betatron phase advance 90º

Inherent beta 47 cm $\approx(\beta_A\beta_B)1/2$

Phase space transformation is shown below



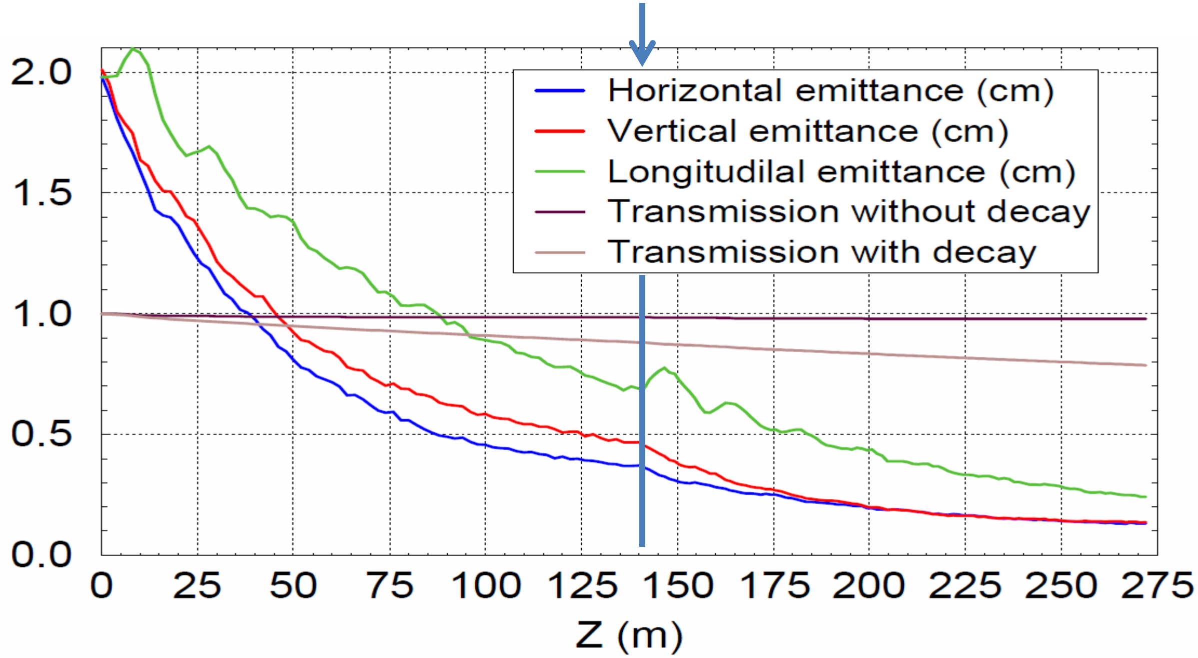
Parameters of the matching section

Section length	76 cm
Coil length	30 cm
Coil inner radius	20 cm
Coil thickness	10 cm
Current density	95.2 A/mm^2
Axial field	3.85 T
Coil field	6.47 T

Cooling by 1st stage with LH_2 absorbers

and self-consistent initial distribution formed by 10 hidden 1A cells)

70 cells 1A   Matching section 0.76 m   100 cells 1B

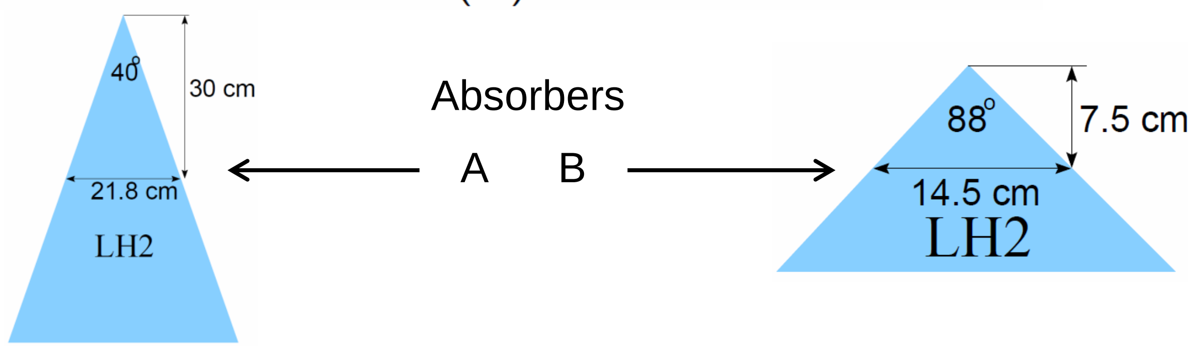


Tr_1 = 97.8%

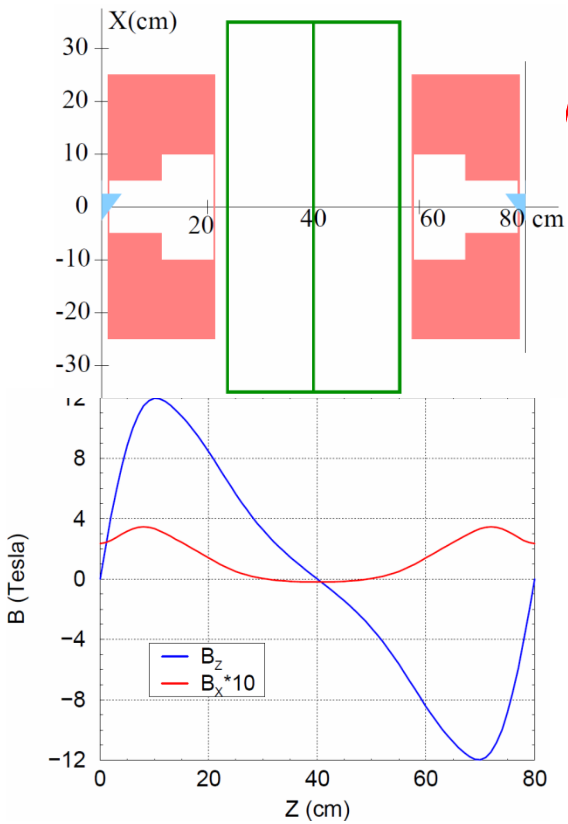
Tr_2 = 78.6%

E_{long} = 2.42 mm

E_{trans}= 1.33 mm



Second stage is not changed



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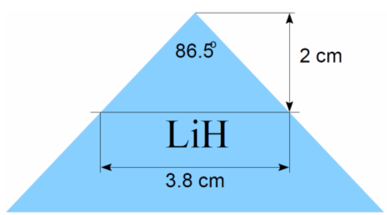
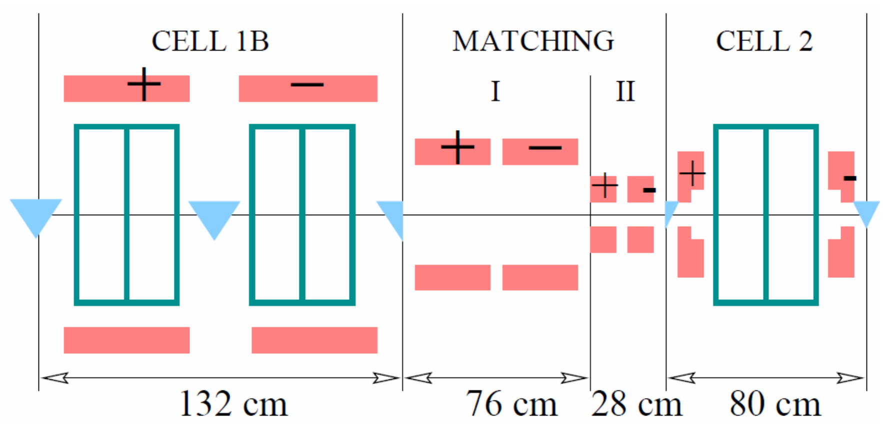


Period length	80 cm
Coil length	20 cm
Coil inner radius	5 cm and 10 cm
Coil thickness	20 cm and 15 cm
Coil tilt	±20 mrad
Current density	134 A/mm^2
Maximal field strength in coil	13.4 T
Reference momentum	200 MeV/c
Accelerating frequency	325 MHz
Accelerating gradient	25 MV/m
Synchronous phase	44.4°
LiH absorber center thickness	3.8 cm
Absorber opening angle	86.5°

Matching of 1st and 2nd stages is effected by two 90º FODO cells



Parameters of the matching section

	Unit	I	II
Section length	cm	76	28
Coil length	cm	30	13
Coil inner radius	cm	20	5
Coil thickness	cm	10	10
Current density	A/mm^2	95.2	254
Axial field	T	3.85	10.3
Coil field	T	6.47	13.1

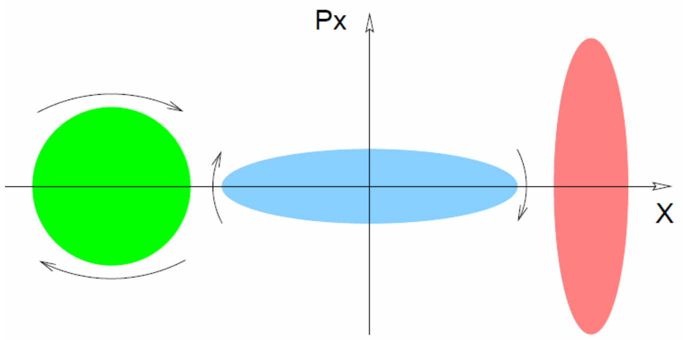
Matching section (200 MeV/c):

Two-parts system is used to decrease maximal field and chromatic effects

Inherent betas of the parts are 47 cm and 17 cm

Betatron phase advances are 90º

Phase space transformations as shown below



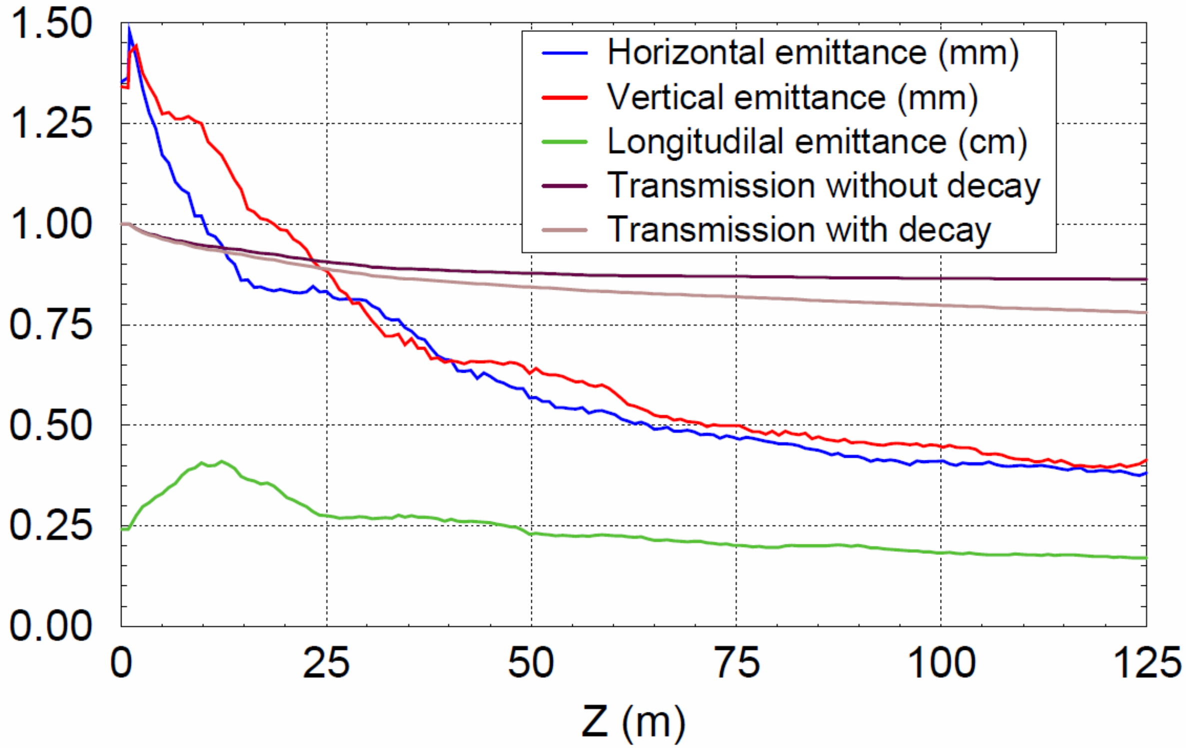
Single 90° cell would require magnetic field up to 20 T

Single 270° cell would require a modest field but creates unacceptable chromatiity.

Cooling by 2nd stage

with preceding matching section and LiH absorbers

Output of 1st stage (1A+1B) is used as injected beam



Tr_1 = 86.2%

Tr_2 = 77.8%

E_{trans}= 0.39 mm

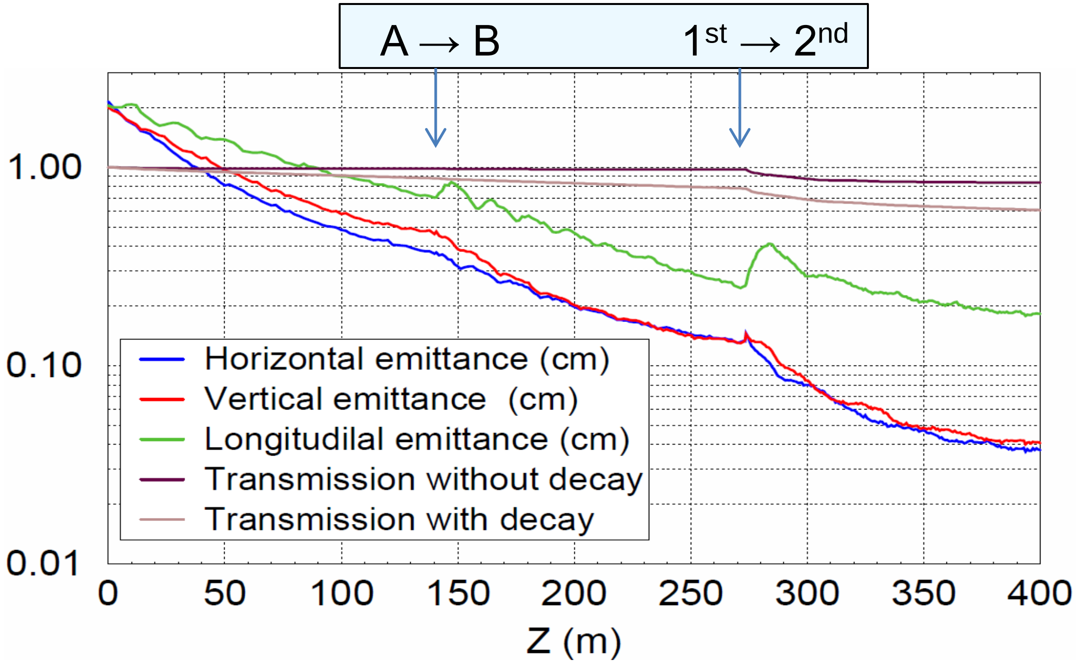
E_{long} = 1.68 mm

The matching is not perfect (chromatic aberrations + trans.-long. correlation resulting some increase of emittances (mostly longitudinal).

Complete system cooling (1^{st}A+1^{st}B+2^{nd} stage)

Self-consistent initial distribution and matching sections are used

First stage with LH_2 absorbers, second stage – with LiH



Tr_1 = 84%

Tr_2 = 61%

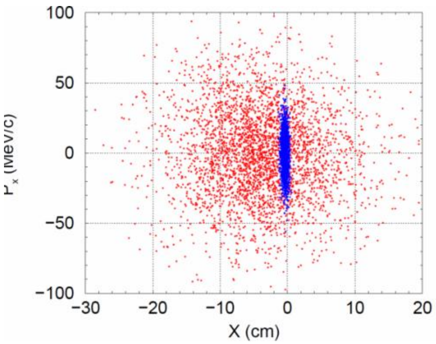
E_{long} = 1.7 mm

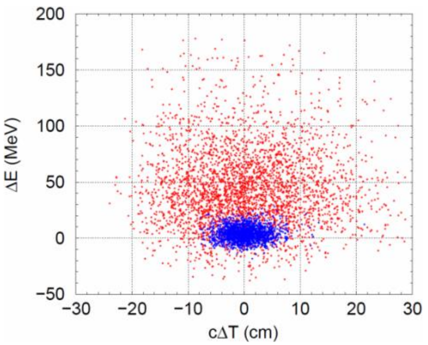
E_{trans}= 0.39 mm

Trans. and long. distributions

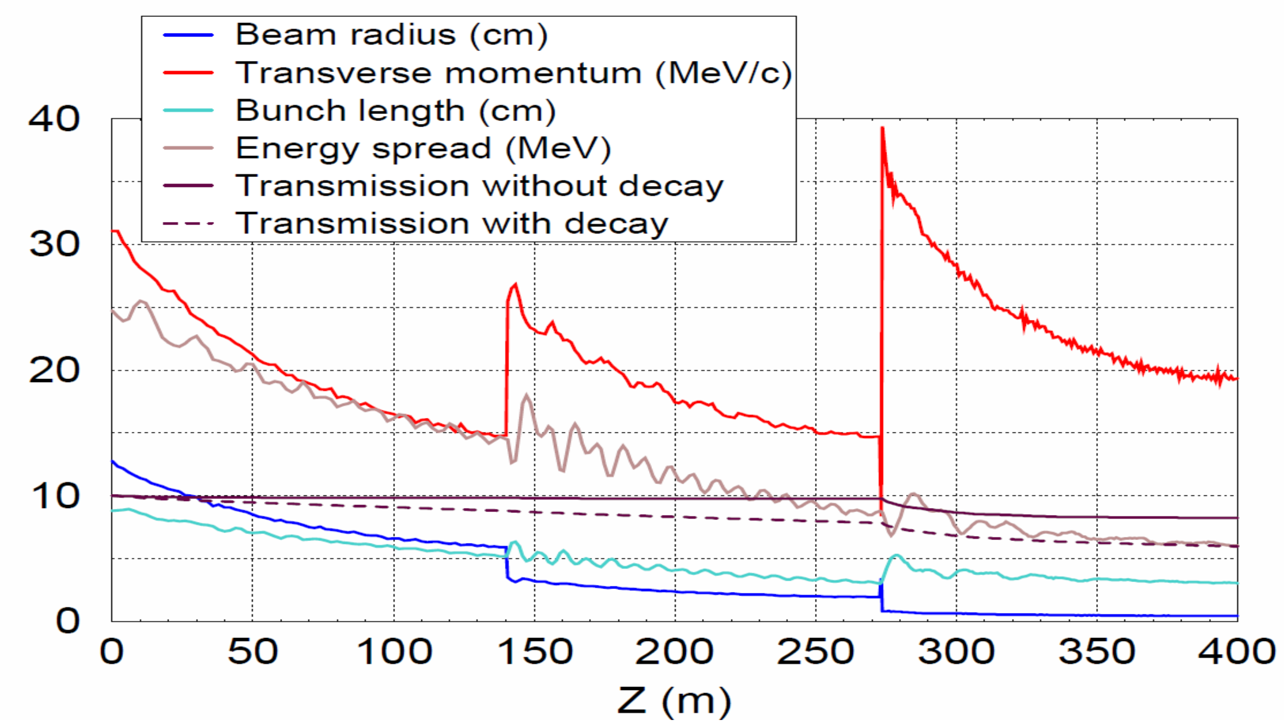
Red – before cooling

Blue – after the cooling





Complete system cooling – beam size evolution



- The beam transverse momentum steeply rises between 1st and 2nd stages.
- It causes a gain of energy spread (correlations!) and higher particle loss
- If so, more smooth momentum rise should be desirable.
- It can be reached by division of 2nd stage in two sub-stages with beta-function increased up to 8 – 10 cm in first of them (the problem is not resolved yet).

How to reach transverse emittance 0.23 mm?

I. Using LH_2 absorbers. The main problem is large length. For example, in my 2nd stage:

central length $L \approx 19$ cm, maximal in the beam length ~38 cm, opening angle ~156º.

Average beta can't be enough small in the absorber:

that is ~11 cm in the example (whereas $\beta_0 < 4.6$ cm)

$$\beta_{average} \approx \beta_0 + \frac{L^2}{12\beta_0} \geq \frac{L}{\sqrt{3}}$$

II. Higher field (20 T) + shorter cell (0.5 m) with LiH absorber.

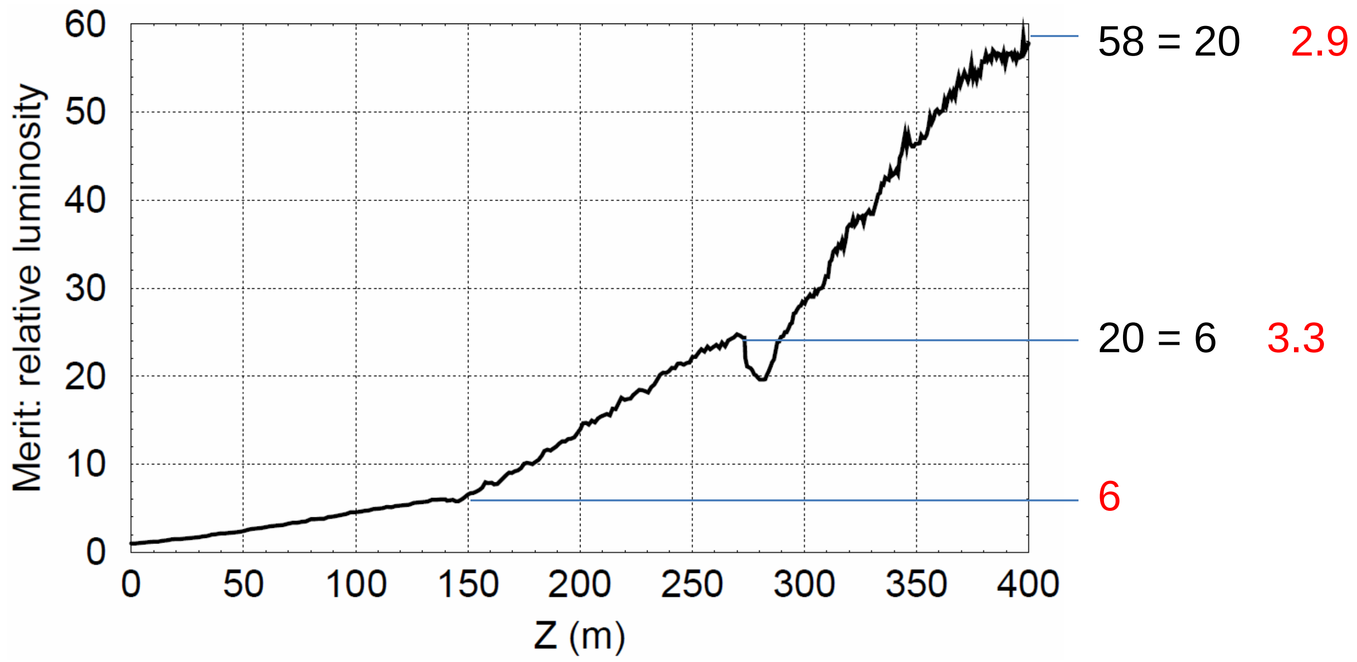
Requires 650 MHz RF that is twice shorter region of longitudinal stability. Very hard.

III. Lower momentum (100 MeV/c ?). Proportionally less magnetic field; admissible cooling rate at less accelerating gradient; shorter absorbers. However, the cells should be short, decay loss are larger, and longitudinal cooling is more complicated. The issue is open.

How much is luminosity increase due to the cooling?

With Gauss distributions

$$L \propto \frac{N^2}{r^2} \propto \frac{N^2}{(\varepsilon\beta)_{trans}} \propto \frac{N^2}{\varepsilon_{trans}\Delta z} \propto \frac{N^2}{\varepsilon_{trans}\sqrt{\varepsilon_z}} \propto \frac{(Transmission)^2}{\sqrt{\varepsilon_{6D}}}$$



- Sub-stage 1A has a maximal efficiency
- If some stage will be added to provid transverse cooling from 0.39 mm to 0.23 mm, its transmission should be not less than 77% (Merit 1.36 with transmission 90%)

Summary

- The three-stages rectilinear cooling channel of length 400 m with tilted solenoids, matching sections, and wedge absorbers allows to reach 0.39 mm transverse emittance at transmission 84% without decay, 61% with decay.
- Required magnetic field is accessible for NbTi – NbSn technology.
- Only 325 MHz RF is used in the channel.
- LH_2 absorbers have to be used in the beginning but only LiH absorbers are applicable in the last stage (a discussible point).
- Expected increase of collider luminosity due to this channel is about 60.
- Extremely steep rising of transverse momentum in the last stage causes particle loss.
  It should be improved by some smoothing of beta-function of the stage.
  Transmission 90 – 95% without decay (65-70% with decay) looks to be achievable.
- Further decrease of transverse emittance without considerable transmission degradation is a problem yet.