Final Cooling System Design

Elena Fol

C. Rogers, D. Schulte, B. Stechauner, A. Latina, A. Grudiev

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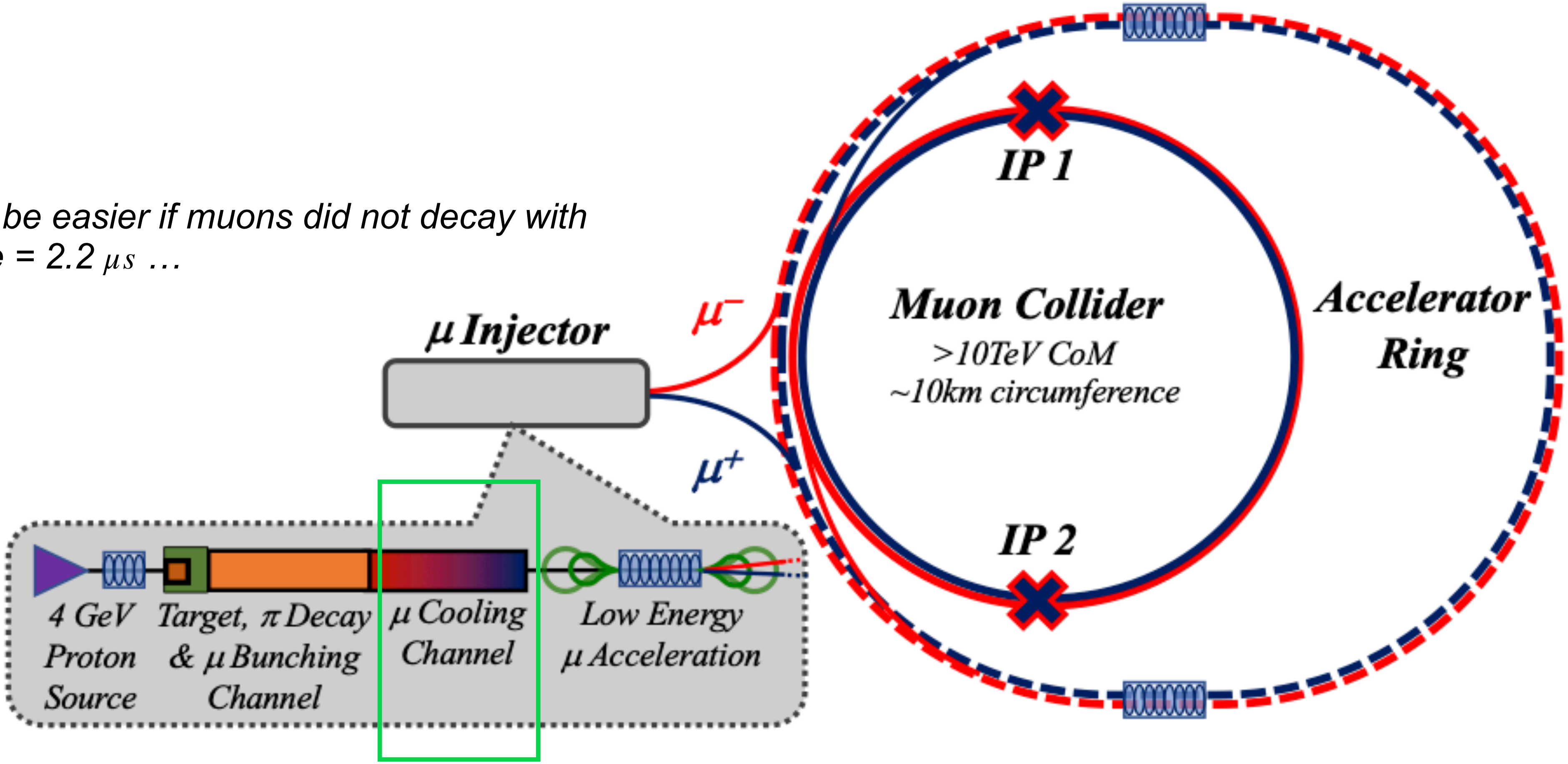
Outline

- Final Cooling overview and baseline
- Design strategy and applied methods
- Estimating optimal cooling path
- Solenoid optics matching
- Longitudinal paramaters control
- Transmission considerations
- Conclusions and next steps

Final Cooling for Muon Collider

Would be easier if muons did not decay with lifetime = 2.2 μs …



Muons are created as decay products and form a beam with a **huge emittance**

- Cooling (the reduction of occupied phase-space by muons) is required

Traditional cooling techniques are not suitable due to **muons lifetime**

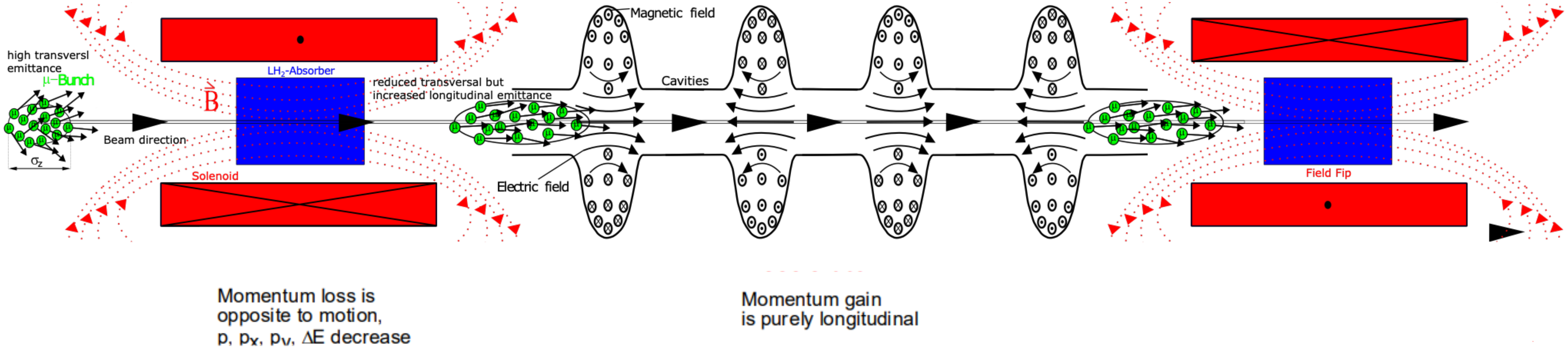
- **Ionisation cooling**: fast novel technique, principle is demonstrated by MICE collaboration

Technology and challenges of Final Cooling

Ionisation cooling: the only technique that works on the **timescale of the muon lifetime**

- Muons passing through a material —> energy loss due to the interaction with absorber material
- Reduction of normalised beam emittance
- Re-accelerating the beam to restore the longitudinal momentum

B. Stechauner



$$\frac{d\varepsilon_T}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_T + \frac{\beta\gamma\beta_T}{2}\frac{d\theta_0^2}{ds}$$

Energy loss term

Multiple scattering term

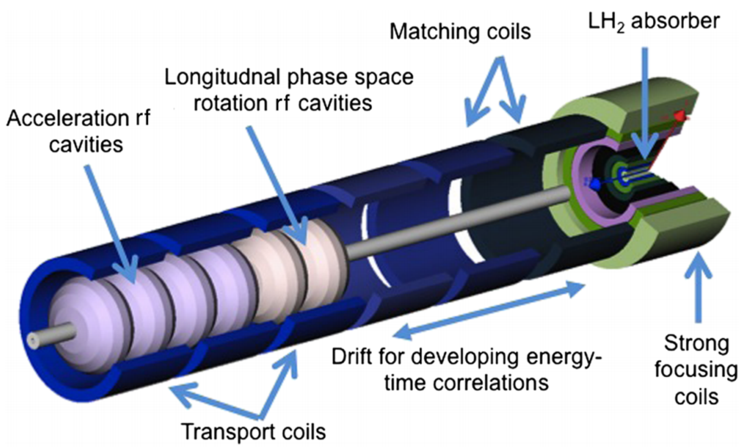
Lowering transverse emittance on the costs of :

➡ Longitudinal emittance growth
➡ Bunch length increasing: challenging RF set-up
➡ Energy spread (needs to be kept within the accelerator acceptance)
➡ Number of survived particles

Baseline Design and simulation tools

Baseline: MAP study

- Starting beam parameters: $\epsilon_{\perp} = 300\mu m, \epsilon_{\parallel} = 1.5mm, \sigma t = 50mm, \sigma E = 3.2MeV$
- High-field magnets **25—32 T**, beam momenta ranging from **135 MeV/c to 70 MeV/c**
- Achieved in previous studies: $\varepsilon_{\perp}$ = 55 µm, with $\varepsilon_{\parallel}$ = 76 mm, transmission of 50%
- Target is $\varepsilon_{\perp}$ = 25µm: should be possible to achieve with stronger focusing fields, alternative absorber configuration, advanced optimisation



High field – low energy muon ionization cooling channel
Hisham Kamal Sayed, Robert B. Palmer, and David Neuffer
Phys. Rev. ST Accel. Beams **18**, 091001 – Published 4 September 2015

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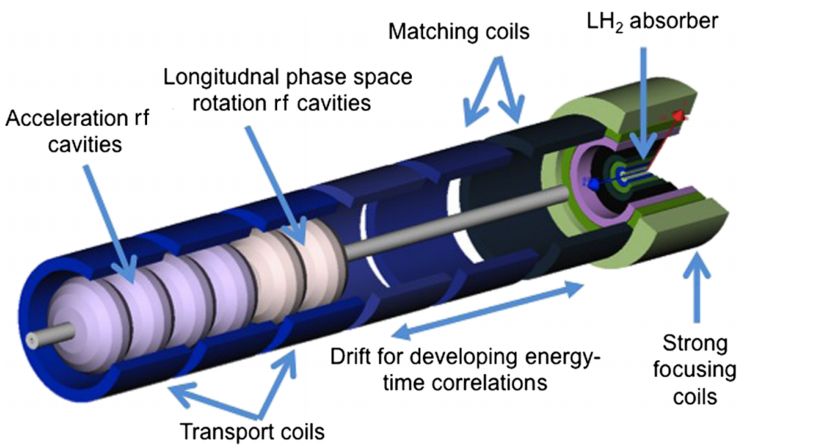

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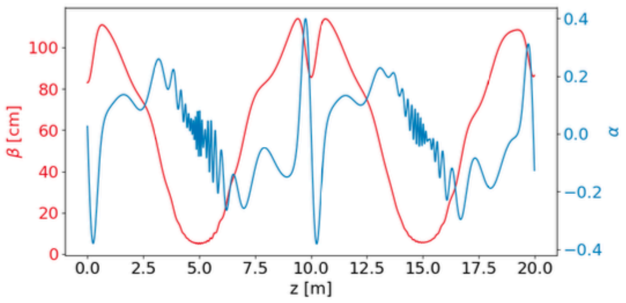
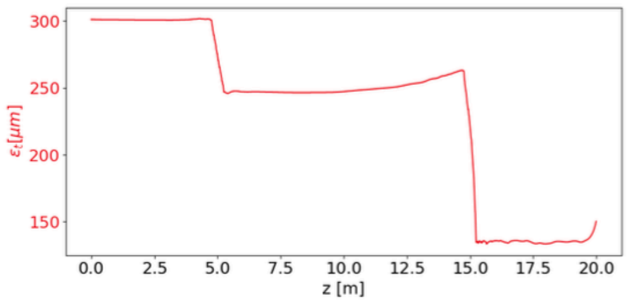
First steps using ICOOL simulations:

✓ Python-wrapper to ease generation of input files and tracking results analysis
✓ Linear optics matching
✓ Transverse cooling using Liquid Hydrogen absorber
▶ No re-acceleration
▶ Studied transverse aspects only





E. Fol, C.T. Rogers, J. Schieck, D. Schulte, and B. Stechauner, "Automated Design and Optimization of the Final Cooling for a Muon Collider", in Proc. IPAC'22
E. Fol, C. Rogers, D. Schulte, "Machine Learning-Based Modelling of Muon Beam Ionization Cooling", in Proc. IPAC'22

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International MUON Collider Collaboration

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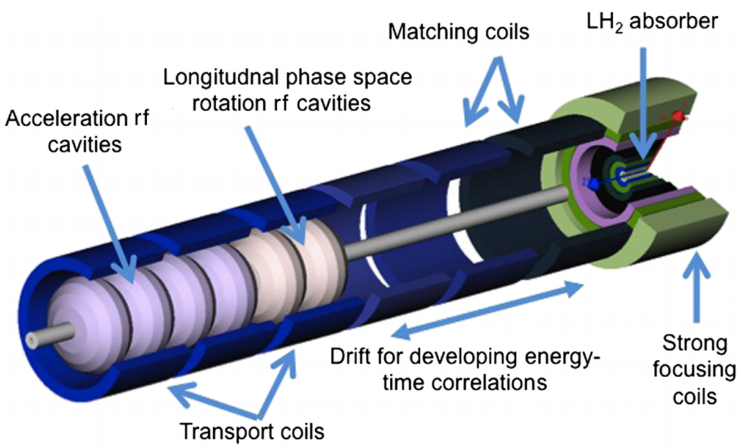

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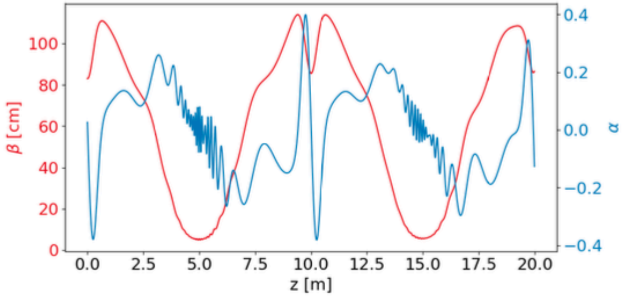

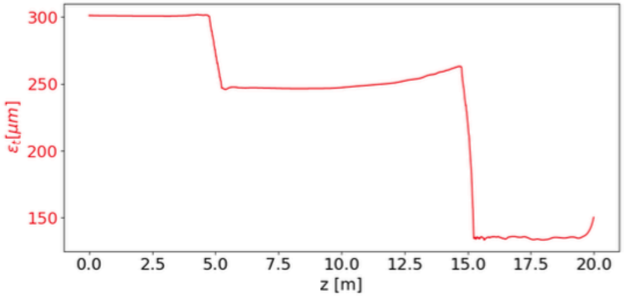

Towards integrated Final Cooling design:

- RF-Track (developed by A. Latina): https://gitlab.cern.ch/rf-track/download
- Includes collective effects, relevant lattice elements, python and octave interface
- Specific ionisation cooling effects have been recently added (multiple scattering, muon decays)
- Allows simulation and optimization of a full cooling cell, including solenoid fields, absorbers and RF

➡ ***Further presented studies are focused on RF-Track simulations (thanks to A. Latina)***

Design optimisation strategy

I. Analytical cooling model for "backwards" optimisation **starting from final** $\epsilon_{\perp} = 25\mu m$

➡ Provides **starting momenta** and **absorber lengths** for all cells

II. Optimize high-field solenoid and matching coils to ensure efficient transverse cooling

➡ **Mitigates emittance blow up** in the fridge fields and **controls the optics in absorber** region

III. Simplified model for the optimization of **bunch rotation and re-acceleration**

➡ Provides **drifts** and **rotation** "kicks" needed to mitigate the increase of longitudinal emittance, initial estimates for RF- system design

Current work in progress

IV. Integrated **end-to-end simulation** of the complete cooling channel using RF-Track

➡ RF frequencies, gradients, and lengths derived from optimised estimations

➡ Considering different RF-system options (e.g. multi-harmonics RF)

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Applying numerical optimization and Machine Learning techniques:

- Comparison of different algorithms and **proof of concept for various ML-based techniques for design optimisation**:
  "Machine Learning in accelerators operation and design", IFAST 2nd annual meeting
- **BOBYQA**: derivative-free and fast executable
- **Bayesian Optimization**: converges much faster compared to e.g. differential evolution algorithm, provides uncertainty estimation
- **Surrogate models** to obtain initial guesses for optimisers or to allow "backwards" optimisation
- Introduction of an **anomaly detection** method for identification of bunch cuts.

Initial beam momenta and absorber thickness

I. Analytical cooling model for "backwards" optimisation **starting from final** $\epsilon_\perp = 25\mu m$

$$\frac{d\epsilon_\perp}{ds} = -\frac{\epsilon_\perp}{\beta^2 E}\frac{dE}{ds} + \frac{\beta_\perp E_s^2}{2\beta^3 m c^2 L_R E}$$

$$\frac{dE}{ds} = 4\pi N_A \rho r_e^2 m_e c^2 \frac{Z}{A}\left[\frac{1}{\beta^2}\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{I(Z)}\right) - 1 - \frac{\delta}{2\beta^2}\right]$$

➡ Provides **starting momenta** and **absorber lengths** for all cells

- 40 T, Liquid hydrogen absorber, initial beam: $P_z = 135MeV/c, \epsilon_\perp = 300\mu m, \epsilon_\parallel = 1.5mm, \sigma t = 50mm, \sigma E = 3.2MeV$

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13	70	15	50	40	55.5
12	76	13	70	50	40
11	75	15	85	70	53.5
10	89.2	22	100	85	67.5
9	92.6	21	115	100	74
8	110	25	125	114.6	93.6
7	115	34	140	124.7	93.4
6	124.5	37	155	140	103.4
5	120	36	175	155	98.5
4	127.5	43	200	175	102.4
3	130	40	225	200	108.5
2	125	45	260	220	99
1	135	55	**300**	250	106

- *Note: this assumes ideal optics matching and control of longitudinal parameters*
- *Transmission is not included*

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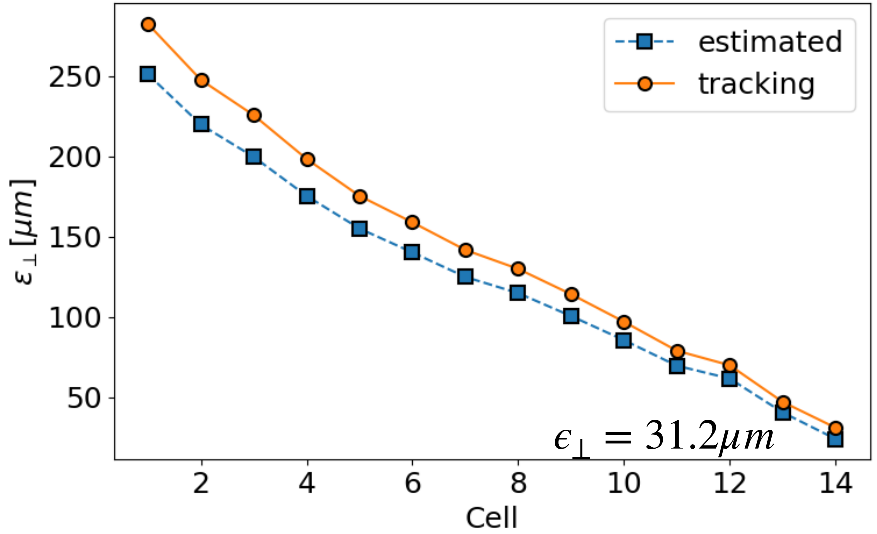

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✓ Tracking simulations using **optimised parameters** confirm the potential for **lower emittance** (compared to the baseline studies)

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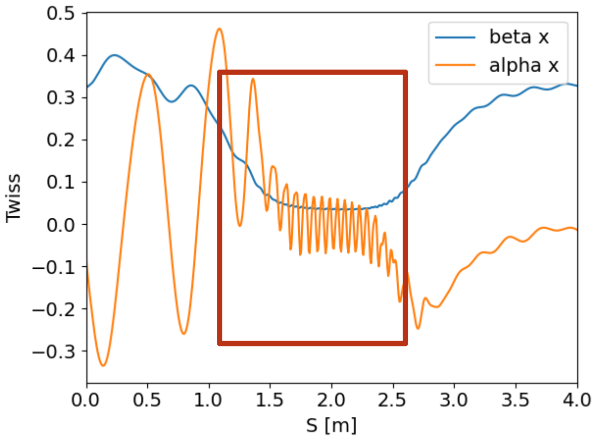
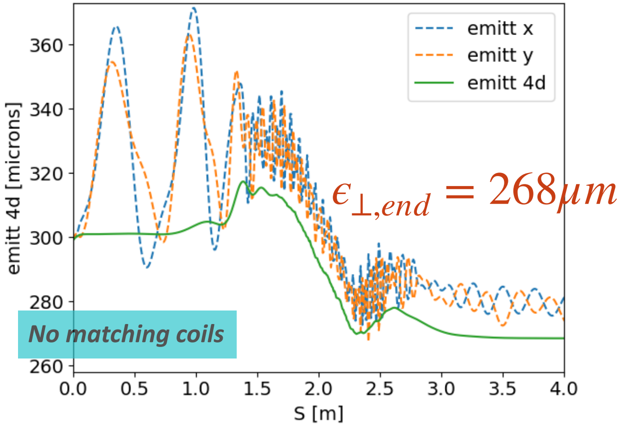
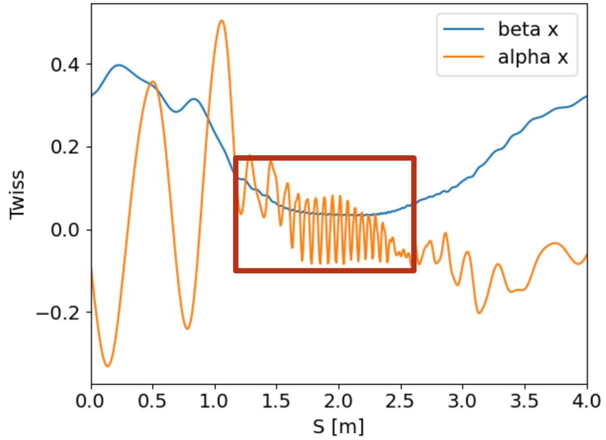
Optics matching

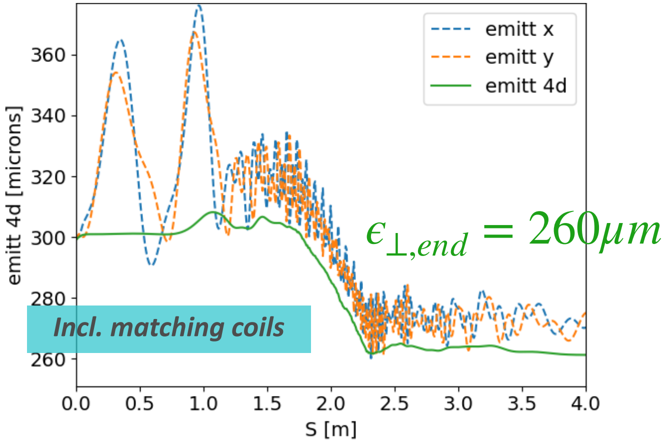
II. Optimize high-field solenoid and matching coils to ensure efficient transverse cooling

➡ **Mitigates emittance blow up** in the fridge fields and **controls the optics in absorber region**









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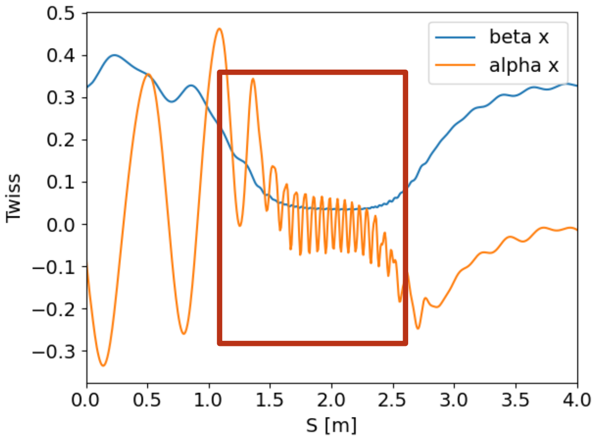
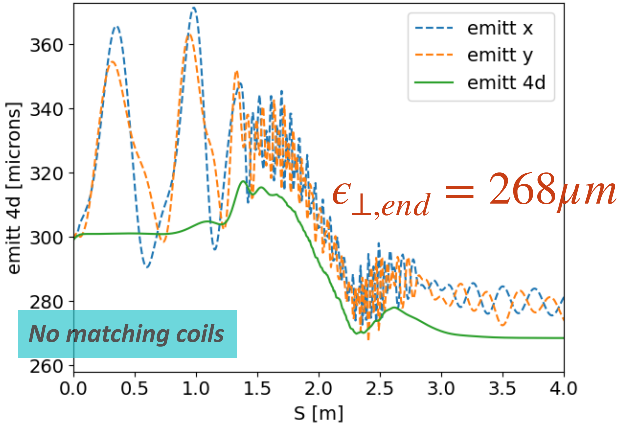
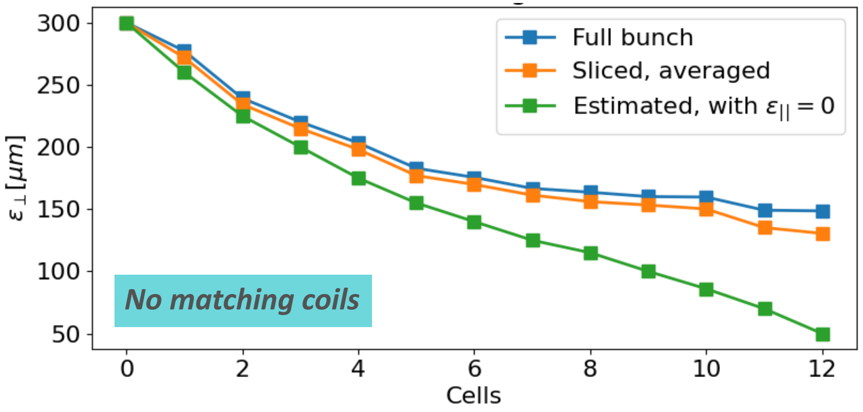
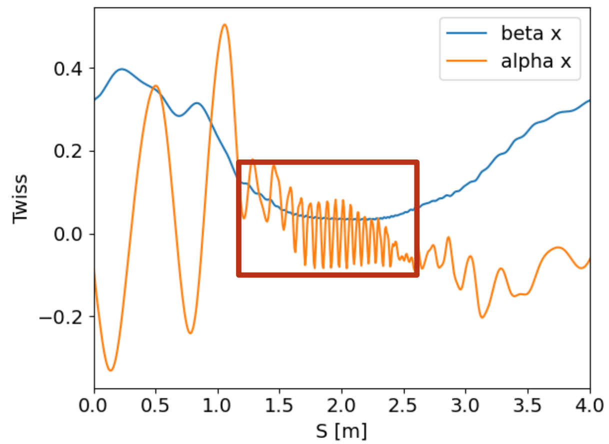
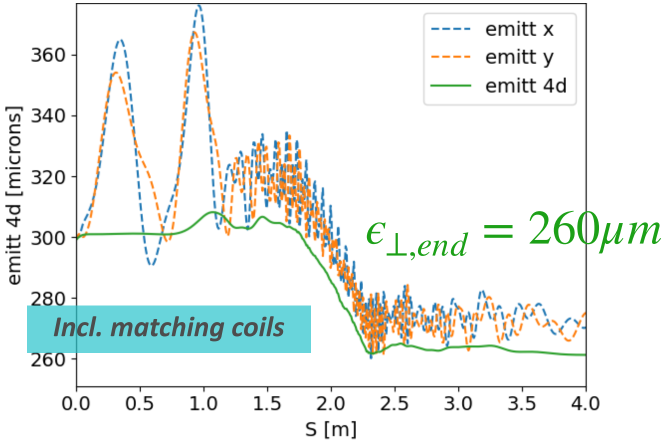
Indicates that the **optics control is crucial** to avoid emittance blow up and **achieve desired cooling performance**

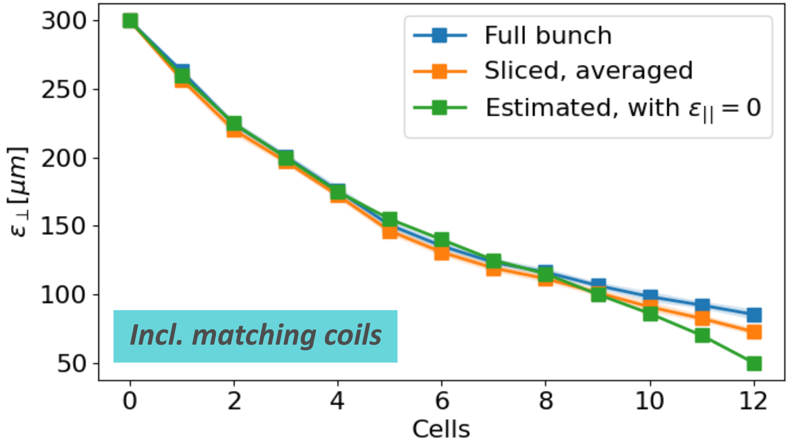










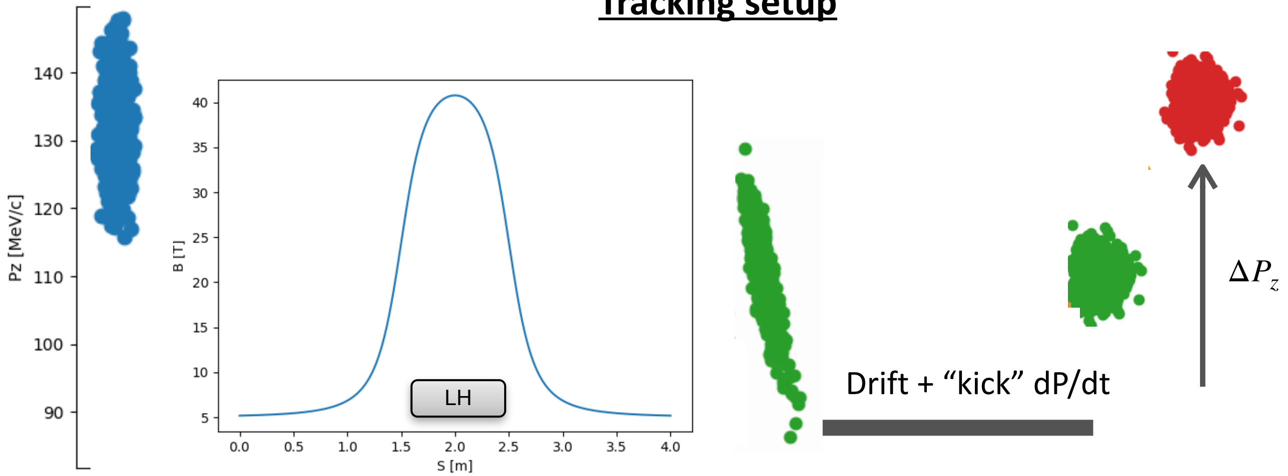


Control of bunch length and energy spread

III. Simplified model for the optimization of **bunch rotation** and **re-acceleration**

➡ Optimise **drift length** (to develop a correlation) and **rotation** (to reduce the energy spread)

Tracking setup



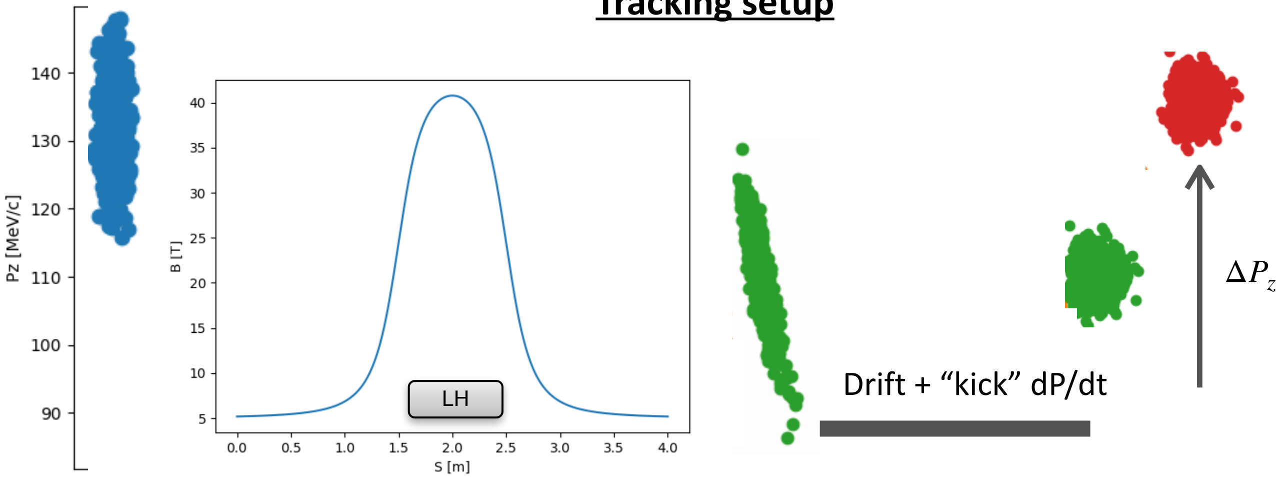
Optimised field and absorber settings

Control of bunch length and energy spread

III. Simplified model for the optimization of **bunch rotation** and **re-acceleration**

➡ Optimise drift length (to develop a correlation) and rotation slope (to reduce the energy spread)

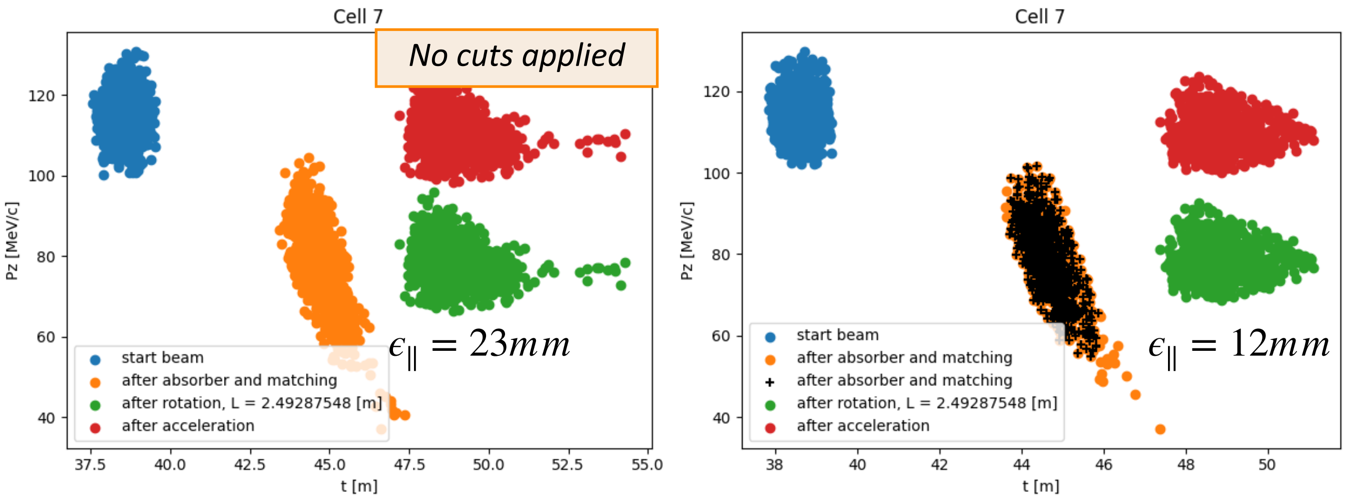
Tracking setup



Optimised field and absorber settings

Problem: "Outlying" particles

- Important to "clean" the beam to estimate the correlation to be corrected
  - Choice of particles included in the bunch affects the rotation slope optimisation
  - Too high emittance can be caused by a few "outliers"
  - 3 sigma-cut not always reliable, especially towards the end of the channel
  - "Anomaly detection" approach - cut off 1% of points which are further away (considering all **6 dimensions** in phase space)



Complete Final Cooling channel: results

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Optimised towards longitudinal emittance reduction

Cell	Drift [m]	f [MHz]	G [MV/m]	$\epsilon_{\|\|} [mm]$	σE	σ_t [mm]
1	0.17	123	11.1	2.5	1.7	122
2	0.61	142	11.9	3.7	2.1	105
3	0.28	118	10.9	3.5	2.5	126
4	0.95	72	8.5	5.8	3.5	210
5	0.2	91	9.5	7.5	4.8	296
6	0.21	65	8	9.1	4.7	232
7	0.61	35	6	12.1	3.6	431
8	0.91	25	5	13.8	3.0	593
9	0.44	18	4.2	20	3.1	828
10	0.5	12	3.5	32	3.4	1248
11	1.29	6.5	2.5	61	5.1	2380
12	0.49	5.3	2.3	80.4	5.3	2870
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Absorber and momenta requirements for transverse cooling

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3	130	40	225	200
2	125	45	260	220
1	135	55	**300**	250

- Scaling for the estimates of RF frequencies and gradients based on optimised simplified model:

  $\sigma_t = \lambda/20, G = 1.2\sqrt{f}$
- Will be further optimised

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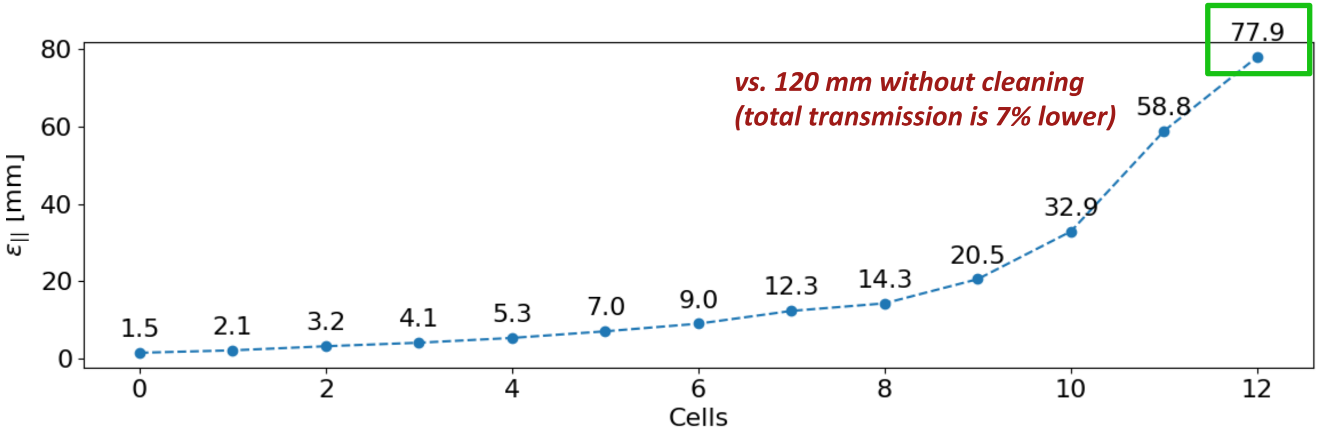
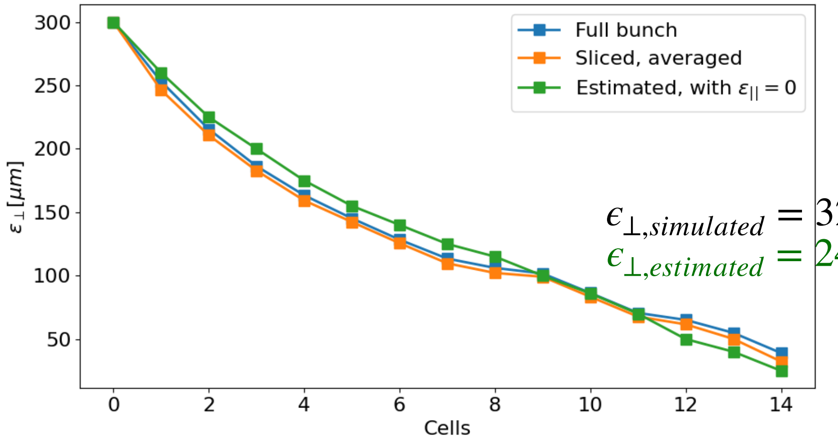
Tracking through the entire channel, using optimal solenoid fields settings





$\epsilon_{\perp,simulated} = 32.3\mu m$

$\epsilon_{\perp,estimated} = 24.5\mu m$

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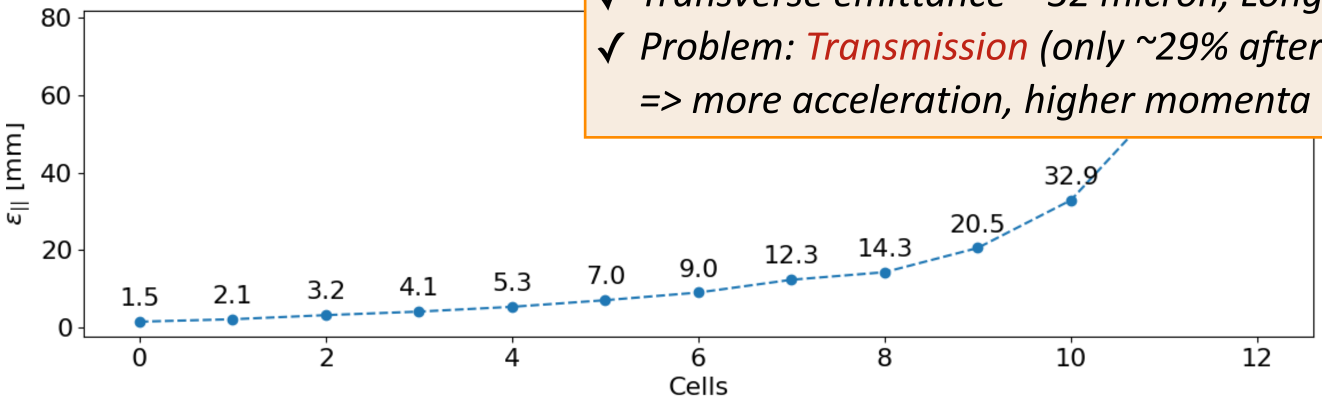
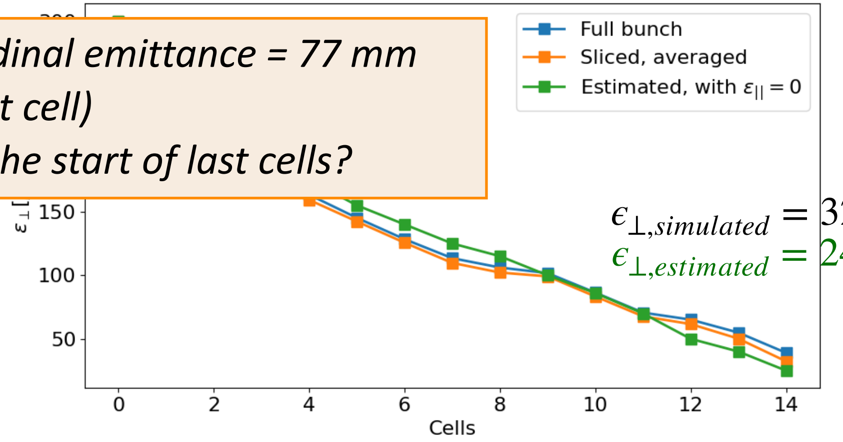
Tracking through the entire channel, using optimal solenoid fields settings

- ✓ *Transverse emittance = 32 micron, Longitudinal emittance = 77 mm*
- ✓ *Problem: Transmission (only ~29% after last cell)*
  => more acceleration, higher momenta at the start of last cells?





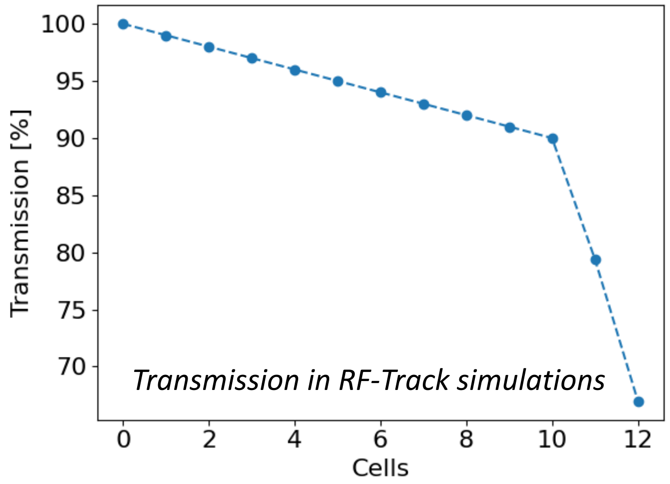
$\epsilon_{\perp,simulated} = 32.3\mu m$

$\epsilon_{\perp,estimated} = 24.5\mu m$

Initial beam momenta and absorber thickness

- Starting momenta in cooling cells are ranging from 135 MeV/c to 65 MeV/c
- High drop in transmission in the last cells: caused by **low initial energy?**
- How big is the **impact of decays** due to the muon lifetime?

➡ **Re-optimisation** of absorber lengths and **initial momenta in a higher range**.



Initial beam momenta and absorber thickness

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Collaboration

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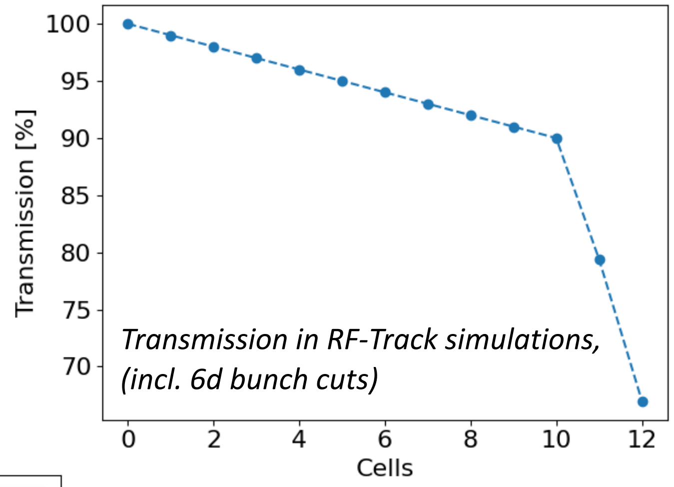
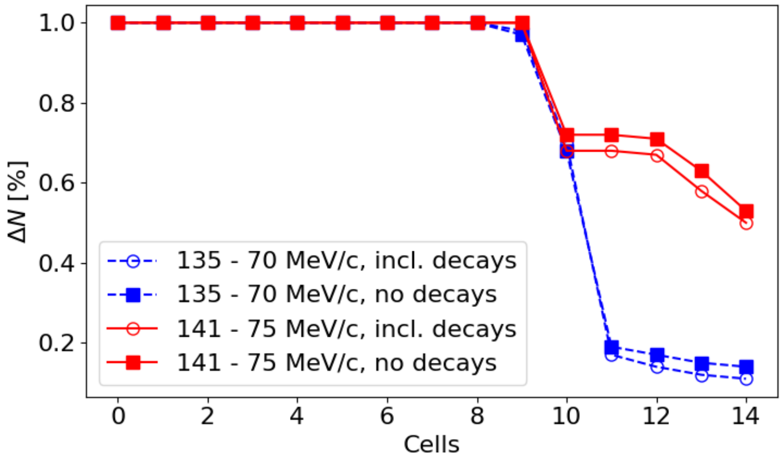
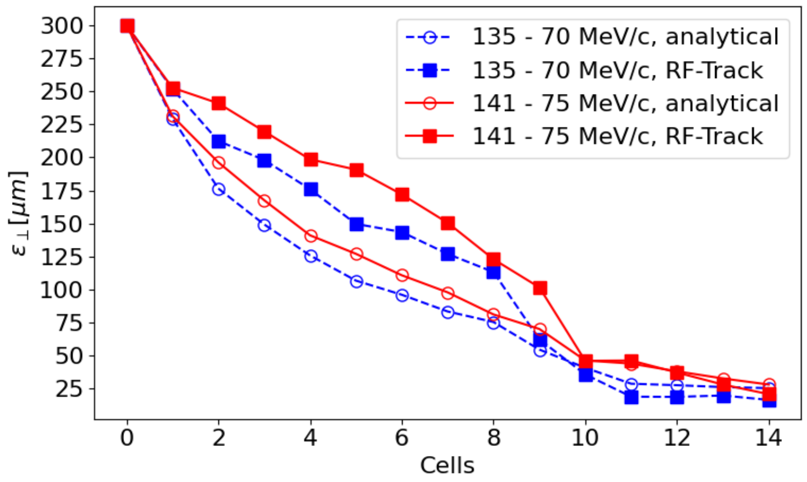


<u>RF-Track simulations after optimisation using higher starting momenta</u>

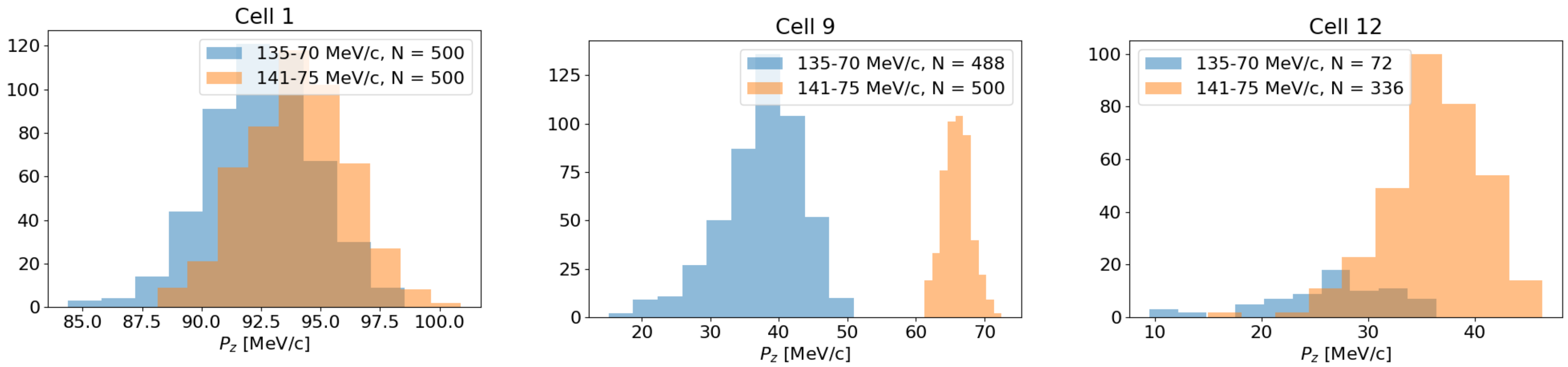




➡ Higher momenta allow **better transmission** while keeping final r**equired emittance** value.
➡ Low impact of decay losses

Initial beam momenta and absorber thickness

- **Momentum distribution in the bunch after passing through the LH absorber**



- Slower particles are lost and cause the transmission reduction towards the end of the channel
- Crucial for the optimisation of the optimal cooling path

➡ Re-optimisation **following the presented strategy** using **higher initial momenta** in progress.

Summary and outlook

- Demonstrated a strategy for the optimisation of final cooling design
- Identification of suitable ML techniques and their integration into optimisation framework
- Values below the baseline results achieved in (simplified) simulations
- Identified bottlenecks and found mitigation approaches
    - significance of optics matching,
    - transmission to be considered in optimal cooling path definition)

- Parametrisation of RF-systems using the optimised bunch rotation and re-acceleration parameters
- Consideration of feasible RF-design options: e.g. multi-harmonics RF (allows the use of higher frequencies, shorter acceleration path is possible.)
- End-to-end simulation using re-optimized parameters for 140-75 MeV/c beam momenta range.