CERN

# Introduction

## About me:

### Bernd Stechauner

- Technical Physics Student at CERN
- M.Sc. Student at TU Vienna, Austria
- Currently finishing off my M.Sc. thesis in a final cooling scheme for muon colliders
- High interests in future particle accelerators

CERN, the globe of science

## Supervision:

### Daniel Schulte

- Muon Collider study leader, CERN

### Jochen Schieck

- Professor at TU Vienna
- Director of the Institute of High Energy Physics

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# Luminosity Goal for Muon Colliders

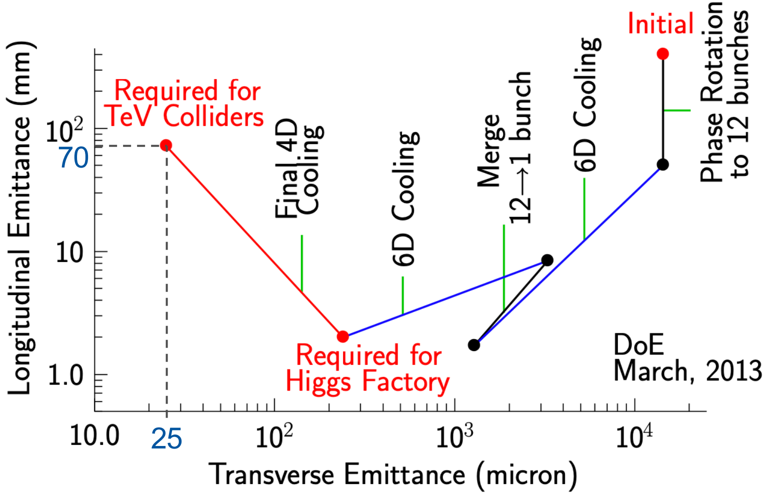
- $\mathcal{L} \approx 4 \cdot 10^{35}$ cm$^{-2}$s$^{-1}$ for c.m. energy of 14 TeV
- For reaching this aim, the beam have to be cooled

$$\mathcal{L} = \frac{N^2}{4\pi\sqrt{\beta_x\beta_y\epsilon_x\epsilon_y/\gamma^2}}\frac{\tau\gamma c}{2C}f_r$$

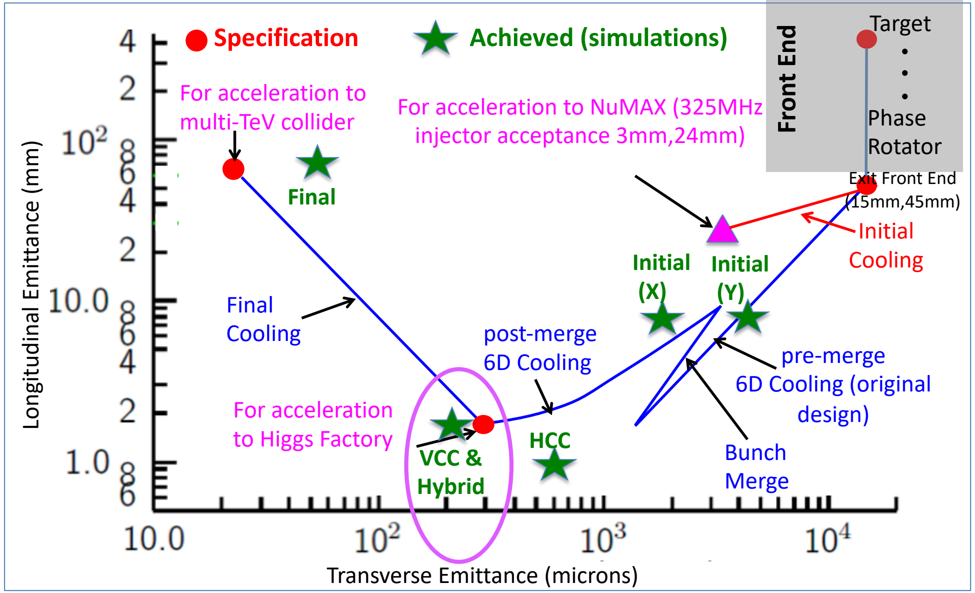
$$\epsilon_\perp = 25\,\mu m$$

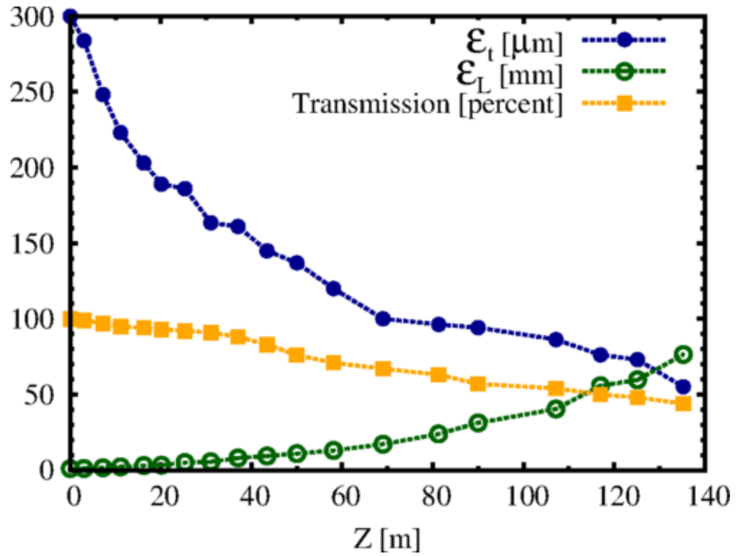
$$(\perp = x, y)$$

| Muon Collider Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Higgs Factory | | Top Threshold Options | | Multi-TeV Baselines | | |
| *Parameter* | *Units* | *Startup Operation* | *Production Operation* | *High Resolution* | *High Luminosity* | | | *Accounts for Site Radiation Mitigation* |
| CoM Energy | TeV | 0.126 | 0.126 | 0.35 | 0.35 | 1.5 | 3.0 | 6.0 |
| Avg. Luminosity | $10^{34}$cm$^{-2}$s$^{-1}$ | 0.0017 | 0.008 | 0.07 | 0.6 | 1.25 | 4.4 | 12 |
| Beam Energy Spread | % | 0.003 | 0.004 | 0.01 | 0.1 | 0.1 | 0.1 | 0.1 |
| Higgs* or Top$^+$ Production/$10^7$sec | | 3,500* | 13,500* | 7,000$^+$ | 60,000$^+$ | 37,500* | 200,000* | 820,000* |
| Circumference | km | 0.3 | 0.3 | 0.7 | 0.7 | 2.5 | 4.5 | 6 |
| No. of IPs | | 1 | 1 | 1 | 1 | 2 | 2 | 2 |
| Repetition Rate | Hz | 30 | 15 | 15 | 15 | 15 | 12 | 6 |
| β* | cm | 3.3 | 1.7 | 1.5 | 0.5 | 1 (0.5-2) | 0.5 (0.3-3) | 0.25 |
| No. muons/bunch | $10^{12}$ | 2 | 4 | 4 | 3 | 2 | 2 | 2 |
| No. bunches/beam | | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Norm. Trans. Emittance, $\varepsilon_{TN}$ | π mm-rad | 0.4 | 0.2 | 0.2 | 0.05 | 0.025 | 0.025 | 0.025 |
| Norm. Long. Emittance, $\varepsilon_{LN}$ | π mm-rad | 1 | 1.5 | 1.5 | 10 | 70 | 70 | 70 |
| Bunch Length, $\sigma_s$ | cm | 5.6 | 6.3 | 0.9 | 0.5 | 1 | 0.5 | 0.2 |
| Proton Driver Power | MW | 4$^\#$ | 4 | 4 | 4 | 4 | 4 | 1.6 |



- The issue, the recent study form H. K. Sayed et al reached a transversal emittance of around 55 microns
- Factor **2** higher than needed for the MAP scheme
- Initial beam parameters before injecting into the cooling channel: $E_{Kin} \approx 70$ MeV (135 MeV/c), $\varepsilon_{x,y} \approx 300\ \mu m$




**High field – low energy muon ionization cooling channel**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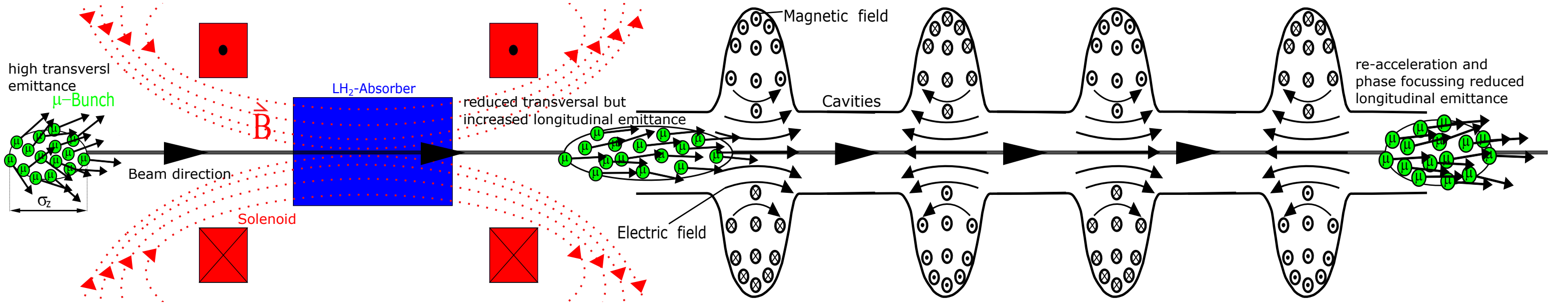
# Final cooling channel, repetition

- Ionization cooling is the only useful technique for cooling muon beams, because e.g., it is fast, and muon-materials interaction is not too strong
- Cooling channel consists off: absorbers, high mag. Fields (e.g. solenoids) and RF for re-acceleration
- Below a certain equilibrium emittance, the beam will be cooled inside the channel
- Heating effects due to Rutherford scattering




A. N. Skrinsky, V. V. Parkhomchuk 1981
D. V. Neuffer 1993

# Final Cooling

$$\frac{d\epsilon_{\perp,\mathrm{N}}}{dz} = -\frac{\epsilon_{\perp,\mathrm{N}}}{E\beta^2}\left\langle\frac{\partial E}{\partial z}\right\rangle + \frac{\beta_\perp(13.6[\mathrm{MeV}])^2}{2\beta^3 E m c^2 L_\mathrm{R}} = \mathrm{cooling} + \mathrm{heating}$$

## How to achieve low emittance?

- Beam below a certain eqil. emittance

$$\epsilon_\mathrm{eq} = \frac{\beta_\perp(13.6[\mathrm{MeV}])^2}{2\beta m c^2 L_\mathrm{R}\left\langle\frac{\partial E}{\partial z}\right\rangle}$$

- Low energies increases the cooling term
- At the same time, this leads higher values for the Bethe-Bloch-eq.
- Low $\beta_\perp$ decreases the heating term

$$\beta_\perp[\mu\mathrm{m}] = \frac{2\mathrm{p}[\mathrm{MeV}]}{\mathrm{c}\cdot\mathrm{B}[\mathrm{T}]}\cdot 10^{12}$$

- High radiation length (low Z elemtens) decreases the heating term

- $\epsilon_N$…normalized emittance
- $\beta_\perp$…Betatron-function
- $\beta$…Lorentz-beta
- $m_\mu c^2$...muon energy at rest
- $L_R$…radiation length
- $E$…energy
- $\left\langle\frac{\partial E}{\partial z}\right\rangle$…Bethe-Bloch-Equation

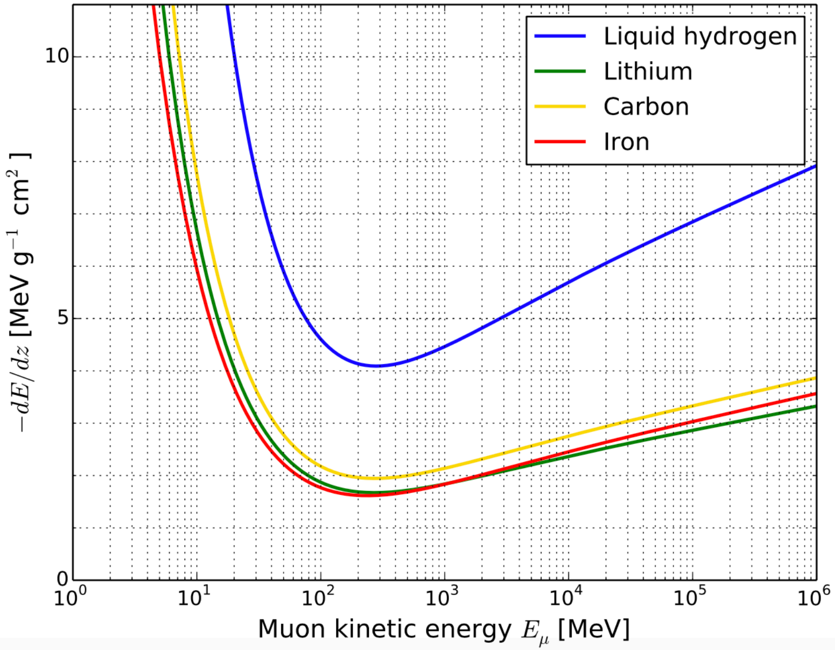
| Z | Material | Z/A | $\rho$ [g/cm$^3$] | $X_0$ [g/cm$^2$] | I [ev] | dE/cm$^9$ | $\theta_0$ [mrad/cm] | equiv.$\theta_0$ [mrad] |
|---|---|---|---|---|---|---|---|---|
| 1 | HYDROGEN liq | 0.99 | 0.071 | 61.3 | 19.2 | 0.31 | 2.61 | 1.48 |
| 2 | HELIUM | 0.50 | 0.125 | 94.3 | 41.8 | 0.26 | 2.80 | 1.74 |
| 3 | LITHIUM | 0.43 | 0.534 | 82.8 | 40 | 0.96 | 6.19 | 1.99 |
| 4 | BERYLLIUM | 0.44 | 1.848 | 65.2 | 63.7 | 3.27 | 13.01 | 2.26 |
| 5 | BORON | 0.46 | 2.370 | 53.2 | 76 | 4.29 | 16.34 | 2.48 |
| 6 | AMORPHOUS CARBON | 0.50 | 2.000 | 42.7 | 81 | 3.89 | 16.76 | 2.67 |

# Thesis goal

$$-\frac{\partial E}{\partial z} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \left( \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} \right) - \beta^2 - \frac{\delta}{2} \right]$$

- Highest magnetic field in solenoids was around 30T in the past studies
- For this thesis, solenoidal fields between 40 and 50T will be included
- In the moment: highest B field at 45.5T with REBCO
- Developed at National High Magnetic Field Laboratory, Florida State University https://doi.org/10.1038/s41586-019-1293-1
- Efficient cooling at $5 < E_{Kin} < 200$ MeV and usage of liquid hydrogen

$$\frac{d\epsilon_{\perp,N}}{dz} = -\frac{\epsilon_{\perp,N}}{E\beta^2} \left\langle \frac{\partial E}{\partial z} \right\rangle + \frac{\beta_\perp (13.6[\text{MeV}])^2}{2\beta^3 E m c^2 L_R}$$

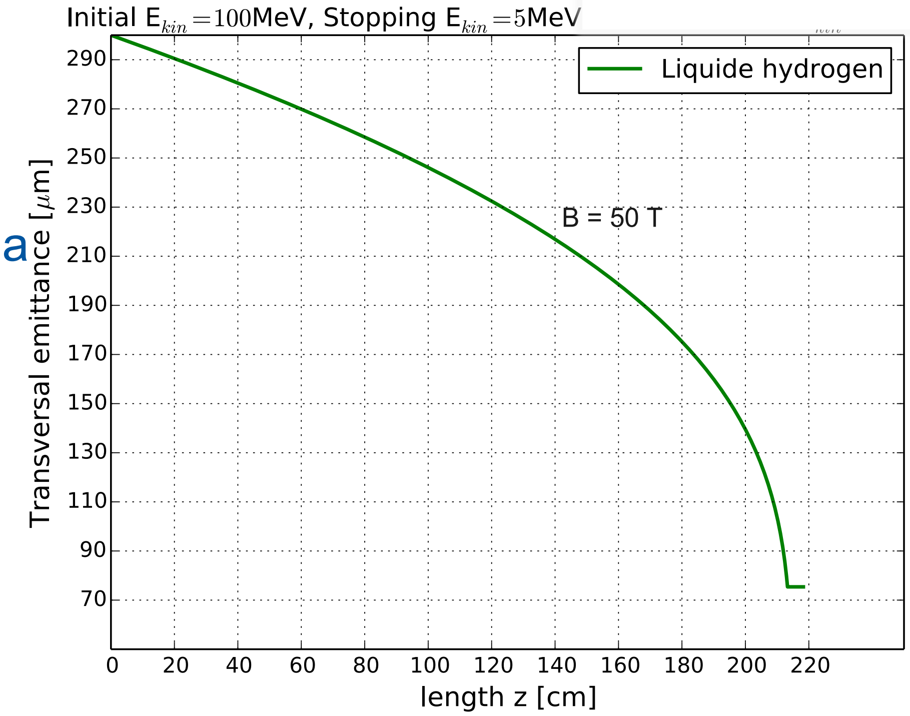


# Calculation 1

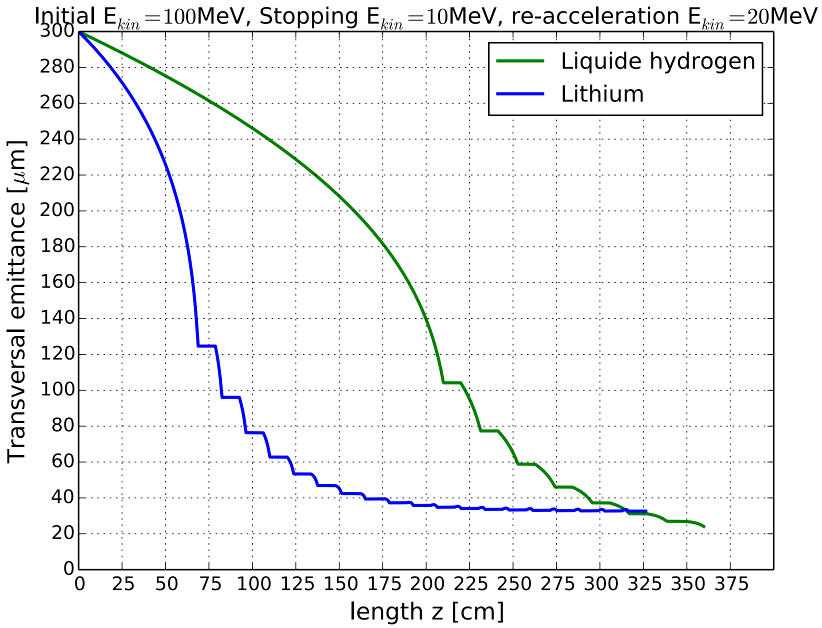
$$\frac{d\epsilon_{\perp,\mathrm{N}}}{dz} = -\frac{\epsilon_{\perp,\mathrm{N}}}{E\beta^2}\left\langle\frac{\partial E}{\partial z}\right\rangle + \frac{\beta_\perp (13.6[\mathrm{MeV}])^2}{2\beta^3 Emc^2 L_\mathrm{R}}$$

Assumtion:

- Muon beam injects into $LH_2$ absorber with $E_{kin}$= 100 MeV and leaves it after reaching 5 MeV
- The Absorber is inside a solenoid, with a $B_z$ = 50 T in beam direction
- It shows, cooling is more efficient the lower the kinetic energy of the beam is



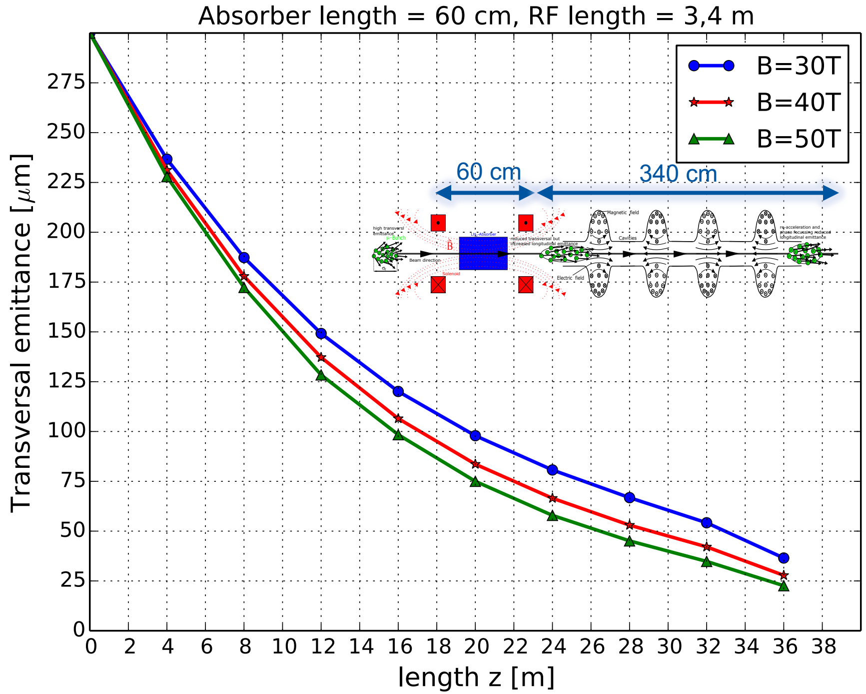
# Calculation 2

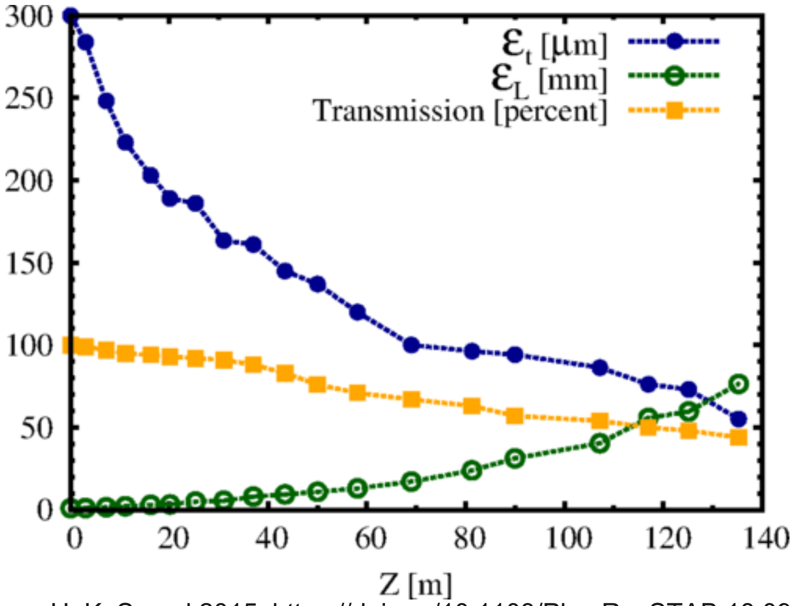



- Alternating sections of Absorbers (inside $B_z$= 50 T) re-accelerations
- Initial beam energy at $E_{kin}$= 100 MeV
- Beam leaves each absorber when reaching 10 MeV
- Afterwards it will be re-accelerated to $E_{kin}$= 20 MeV
- No complex RF sections are included
- For comparison: channel with only $LH_2$ and one with only Li absorbers
- Beam cooling more efficient with $LH_2$, due to larger radiation length and higher Bethe-Bloch values

# Calculation 3

Initial $E_{kin}$= 60 MeV




H. K. Sayed 2015; https://doi.org/10.1103/PhysRevSTAB.18.091001

# Current work

**ICOOL**

- Simulate beam behave through a basic cooling lattice with ICOOL
- First lattice contains $LH_2$ absorber, with/without solenoidal field
- Compare emittance with/without absorber
- Further, adding RF section after absorber, etc.

**Geant4**

- Try to re-produce the ICOOL values with a Geant4 simulation