International
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Final Cooling Design Progress

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Outline

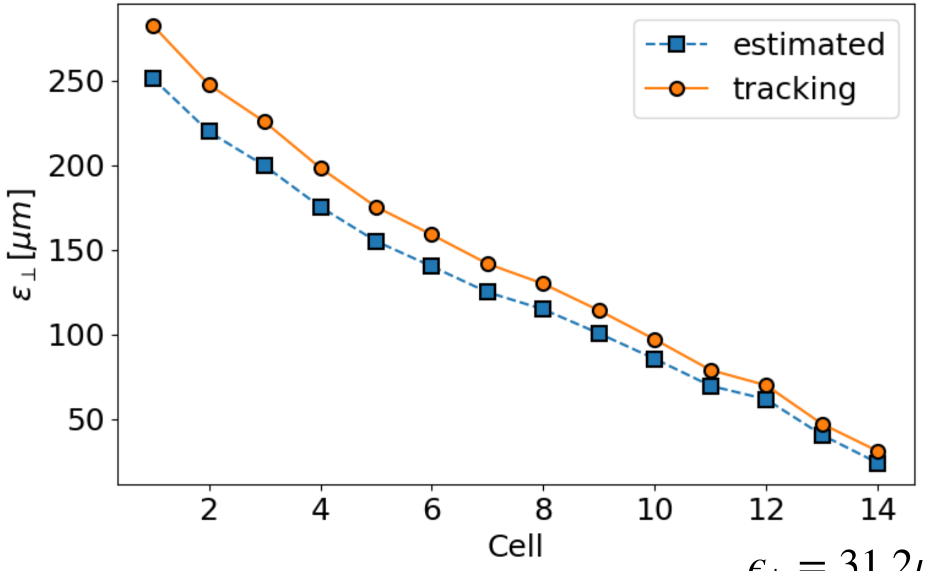
- Recap: transverse emittance optimisation results
- Emittance blow-up reduction: matching coils
- Longitudinal parameters optimisation using a simplified RF-model for phase-space rotation and acceleration
- Impact of appropriate bunch distribution cuts
- Results using optimised bunch rotation and optimised optics
- RF structures parameterisation
- Next steps

Transverse emittance reduction: RF-Track vs. cooling equations

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

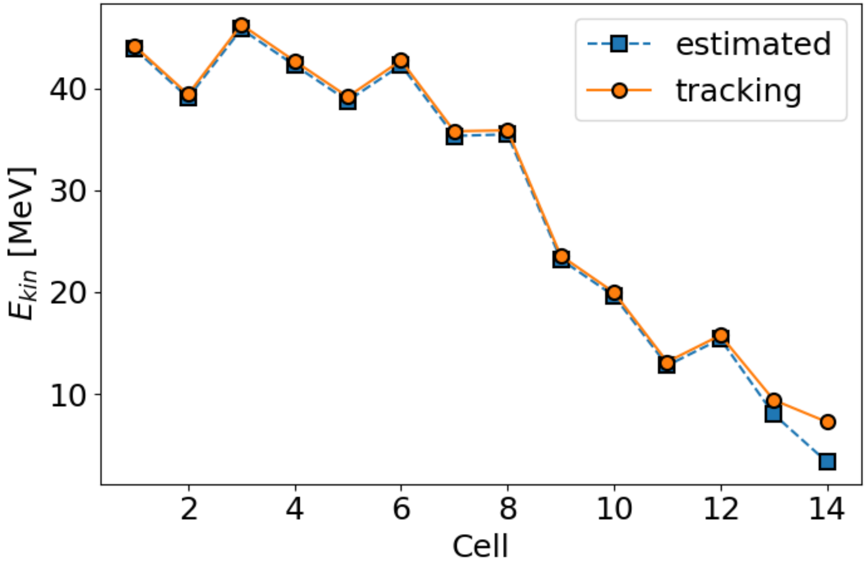
$$\frac{dE}{ds} = 4\pi N_A \rho r_e^2 m_e c^2 \frac{Z}{A}\left[\frac{1}{\beta^2}\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{I(Z)}\right) - 1 - \frac{\delta}{2\beta^2}\right]$$

- 40 T (static field), Liquid hydrogen absorber, initial beam: $P_z = 135MeV/c, \epsilon_\perp = 300\mu m, \epsilon_{\|} = 50mm, \sigma t = 50mm, \sigma E = 3.2MeV$



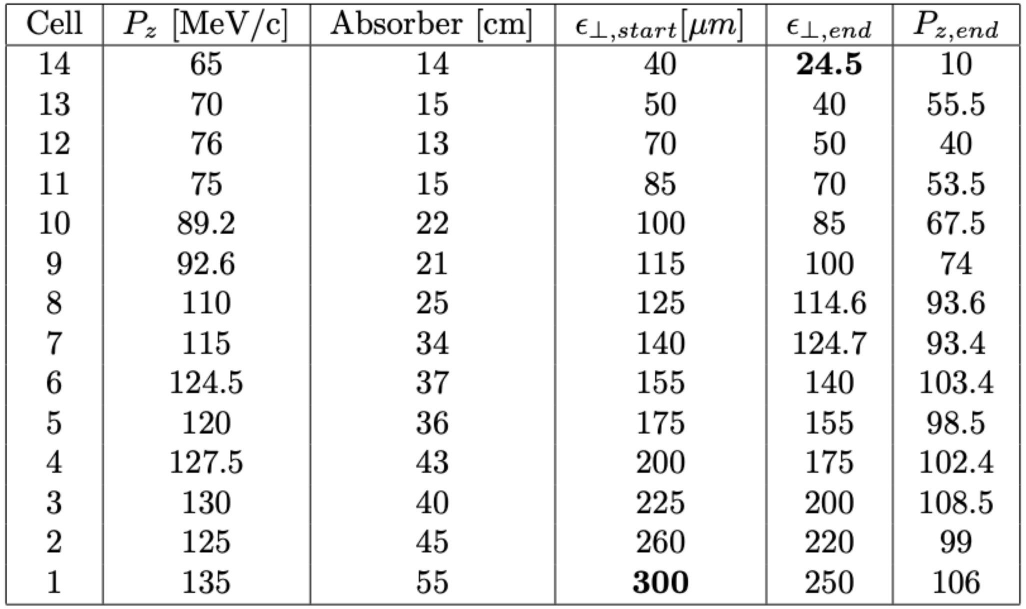
$\epsilon_\perp = 31.2\mu m$

Longitudinal spread included

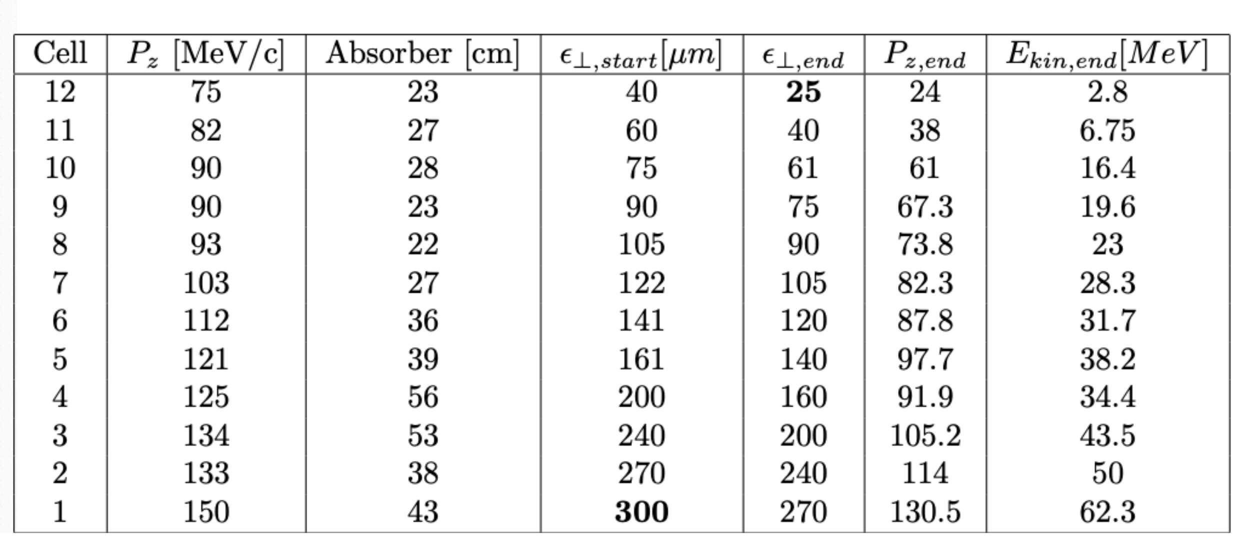


Optimising transverse emittance only

- Optimisation starting from last cell, to meet the required transverse emittance
- Free parameter: starting Pz, absorber length
- Cooling computed analytically, assuming 40 T (or 50 T) peak B-field



Cell	P_z [MeV/c]	Absorber [cm]	$\epsilon_{\perp,start}[\mu m]$	$\epsilon_{\perp,end}$	$P_{z,end}$
14	65	14	40	**24.5**	10
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



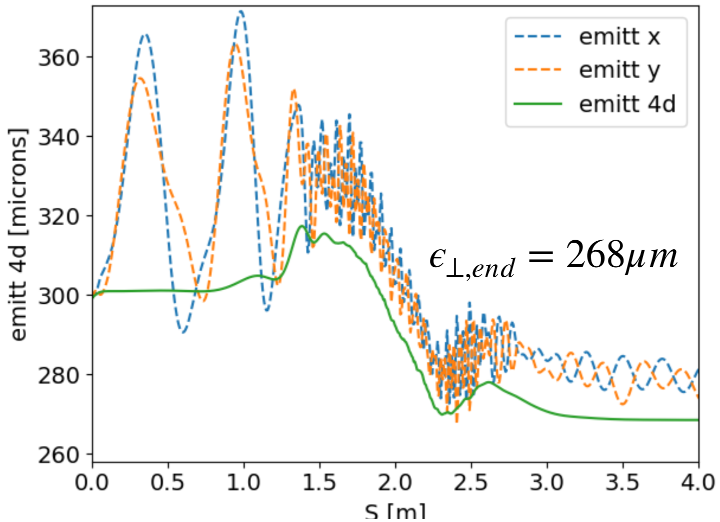
Cell	P_z [MeV/c]	Absorber [cm]	$\epsilon_{\perp,start}[\mu m]$	$\epsilon_{\perp,end}$	$P_{z,end}$	$E_{kin,end}[MeV]$
12	75	23	40	**25**	24	2.8
11	82	27	60	40	38	6.75
10	90	28	75	61	61	16.4
9	90	23	90	75	67.3	19.6
8	93	22	105	90	73.8	23
7	103	27	122	105	82.3	28.3
6	112	36	141	120	87.8	31.7
5	121	39	161	140	97.7	38.2
4	125	56	200	160	91.9	34.4
3	134	53	240	200	105.2	43.5
2	133	38	270	240	114	50
1	150	43	**300**	270	130.5	62.3

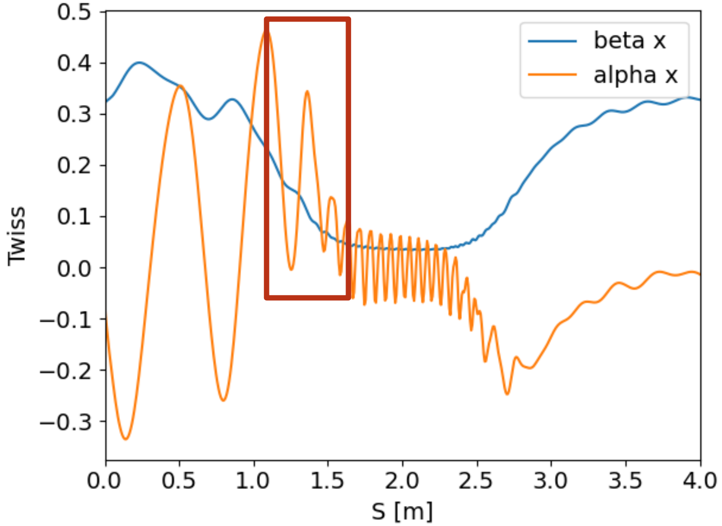
Less cells are needed in 50T case
(might improve the transmission and costs?)

- *Note: this assumes ideal optics matching and control of longitudinal parameters (acceleration, optimal energy spread and bunch lengths)*
- *Transmission is not included*

1st cell (40 T, LH): after optimisation

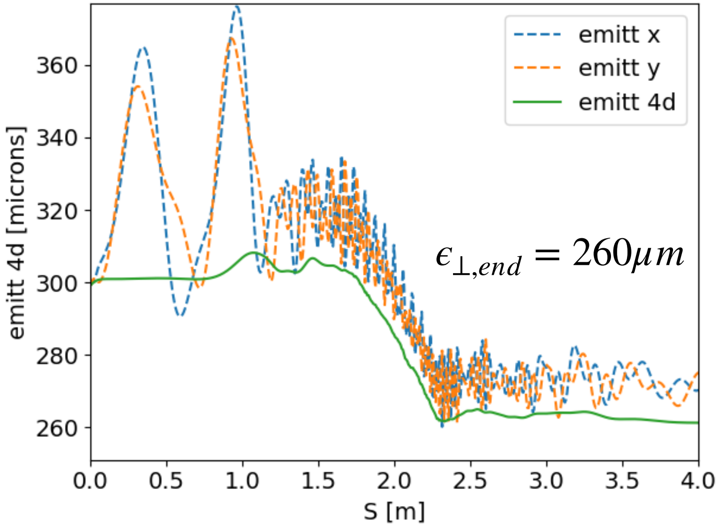
No matching coils

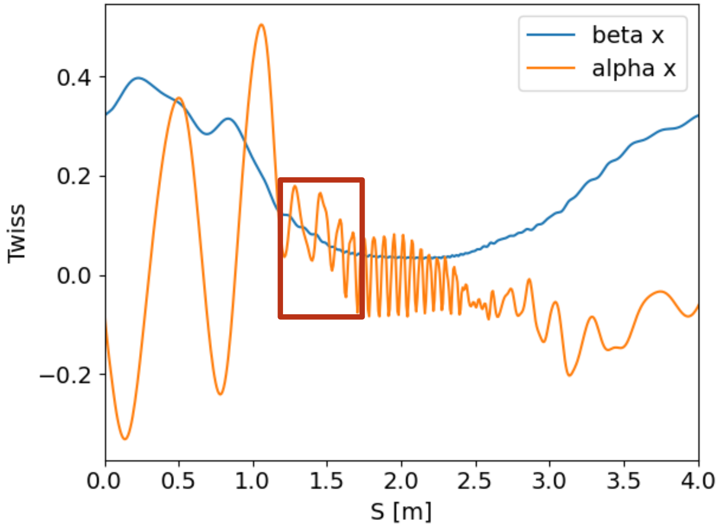




Larger alpha function values on the location of emittance bumps -> optics optimization is crucial for desired emittance reduction

Incl. matching coils in the entrance and exit of high-field solenoid



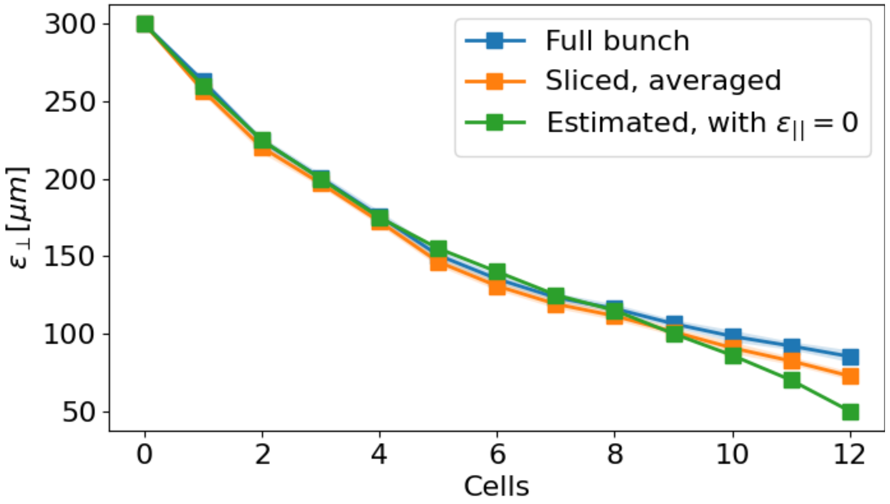


$$\beta_{\perp,start} = 0.34m$$
$$B(z) = 3.8T$$
$$\beta_{\perp,center} = 3cm$$

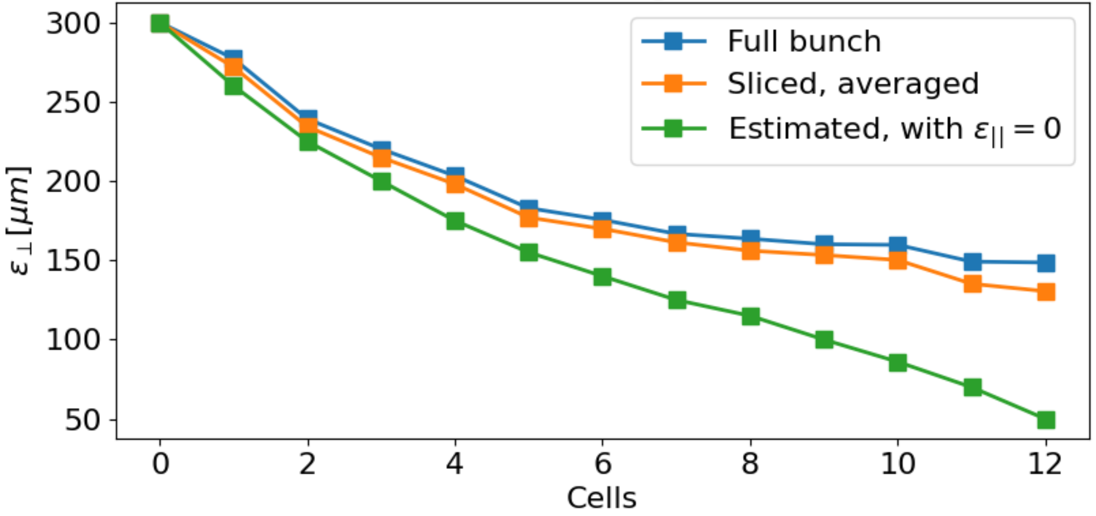
Solenoid field optimisation using matching coils

- With estimated optimal transverse emittance at the end of each cell as objective

<u>Transverse emittance reduction using optimised matching coils</u>



No matching coils



- First 4 cells share exactly the same parameters for solenoid and matching coils (the analytically estimated emittance value could be achieved with these settings)

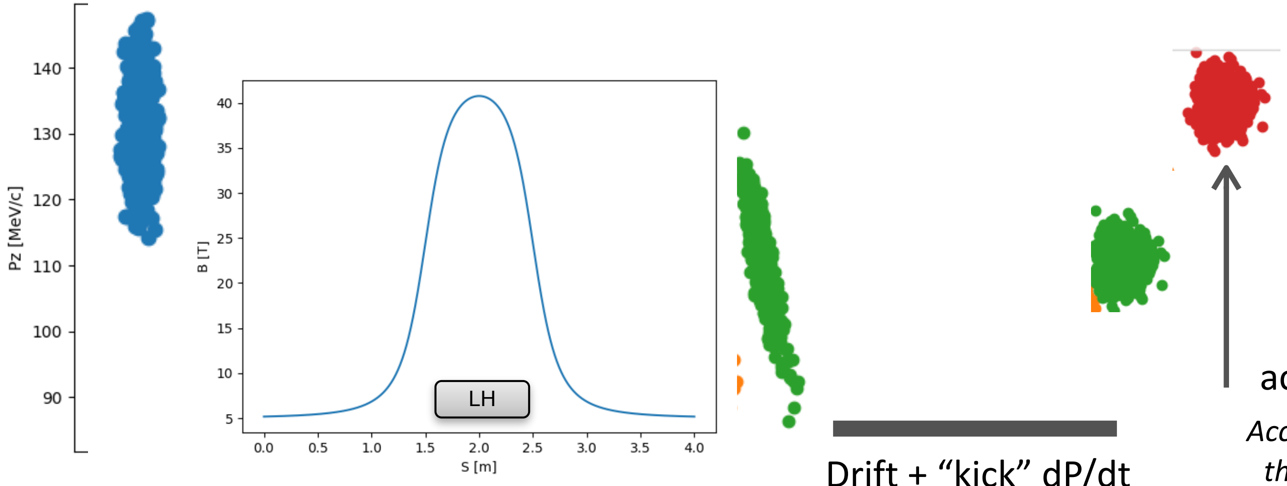
- Observed **differences between the emittance computed from full bunch** and **averaged emittance over the slices**

➡ Optics matching is crucial to avoid emittance blow up and achieve desired cooling performance

Simplified RF model for phase-space rotation and acceleration

- Longitudinal emittance increases after absorber:
  - Compute the slope of the particles distribution
  - Optimise drift length (develop correlation) and “slope factor” (minimise energy spread or bunch length)
  - Objective function longitudinal emittance / transmission

Tracking setup



Optimised field and absorber settings to achieve target transverse emittance

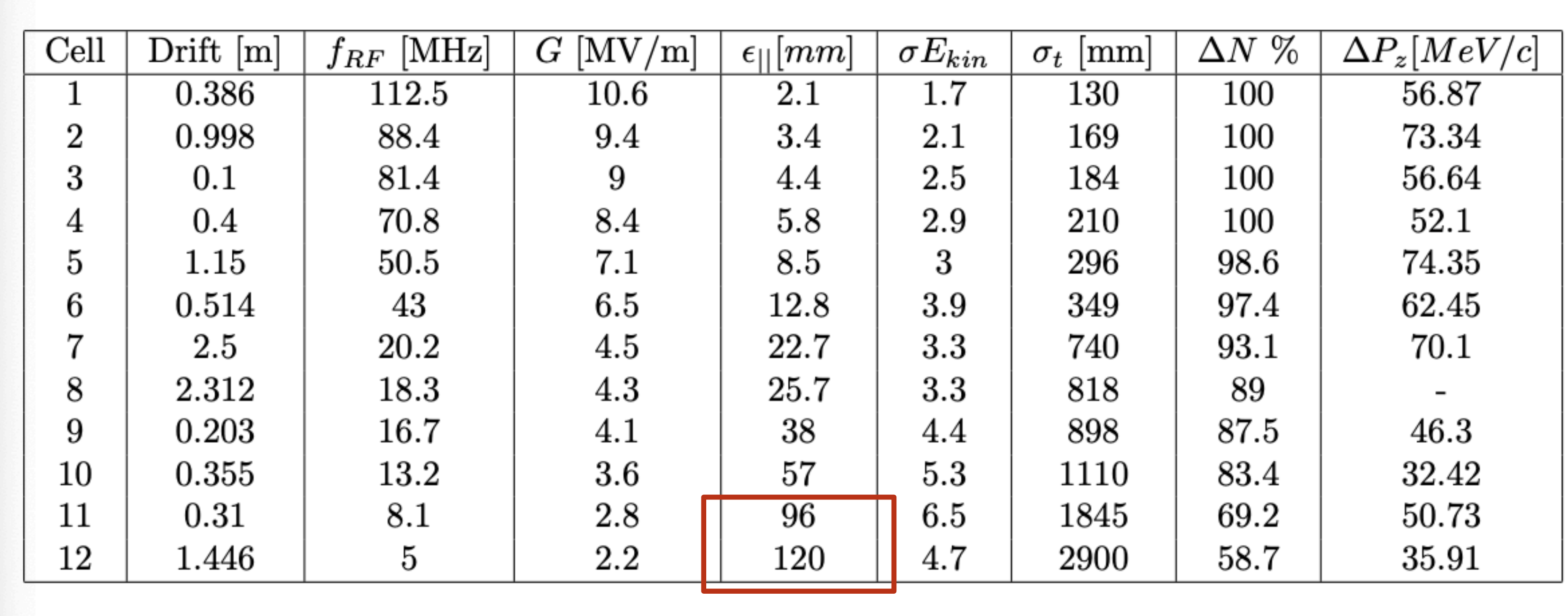
Drift + “kick” dP/dt

acceleration

According to optimal Pz at the start of the next cell

Longitudinal emittance optimization: First result

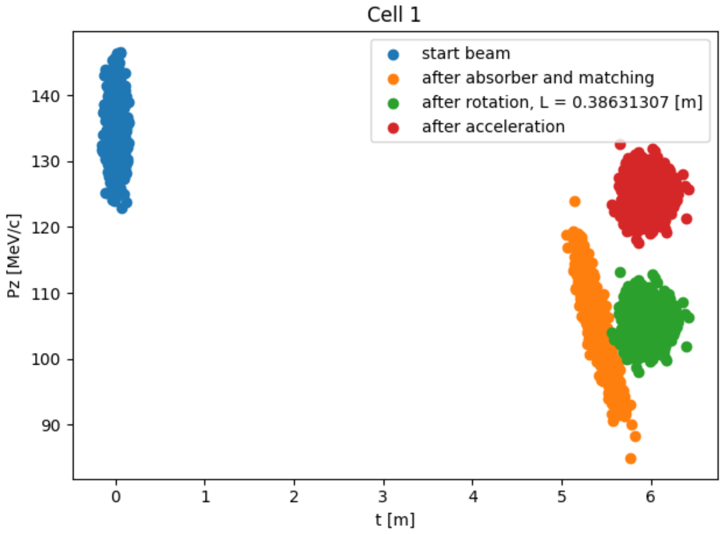
Frequencies are computed according to $\sigma_t = \lambda/20$ and gradients as $G = \sqrt{f}$.
ΔP_z is the momentum gain to be achieved with accelerating cavities.

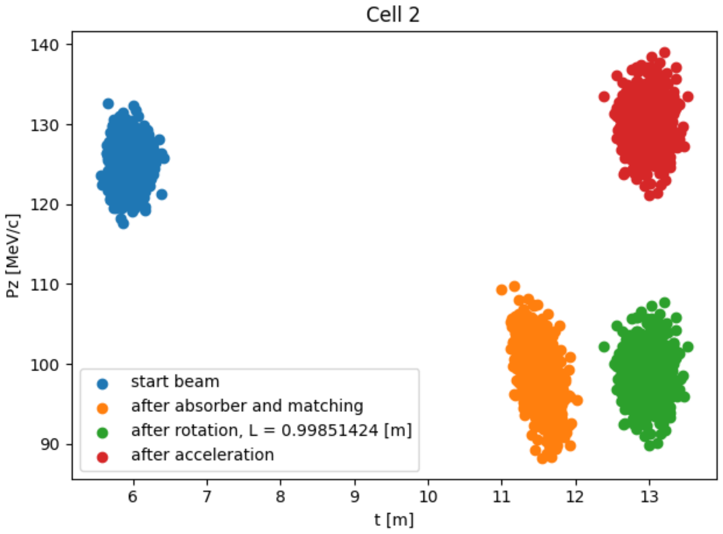


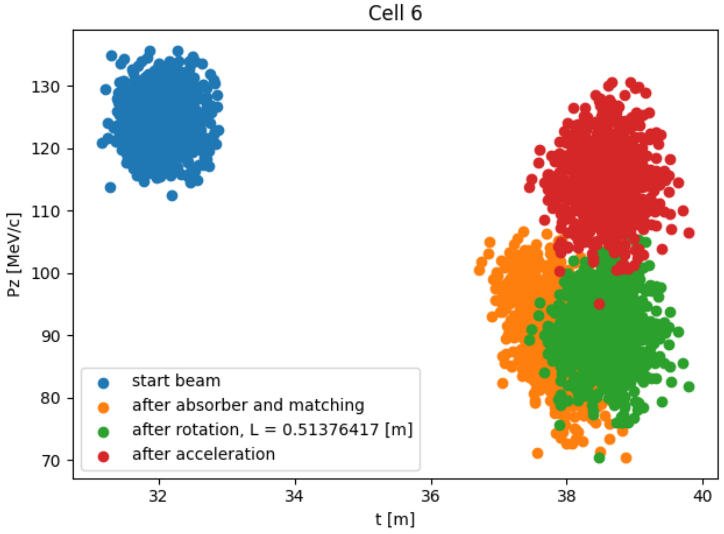
Cell	Drift [m]	f_{RF} [MHz]	G [MV/m]	$\epsilon_{\|\|}[mm]$	σE_{kin}	σ_t [mm]	ΔN %	$\Delta P_z[MeV/c]$
1	0.386	112.5	10.6	2.1	1.7	130	100	56.87
2	0.998	88.4	9.4	3.4	2.1	169	100	73.34
3	0.1	81.4	9	4.4	2.5	184	100	56.64
4	0.4	70.8	8.4	5.8	2.9	210	100	52.1
5	1.15	50.5	7.1	8.5	3	296	98.6	74.35
6	0.514	43	6.5	12.8	3.9	349	97.4	62.45
7	2.5	20.2	4.5	22.7	3.3	740	93.1	70.1
8	2.312	18.3	4.3	25.7	3.3	818	89	-
9	0.203	16.7	4.1	38	4.4	898	87.5	46.3
10	0.355	13.2	3.6	57	5.3	1110	83.4	32.42
11	0.31	8.1	2.8	96	6.5	1845	69.2	50.73
12	1.446	5	2.2	120	4.7	2900	58.7	35.91

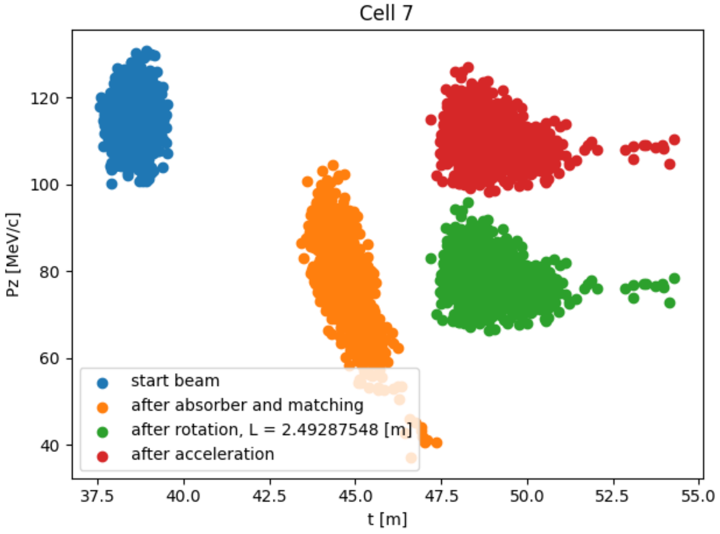
Longitudinal emittance growth
towards the end of the channel is too
large compared to previous studies.
=> Caused by a few outlier-particles!

Impact of appropriate bunch distribution cuts









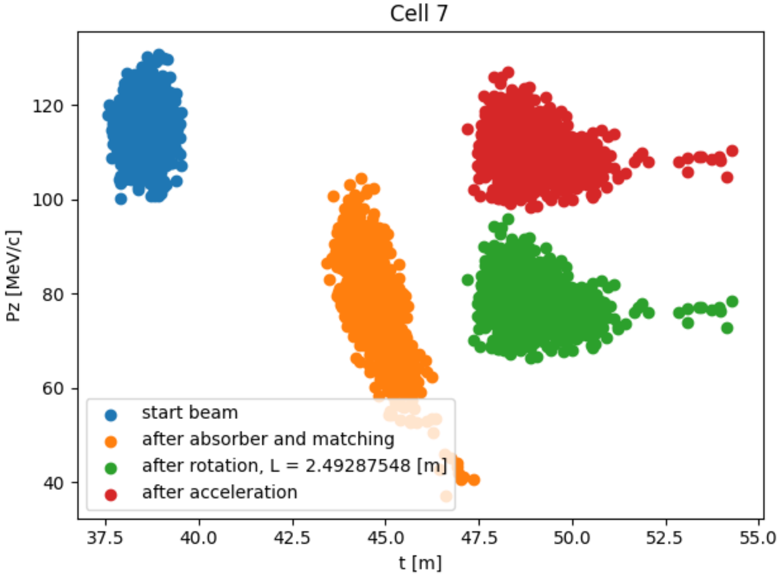
Problem: "outlier"-particles in the tails

- *3-sigma cut not always effective*
- *Stronger cuts? How to determine?*
- *Thresholds which are always valid?*

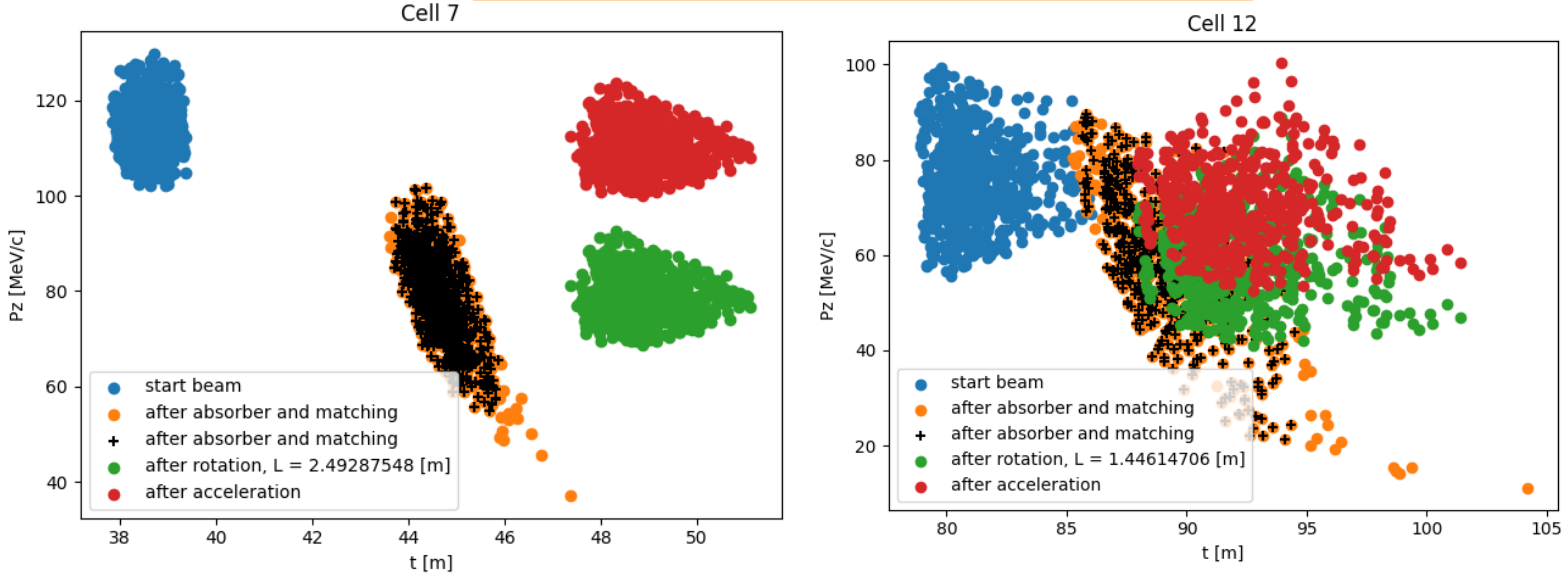
Impact of bunch cuts: rotation kick

- Important to “clean” the beam after the absorber to estimate the slope to be corrected
  - 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!)*

No cuts applied



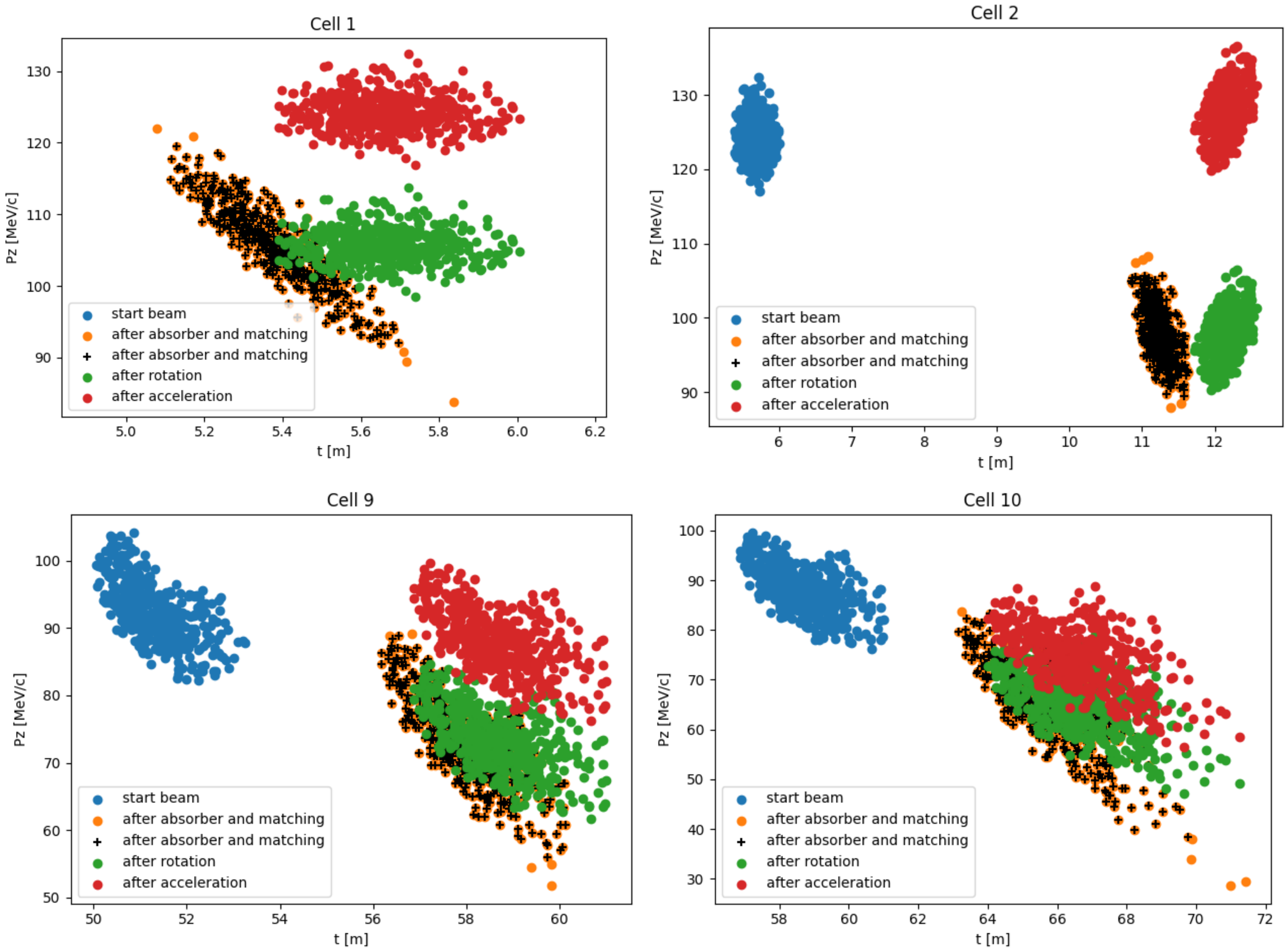
*Finding “relevant” particles using Isolation Forest algorithm for anomaly detection**



<u>* Isolation forest algorithm:</u>

https://scikit-learn.org/stable/modules/generated/sklearn.ensemble.IsolationForest.html#sklearn.ensemble.IsolationForest

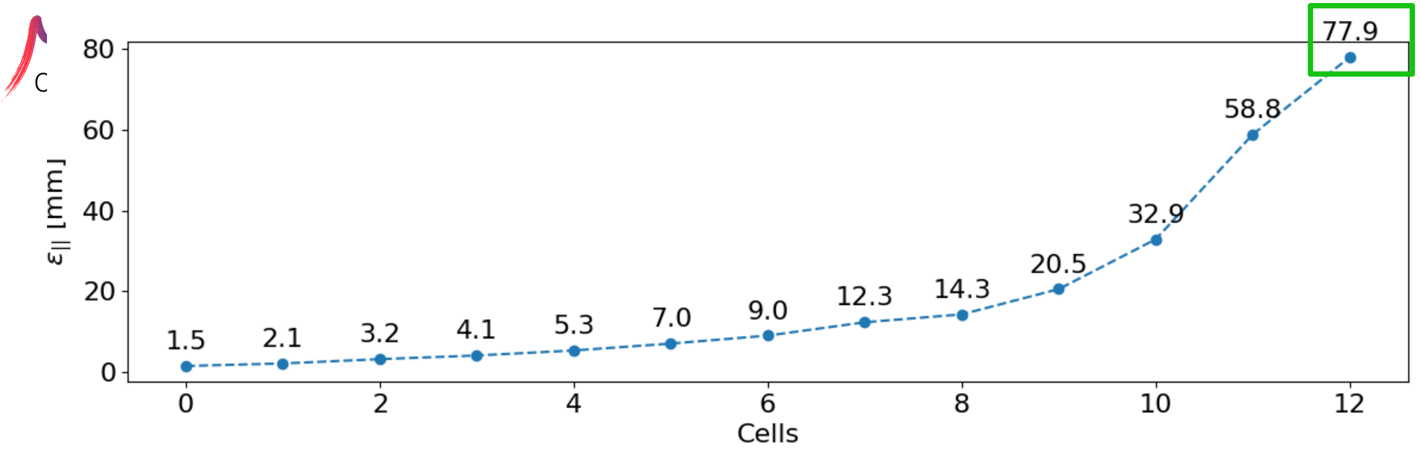
Impact of appropriate bunch distribution cuts

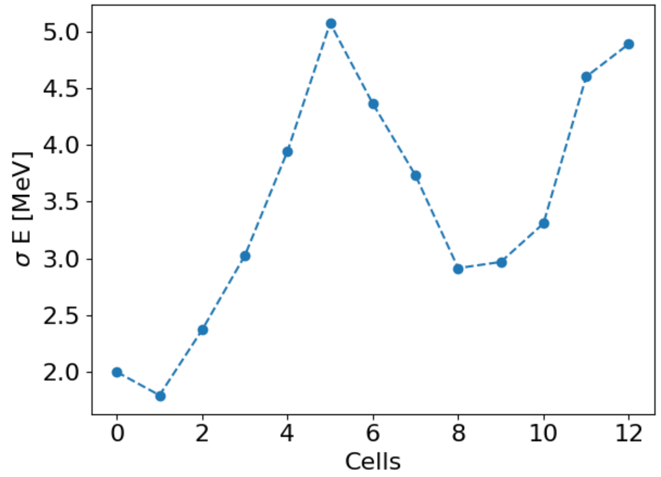


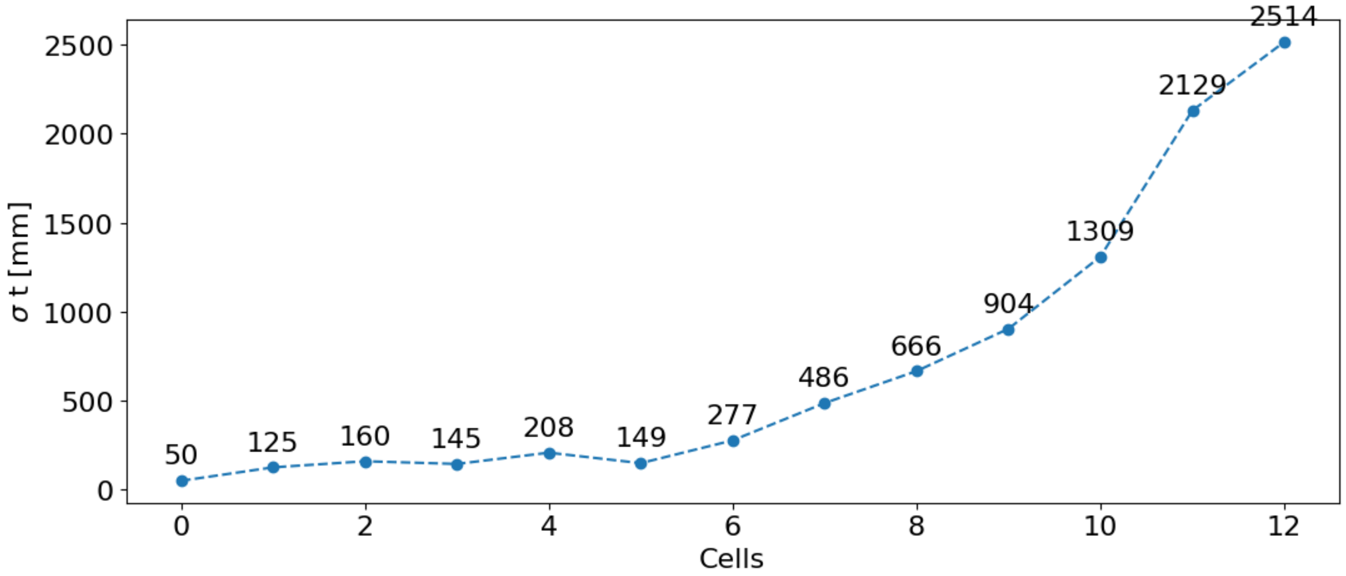
"+" marked particles indicate the "good" particles used for kick and emittance computation

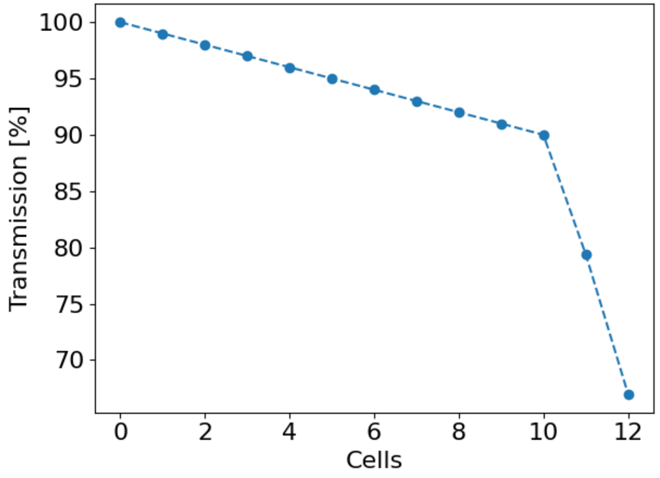
Results incl. bunch “cleaning”

vs. 120 mm without cleaning (total transmission is 7% lower)

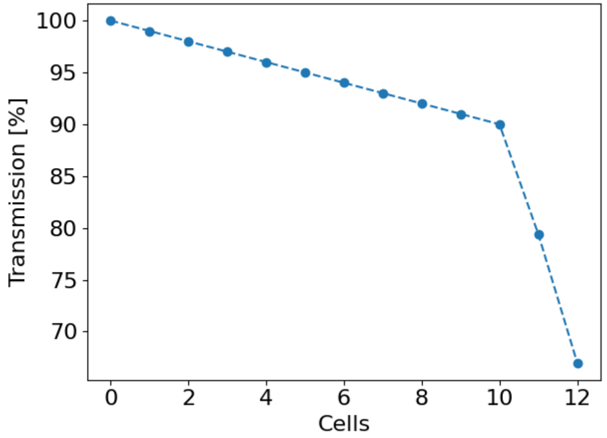








Analysis of transmission reduction: cell 11 and 12



- Transmission losses in the first 10 cells are dominated by the necessary cuts for emittance computation
- Cell 11 and 12 show a high drop in transmission:
  - Caused by **lower energies**, losses due to lifetime?

Note: here no cuts are applied, all particles are included

pz = 75 MeV/c

Cell 11: N particles start of the cell -> N particles after absorber: 450 -> 438

Cell 12: start -> absorber: 438 ->**371**

Higher momenta at the start of the cell 11:

pz = 90 MeV/c:

Cell 11: start -> absorber: 450 -> 450

Cell 12: start -> absorber: 450 -> **445**

=> pz = 85 MeV/c:

Cell 12: start -> absorber: 450 -> 441

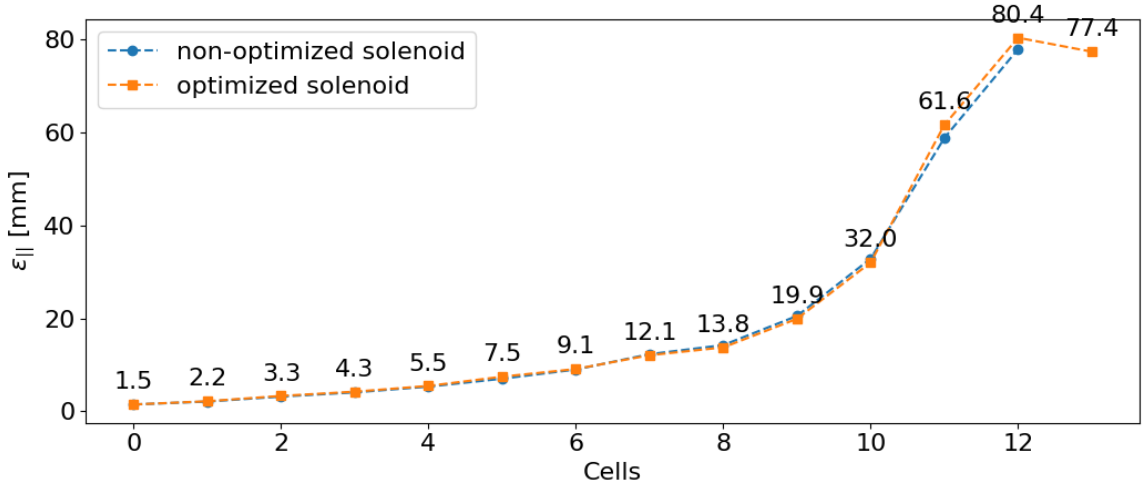
=> pz = 80 MeV/c:

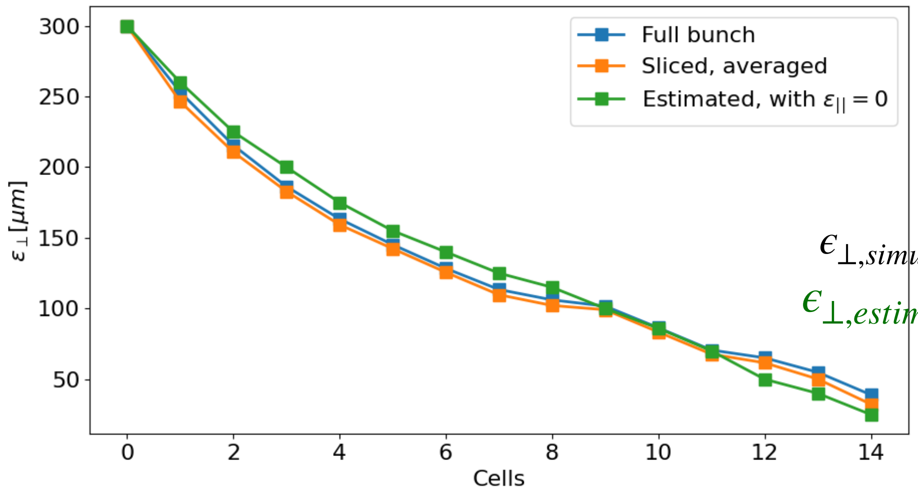
Cell 12: start -> absorber: 450 -> 418

➡ *Transmission decreases due to lower energies:*
➡ *“optimal” cooling path studies should include transmission*

Optimise drifts and kick, using <u>optimised solenoid settings</u>

13 cells, longitudinal parameters are computed up to the end of the cell 13 only
(assuming re-acceleration will be done separately after the last cooling cell)





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

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

- ✓ *Transverse emittance = 32 micron, Longitudinal emittance = 77 mm (B(z)=40 T)*
- ✓ *Achievable only if using optimised RF settings to control longitudinal parameters*

Problem: Transmission (only ~29% after last cell)

<u>Applied optimization algorithms / ML-techniques:</u>

- BOBYQA: Bound Optimization BY Quadratic Approximation, derivative-free, solves “trust-region” subproblems
- Bayesian Optimization (converges much faster compared to e.g. differential evolution algorithm), uncertainty estimation
- Surrogate model to obtain initial guesses for optimisers => produced significant improvement for optics optimisation

Note: choice of algorithms strongly depends on number of free parameters and robustness of tracking results

Optimise drifts and kicks, using optimised solenoid settings

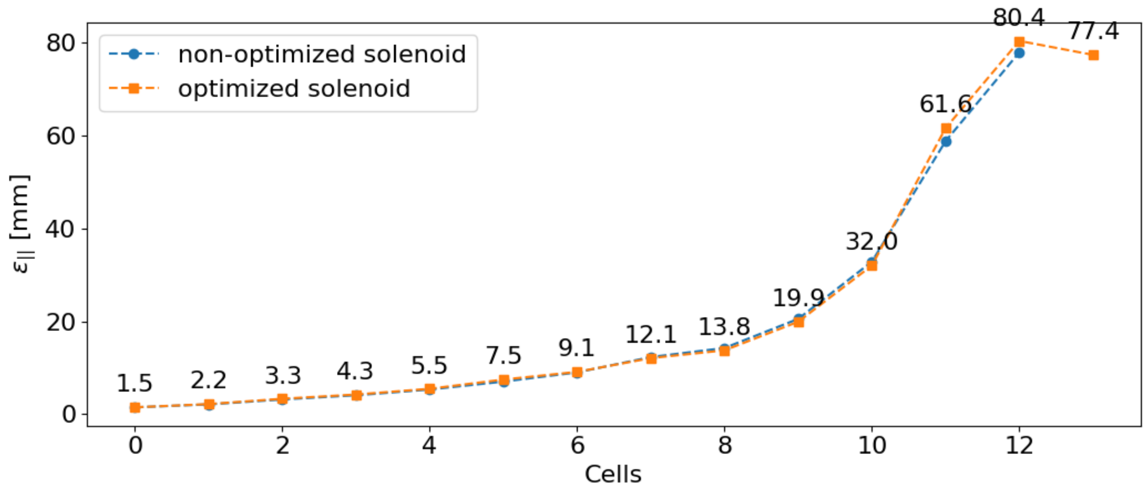
14 cells, longitudinal parameters are computed up to the end of the cell 13 only (assuming re-acceleration will be done separately after the last cooling cell)

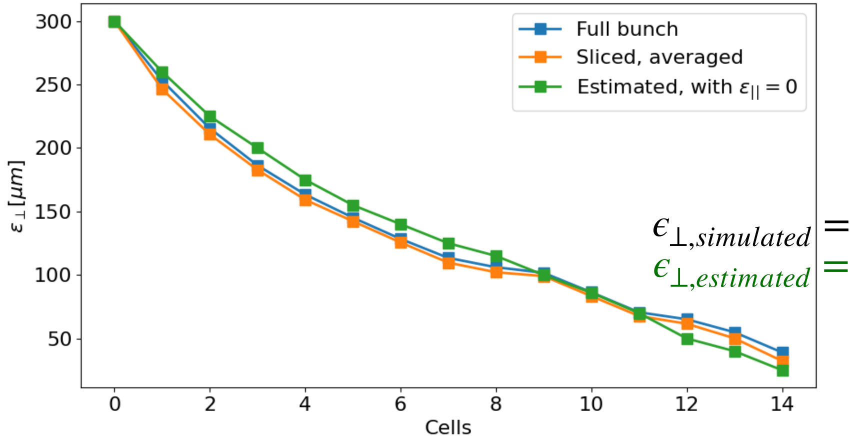
Cell	Drift [m]	f [MHz]	G [MV/m]	$\epsilon_{\|\|}[mm]$	σE	σ_t [mm]
1	0.17	123	11.1	2.5	1.7	122
2	0.61	142	11.9	3.7	2.1	105
3	0.28	118	10.9	3.5	2.5	126
4	0.95	72	8.5	5.8	3.5	210
5	0.2	91	9.5	7.5	4.8	296
6	0.21	65	8	9.1	4.7	232
7	0.61	35	6	12.1	3.6	431
8	0.91	25	5	13.8	3.0	593
9	0.44	18	4.2	20	3.1	828
10	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
13	1.0	5.7	2.4	77	4.0	2630

Cell	P_z [MeV/c]	Absorber [cm]	$\epsilon_{\perp,start}[\mu m]$	$\epsilon_{\perp,end}$
14	65	14	40	**24.5**
13	70	15	50	40
12	76	13	70	50
11	75	15	85	70
10	89.2	22	100	85
9	92.5	21	115	100
8	110	25	125	114.6
7	115	34	140	124.7
6	124.5	37	155	140
5	120	36	175	155
4	127.5	43	200	175
3	130	40	225	200
2	125	45	260	220
1	135	55	**300**	250

RF parameters optimised towards longitudinal emittance reduction and transmission maximisation *(incl. decays and 1-2% cuts on bunch distribution)*

Corresponding absorber and momenta requirements for transverse cooling (assuming 40 T max B(z), analytically estimated)





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Optimise drifts and kicks, using <u>optimised solenoid settings</u>

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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
13	1.0	5.7	2.4	77	4.0	2630

RF parameters optimised towards longitudinal emittance reduction and transmission maximisation *(incl. decays and 1-2% cuts on bunch distribution)*

Cell	P_z [MeV/c]	Absorber [cm]	$\epsilon_{\perp,start}[\mu m]$	$\epsilon_{\perp,end}$
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9	92.5	21	115	100
8	110	25	125	114.6
7	115	34	140	124.7
6	124.5	37	155	140
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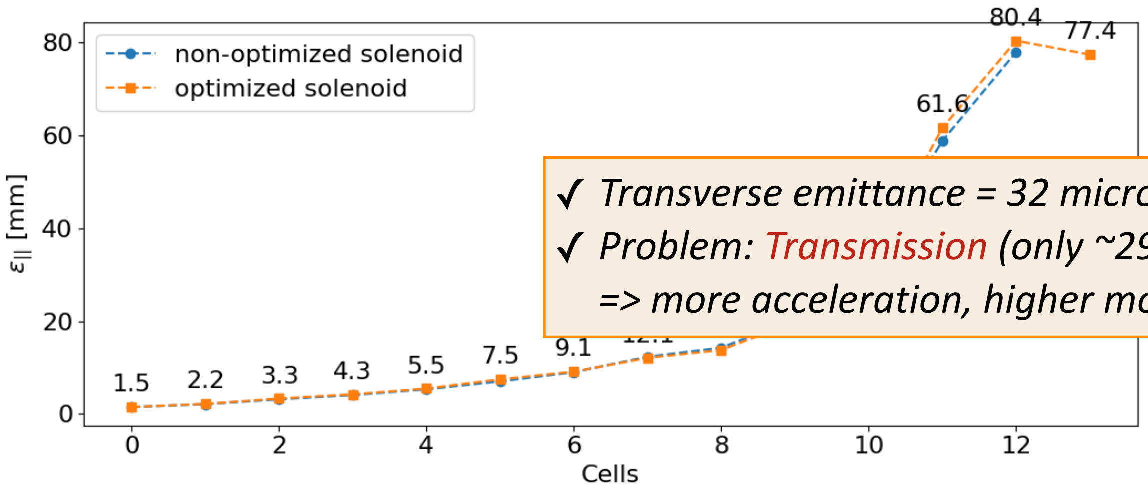
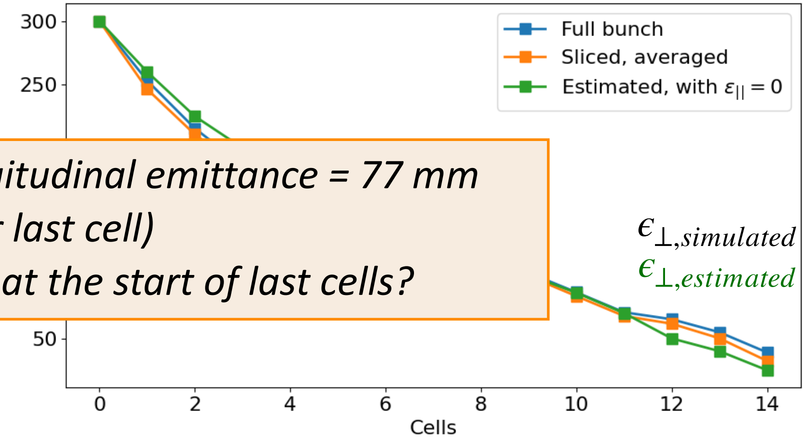
Corresponding absorber and momenta requirements for transverse cooling (assuming 40 T max B(z), analytically estimated)





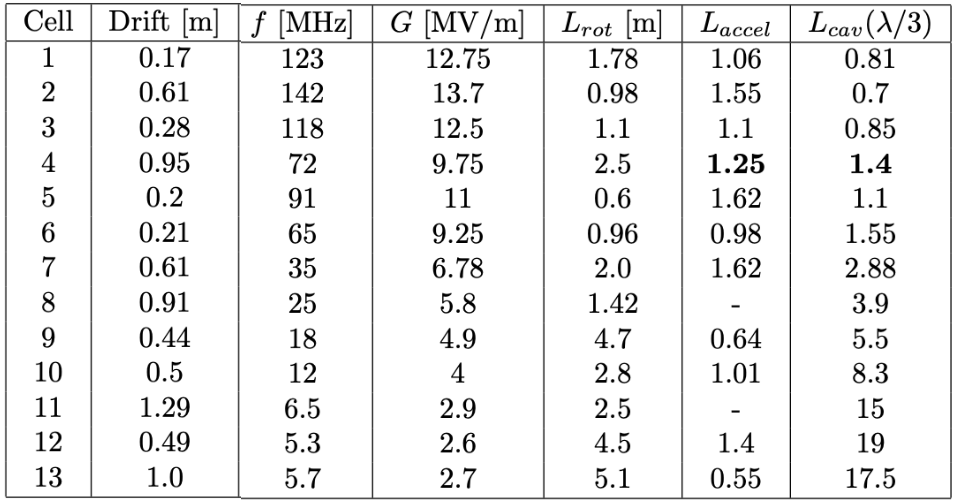
$\epsilon_{\perp,simulated} = 32.3\mu m$

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

- ✓ *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?

Next steps

- Translate optimised simplified RF-model into full RF-track simulations
    - Using optimised solenoid fields
    - RF SW-structures with parameters according to computed optimal kicks for bunch rotation and acceleration, and resulting bunch lengths .



Cell	Drift [m]	f [MHz]	G [MV/m]	L_{rot} [m]	L_{accel}	$L_{cav}(\lambda/3)$
1	0.17	123	12.75	1.78	1.06	0.81
2	0.61	142	13.7	0.98	1.55	0.7
3	0.28	118	12.5	1.1	1.1	0.85
4	0.95	72	9.75	2.5	**1.25**	**1.4**
5	0.2	91	11	0.6	1.62	1.1
6	0.21	65	9.25	0.96	0.98	1.55
7	0.61	35	6.78	2.0	1.62	2.88
8	0.91	25	5.8	1.42	-	3.9
9	0.44	18	4.9	4.7	0.64	5.5
10	0.5	12	4	2.8	1.01	8.3
11	1.29	6.5	2.9	2.5	-	15
12	0.49	5.3	2.6	4.5	1.4	19
13	1.0	5.7	2.7	5.1	0.55	17.5

$$\sigma_t = \lambda/20$$

$$G = \sqrt{f}$$

- Starting from cell 4:
  given the computed gradients,
  total acceleration length < length of one cavity
  => find other scaling?
  => reduce gradients for long cavities?

- Next: optimize RF phases and frequencies (estimated frequencies to be used as lower bounds)

- Re-optimise starting momenta and absorber thickness at every cell using higher energies to improve the transmission?
- COOL23: 2 abstracts to submit
  - "Final Cooling Design for Muon Collider: challenges and progress"
  - "Machine Learning assisting muon final cooling modelling and optimisation"