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6D Cooling for a Muon Collider

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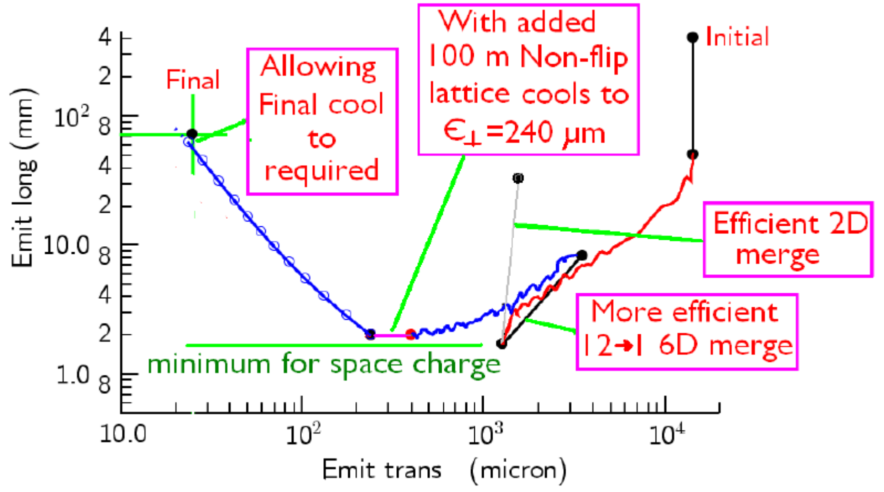
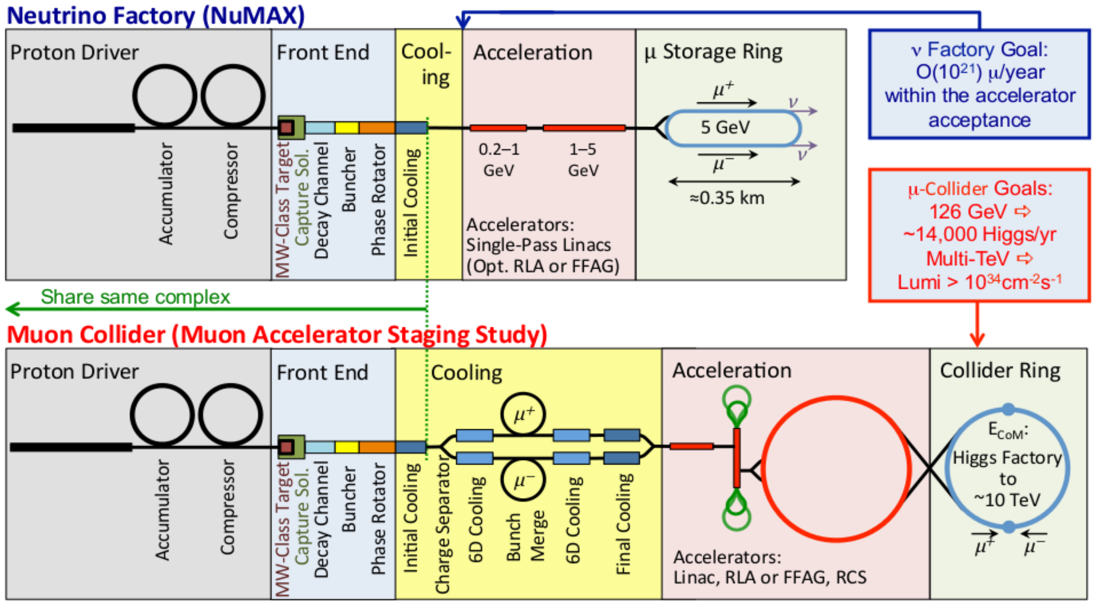
Muon Collider Facility

- Muon Collider will provide collider physics using leptons with high quality beams and compact footprint.
- The scenarios for low and high luminosity have been sketched but intensive R&D studies are required.
- The studies on Muon Collider have a strong synergy with the Neutrino Factory program.
- First demonstration of ionisation cooling (MICE) has been performed
    - What are the next steps?





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Cooling theory

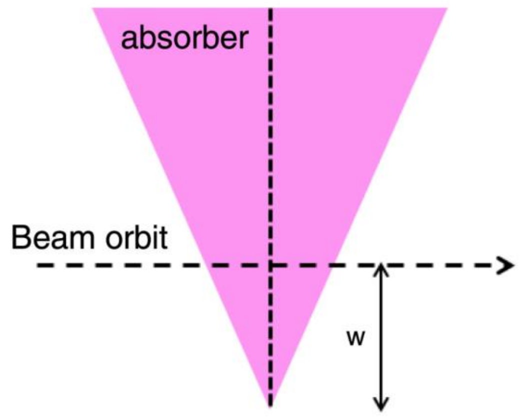
Cooling equations:

$$\frac{d\varepsilon_T}{ds} = -\frac{g_T}{\beta^2 E}\frac{dE}{ds}\varepsilon_T + \frac{\beta_T E_s^2}{2\beta^3 m_\mu c^2 L_R E}$$

$$\frac{d\varepsilon_L}{ds} = -\frac{g_L}{\beta^2 E}\frac{dE}{ds}\varepsilon_L + \frac{\beta_L}{2}\frac{d\langle \Delta E^2 \rangle}{ds}$$

$$\beta_L = \sqrt{\frac{2\pi\alpha_p}{\beta^3 \gamma e V' \sin\varphi_s \lambda_{\mathrm{RF}} m_\mu c^2}}$$

$$g_T = 1 - D/w$$



$$g_L = \frac{2\gamma^2 - 2\ln[K(\gamma^2-1)]}{\gamma^2 \ln[K(\gamma^2-1)] - (\gamma^2-1)} + \frac{D}{w}$$

$$K = 2m_e c^2/I$$

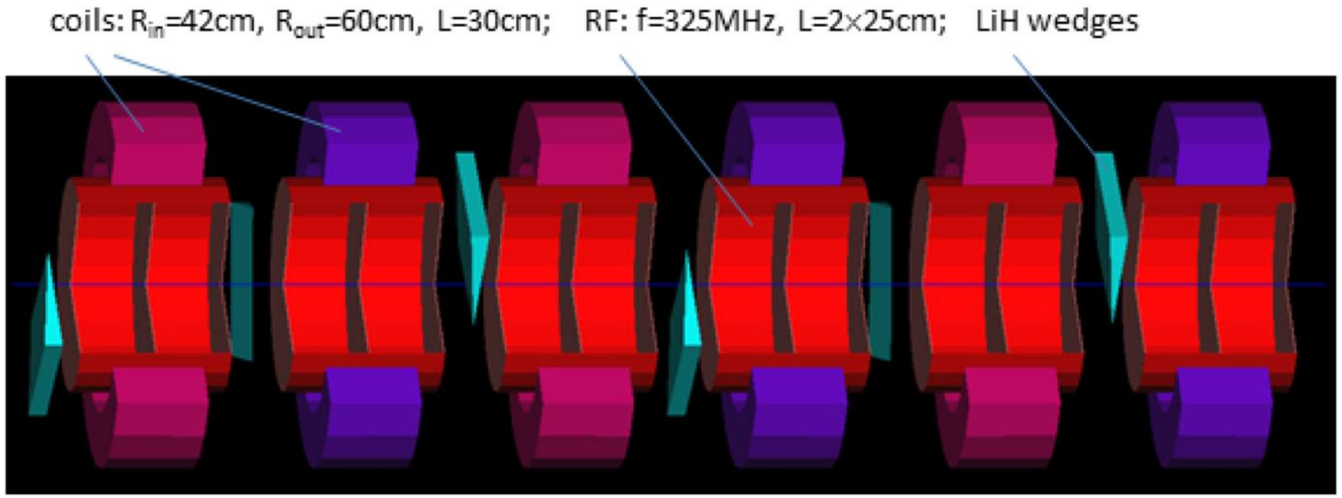
Equilibrium emittances:

$$\varepsilon_T^{\mathrm{eq}} = \left(\frac{dE}{ds}\right)^{-1} \frac{\beta_T E_s^2}{2\beta g_T m_\mu c^2 L_R}.$$

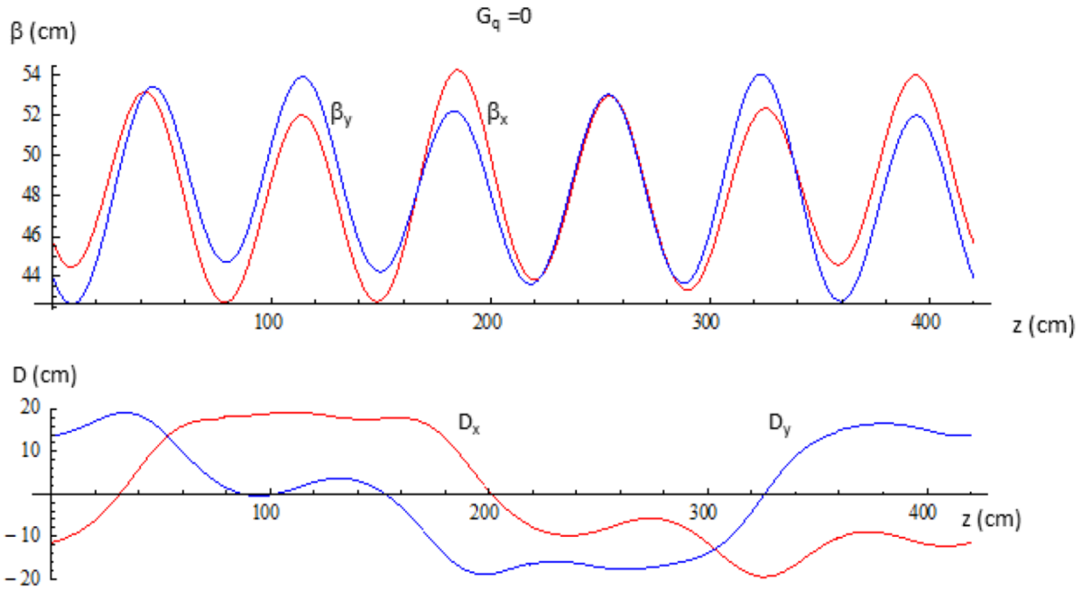
$$\varepsilon_L^{\mathrm{eq}} = \left(\frac{dE}{ds}\right)^{-1} \frac{\beta^2 E \beta_L}{2 g_L}\frac{d\langle \Delta E^2 \rangle}{ds}$$

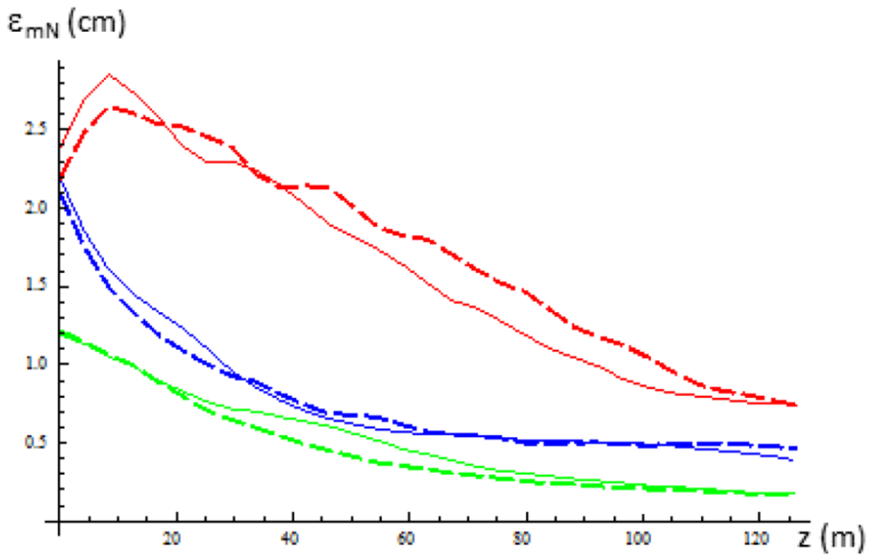
- Tight focusing
- Low Z material
- Wedge (or path length variation through absorber) with dispersion
- High RF gradient
- Momentum compaction
- Energy

Initial cooling, HFOFO Snake, Y. Alexahin

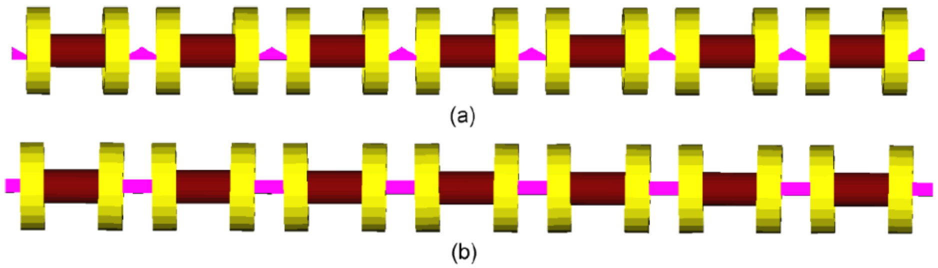


- Cools both signs of muons!
- LiH wedges + hydrogen gas
  - Safety concerns
- 6D cooling from the start
- Transverse focusing comparable to MICE

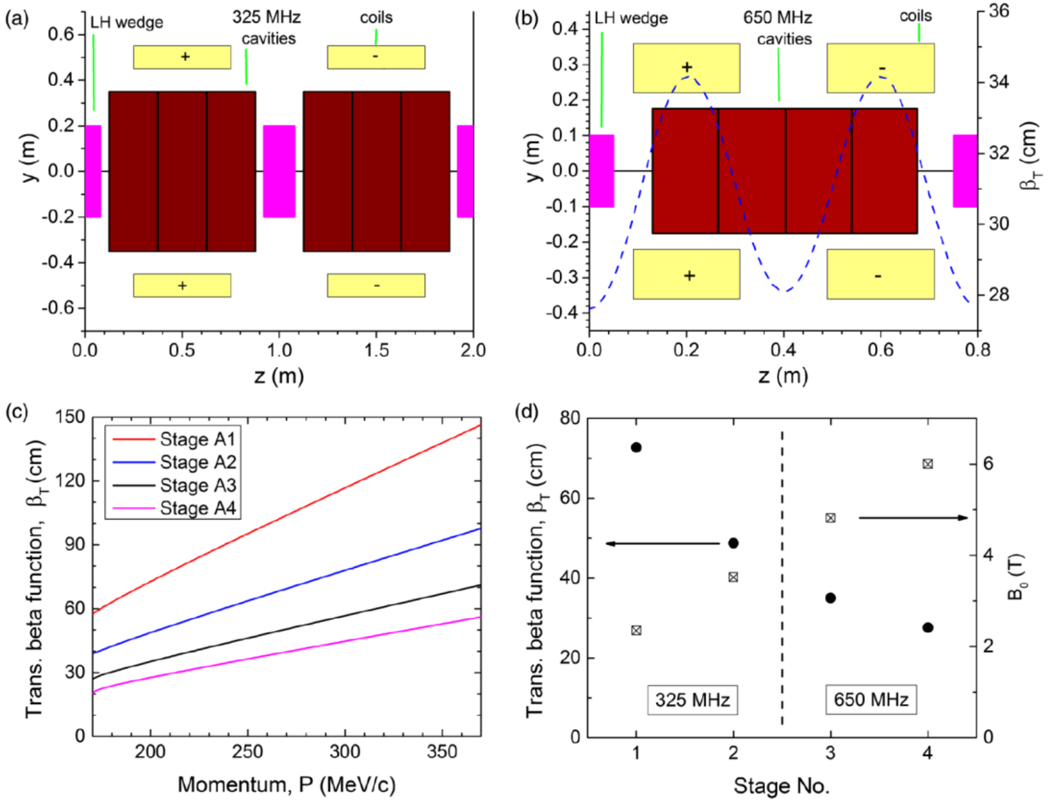




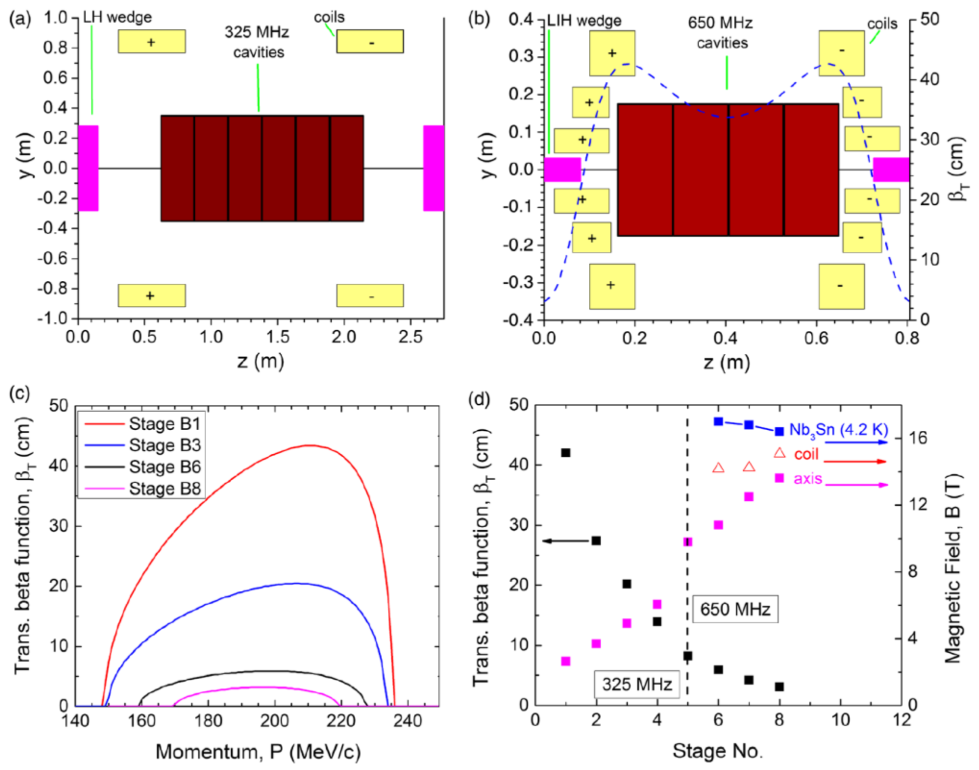
6D cooling after charge separation (I)



Rectilinear Channel



Initial stages



Advanced stages

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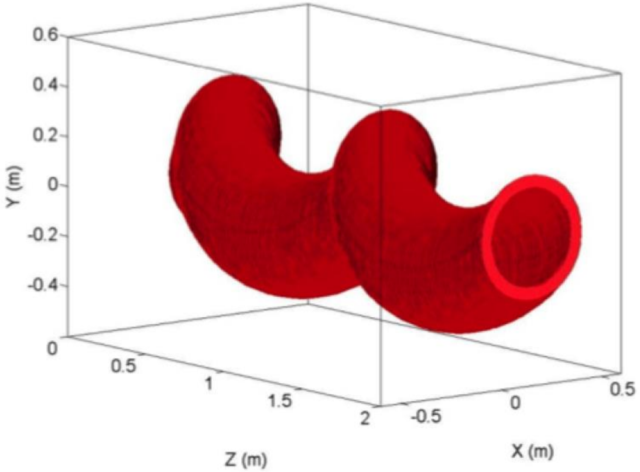
6D cooling after charge separation (I)

- Cools in 6D
- Very tight focusing in advanced stages
  - β_T~3cm, B~14T
- Good cooling performance
- Alternative: Helical Channel



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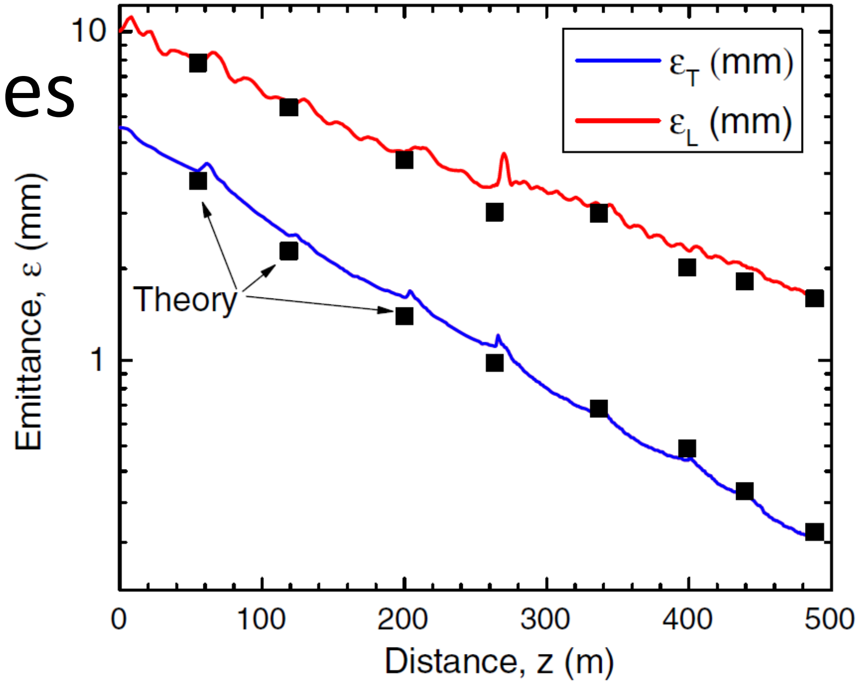

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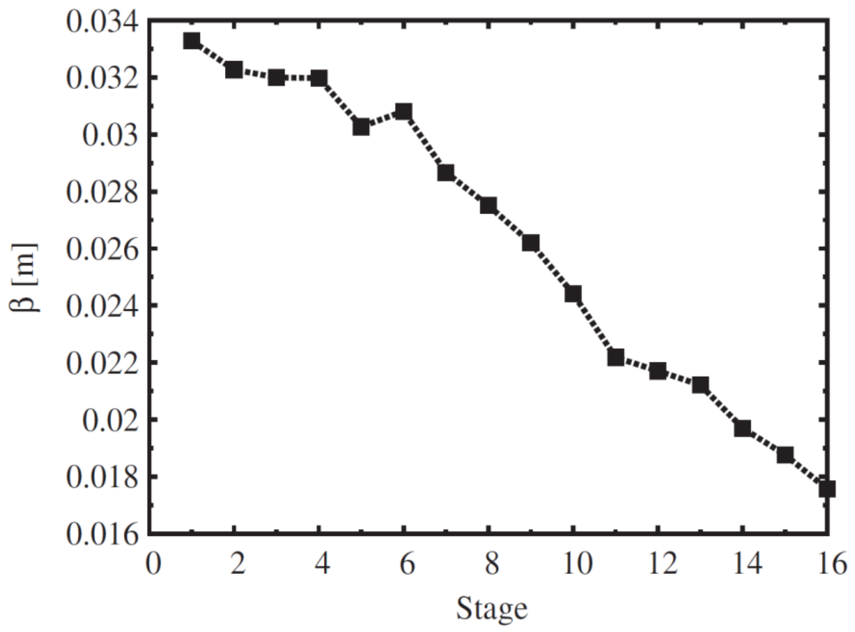
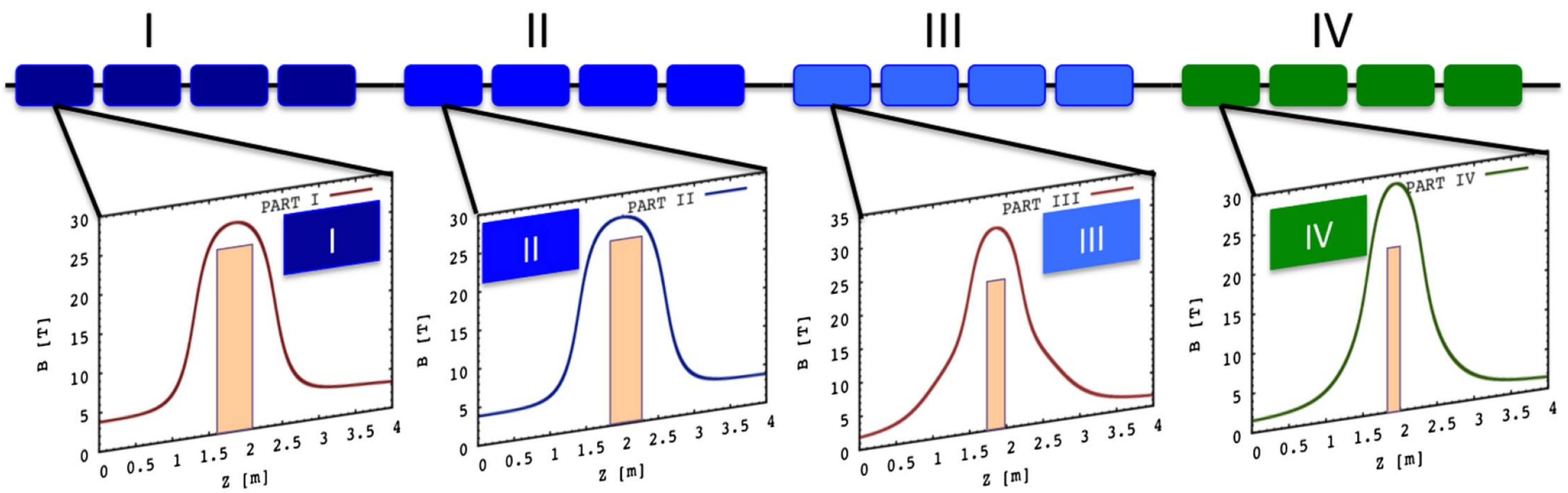
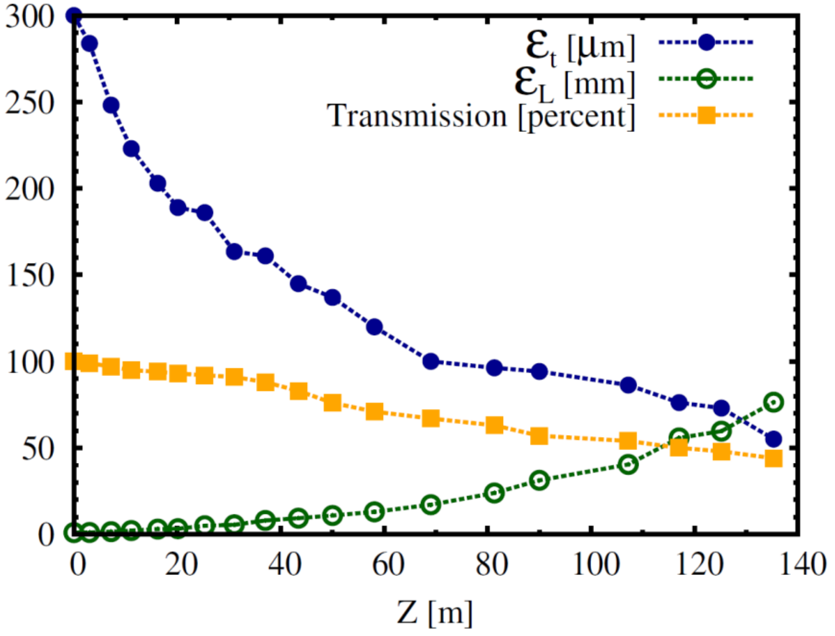
Final Cooling (for high luminosity)

- Final cooling channel:







- Mean energy gradualy reduced, RF frequency as well
- Strong 4D cooling with longitudinal heating
  - Is this the only way?
- Very tight focusing: β_T less than 2cm, B~30T
- Very challenging magnets, high cost

Phys. Rev. STAB 18.09001

Some thoughts (1)

- Design work mainly focused on performance in the past
  - Some thoughts on technology feasibility as well
  - Safety and cost reduction mostly not considered so far
- Initial cooling:
  - Liner channel of a similar behaviour definitely needed (even for the Neutrino Factory)
    - Until the injection into a ring becomes possible
  - Concerns on the use of gas hydrogen -> exchange with LiH (is RF gradient an issue)?
- 6D cooling in the rectilinear channel:
  - Very good solution, but advanced stages are challenging
    - Construction of the lattice cell(s) prototype could be very useful
- Final cooling
  - Very challenging due to a high B field
  - Is this the only route to the high luminosity machine?
    - Can we avoid the longitudinal heating?

Some thoughts (2)

- Cost reduction may be an important part of “feasibility”
  - Consider ring coolers beyond initial cooling and for the final cooling
    - Dispersion appears in a natural way
    - Injection/extraction
    - Some staging is probably unavoidable
  - Gabor Lenses for positive muons or channels, which cool both signs simultaneously (rings again)
  - MICE results might suggest that the effective equilibrium emittance for LiH and LH (with windows) is similar -> use LiH

Some thoughts (3)

- MICE demonstrated 4D cooling and can further contribute to validate material interactions and quantitative cooling figures
- MICE aims to further demonstrate principles of the emittance exchange so to validate the longitudinal cooling equation (in heating regime?) using the wedge absorber
  - Do we need further demonstration? Some work was/is planned to be addressed with proton rings (ERIT)
- Addressing a very tight focusing required for the advanced stages seems the main technological challenge
  - There would be a real benefit from constructing a prototype cell
    - It could be tested in operation with and without the beam (using the nuSTORM facility?)
- Design effort for novel advanced solutions (ring coolers, final cooling stages) seems very well in place!
  - Prototype could again be tested with and without the beam