IMCC Annual meeting 2024
14 March 2024

Plans for collective effects studies in the ionisation cooling system

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Outline

1. **Collective effects in cooling** - introduction & motivation
2. **Optimized cooling line** - rectilinear (RC) & final (FC) cooling
3. **Basic collective effects** – theory & first results
    1. Transverse & longitudinal space charge
    2. Beam loading
    3. Beam break-up
4. **Conclusion** – next steps

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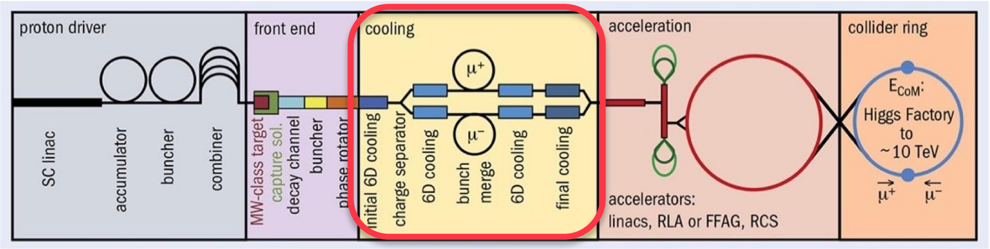
Ionisation cooling of a muon beam



The ingredients for ionisation cooling

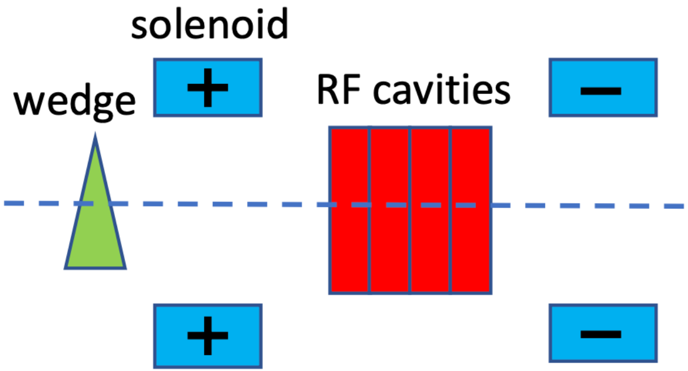
Solenoid → focus the beam transversly
Absorber (LH2 or LiH) + dipoles → reduce 4/6D emittance
RF cavities → restore longitudinal momentum

The goal of ionisation cooling

- Reduce **emittance** $\epsilon_{\perp} \sim \mu m$, $\epsilon_{\parallel} \sim mm$ → low beam sizes $\sigma_{x,y}, \sigma_z$
- At **low energy** (< 200MeV)
- With good muon transmission → high **beam intensity** N_q

➢ To get high luminosity in collision

$$L \propto N_q^2/(\sigma_{x,y}\sigma_z)$$



Zhu Ruihu @ Muon Cooling Working Group Meeting,01.26.2023

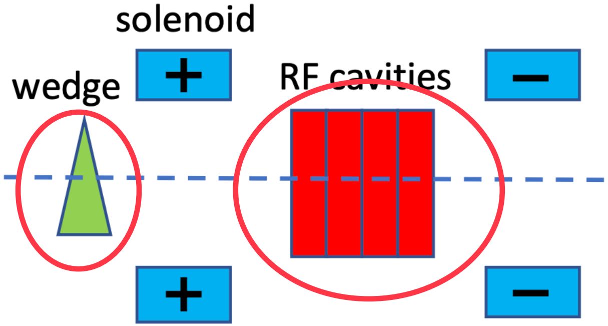
Study of collective effects in ionisation cooling

Important to study for muon collider to **understand** and **mitigate** what may cause limitations to

- Beam intensity → beam loss
- Beam quality → coherent & incoherent instabilities / tune & energy spread → emittance blow-up
- **Decrease of luminosity**

Collective effects will impact the line design

- Absorber material choice **because of wakes**
  - LH_2 → liquid, not conductor
  - LiH → solid, conductor
- RF cavity choice **because of beam loading**
- Lattice design (e.g. DA **with space charge**)



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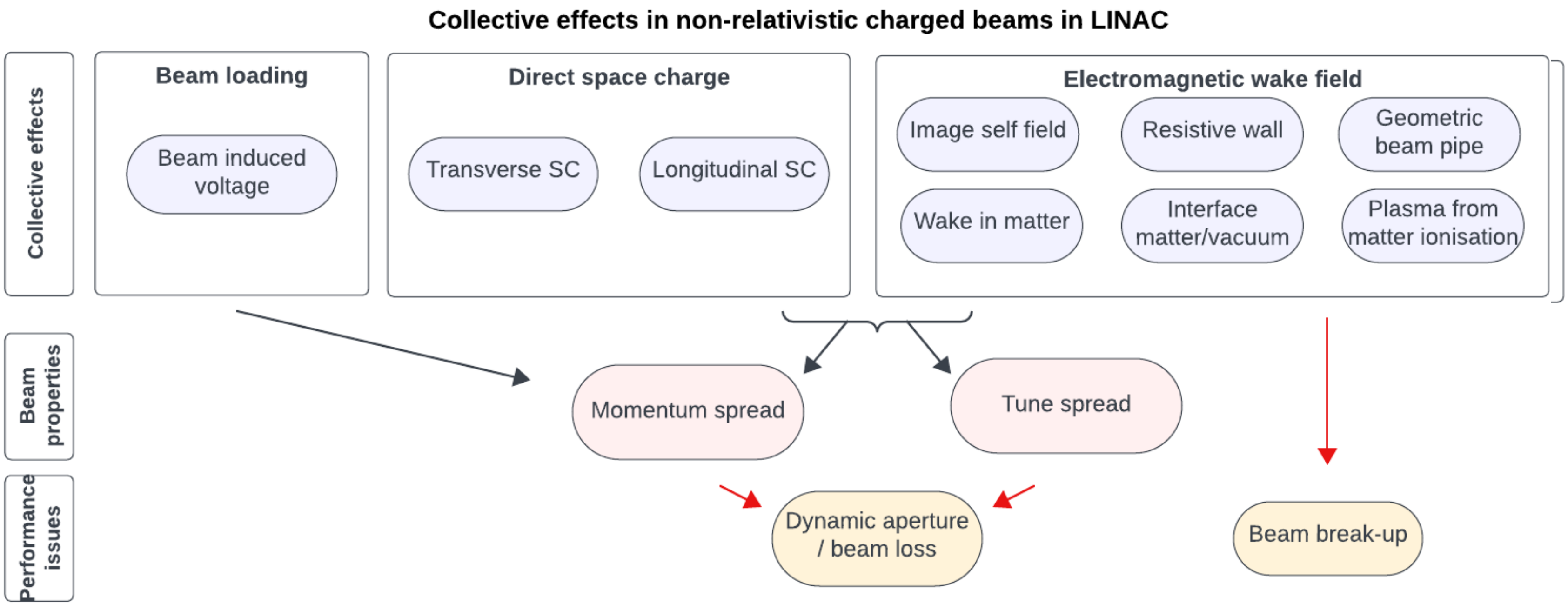
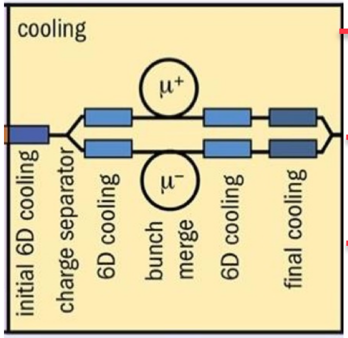


Approach to problem solving

- Reasonably define an **optimized cooling line** parameters since there is no baseline yet

- Make **coarse approximations** to
  - Discern potential problems areas & understand overall limitations
  - Identify where require more thorough theory derivation & simulation on RF track

- Today examine initial analytical estimation of 3 effects that can degrade the quality of the beam
  - Transverse & longitudinal space charge
  - Beam loading
  - Beam break-up



1. A-stages - *6D cooling of 21 μbunchs*
2. B-stages - *6D cooling of merged bunch*
3. FC-cells - *4D final transverse cooling before acceleration and collision*

Rectilinear cooling (RC) (1–2)

Final cooling (FC) (3)

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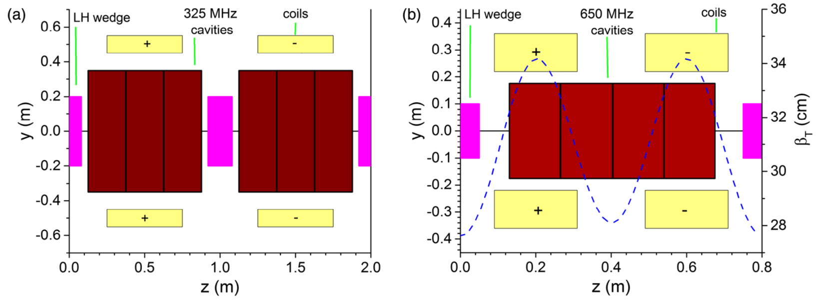
Optimized cooling line

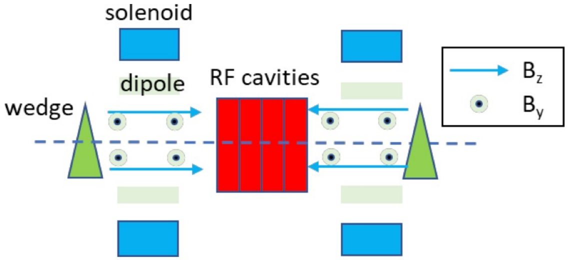
D. Stratakis, R. Palmer, DOI: 10.1103/PhysRevSTAB.18.031003



A-stages

- Goal → initial 6D cooling of 21 micro bunches
- Parameters → from Stratakis & Palmer paper
- Composition → 4 stages of # cells (66-130)

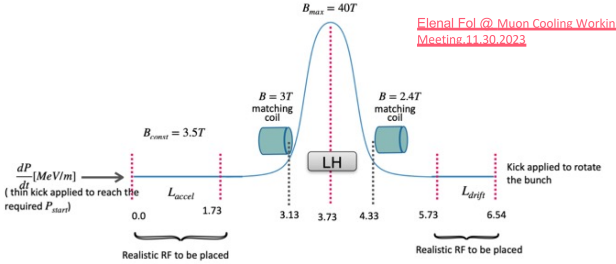
Zhu Ruihu @ Muon Cooling Working Group Meeting 01.26.2023



B-stages

- Goal → carry on 6D cooling of 1 bunch
- Parameters → from Zhu Ruihu
- Composition → 10 stages of # cells (21-69)

Elenal Fol @ Muon Cooling Working Group Meeting 11.30.2023



FC-cells

- Goal → final 4D cooling under high magnetic field ~40T
- Parameters → from Elena Fol
- Composition → 9 cells each divided in 2 parts, *cooling* & *acceleration*

All parameter tables of the cooling line as well as the methodology behind finding / approximating the parameter can be found in back-up slides

Optimized cooling line

A-stages

- Goal → initial 6D cooling of 21 micro bunches
- Parameters → from Stratakis & Palmer paper
- Composition → 4 stages of # cells (66-130)

B-stages

- Goal → carry on 6D cooling of 1 bunch
- Parameters → from Zhu Ruihu
- Composition → 10 stages of # cells (21-69)

FC-cells

- Goal → final 4D cooling under high magnetic field ~40T
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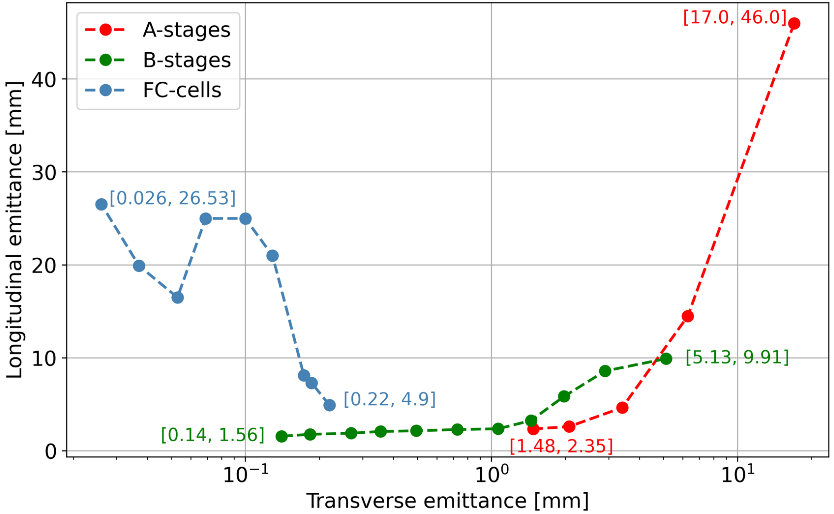

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Transverse space charge - theory

Theory

- Forces generated directly by the charge distribution of beam line
- **Defocusing** effect → expect optical quantities to depend on beam current
- Non linear forces → **transverse tune spread**

Approximation

- Gaussian bunched beam ✅
- Equation derived for decoupled beam ❌
- Space charge treated as small focusing error ✅
- Emittance ~ constant for whole cell ✅

As in muon collider configuration, beam is fully coupled, $\beta_x = \beta_y$ and $\epsilon_x = \epsilon_y$, end up with

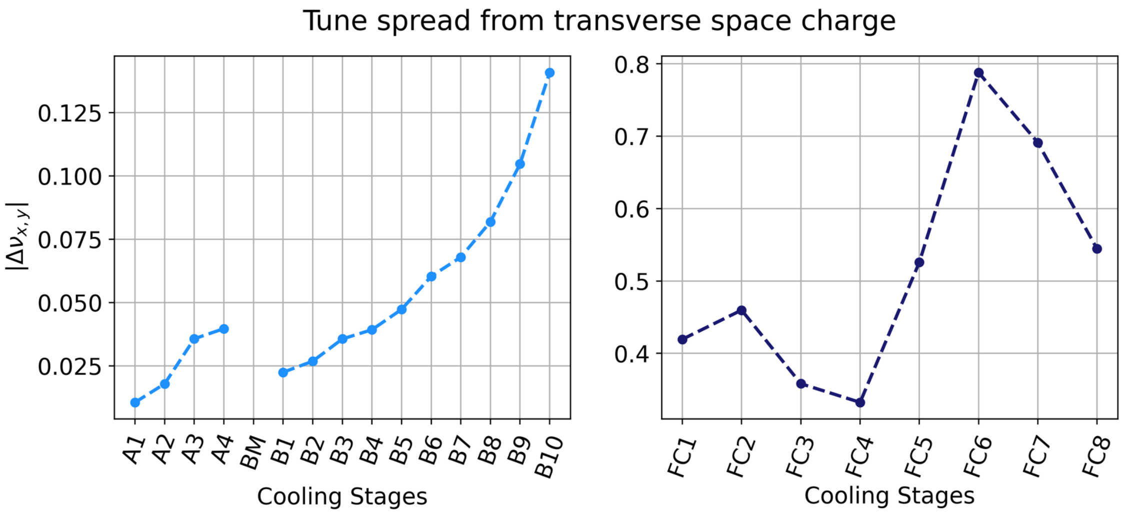
$$\Delta\nu_\perp \approx -\frac{KL}{8\pi\epsilon}$$

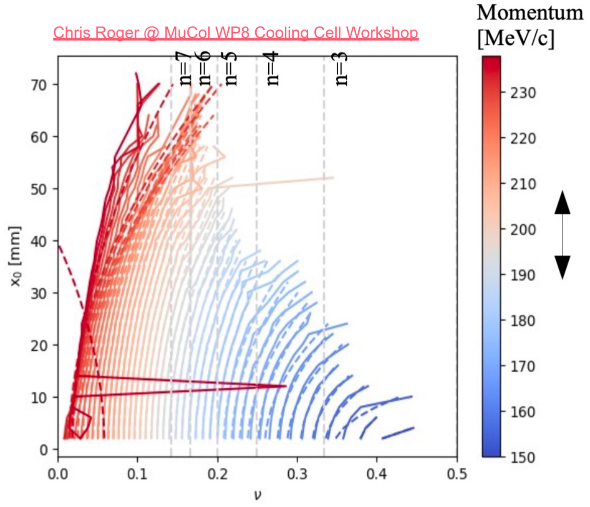
with

- Perveance $K = \frac{2I}{\beta_0^3\gamma_0^3 I_c}$,
- Characteristic beam current $I_c = \frac{4\pi\epsilon_0 mc^3}{q}$
- Peak beam current $I = qn_q\beta_0 c$
- Muon linear density $n_q = \frac{N_q}{\sqrt{2\pi}\sigma_z}$
- Cell length L

From Wolski, 'Beam dynamics in high energy particle accelerators', Chp13

Transverse space charge - Results





- SC higher at end of cooling → smallest $\sigma_{x,y}$ and $\epsilon_{x,y}$
- SC not negligible at initial cooling → higher charge intensity
- SC causes maximum tune shifts comparable to maximum tune accepted for DA

Chris' plot *(done on initial cooling → let's see for FC)* shows that tune spread has consequences of DA

- ➢ Need to derive more appropriate equation for fully coupled beam
- ➢ Need simulate beam losses / DA including SC

❖ D.Stratakis et al. found mainly longitudinal space charge effect that can be compensated with higher RF gradiant → to be further studied

Longitudinal space charge - theory

Theory

- Forces generated directly by the charge distribution of beam line
- **Modification of focusing potential**
- Non linear longitudinal forces → **momentum spread**

Approximation

- Gaussian bunched beam ✅
- Longitudinal variations in charge density slow ✅
- Emittance, current, energy ~ constant for whole cell ✅
- Beam pipe radius ~5 x beam transverse size ✅

Space charge longitudinal potential

$$V(z) = \frac{I Z_0 g c}{2\beta_0 \gamma_0^2 \sigma_z^2 \omega_0} z \exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

Longitudinale space charge momentum spread

$$\Delta\delta(z) = \frac{qV(z)}{cP_0}$$

Evaluate the potential difference between $z \in \{-\sigma_z, \sigma_z\}$ to find maximum energy difference between head and tail of bunch

→

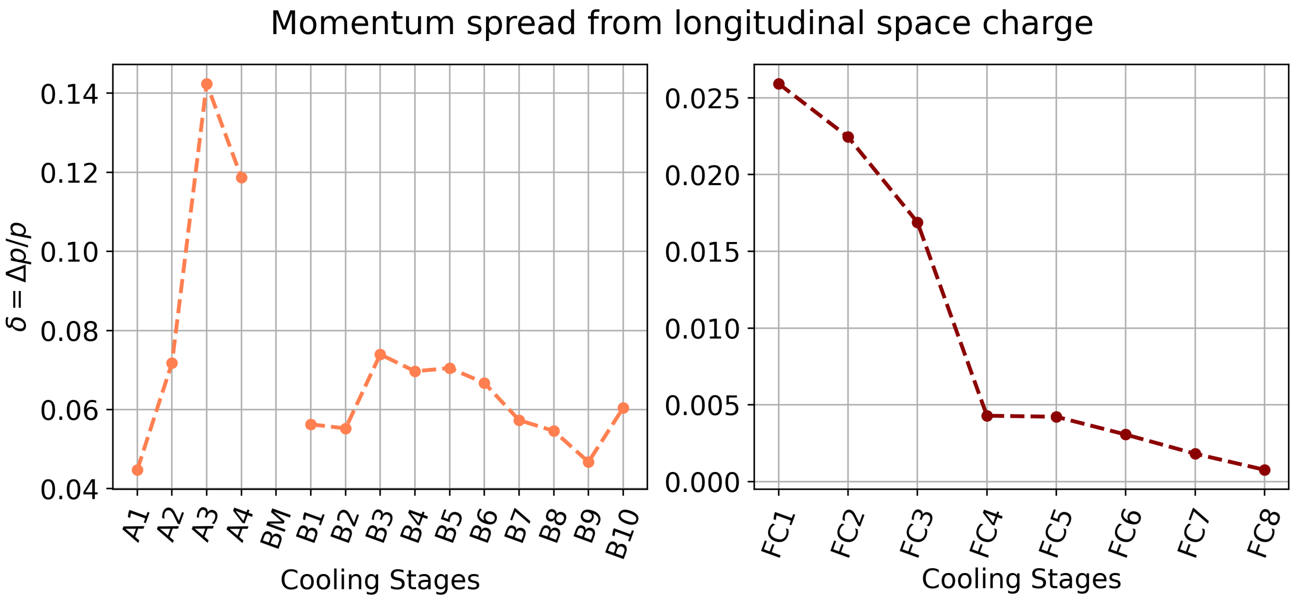
$$V(\sigma_z) - V(-\sigma_z) = \frac{I Z_0 g L e^{-1/2}}{2\pi\beta^2\gamma^2\sigma_z}$$

with

- Geometry factor $g = 1 + 2\ln\left(\frac{b}{a}\right)$
- Beam pipe radius $b = 5\sigma_z$
- Beam cross section radius σ_z
- Impedance of free space $Z_0 = 376.73\Omega$
- Peak beam current I
- Cell length L

From Wolski, 'Beam dynamics in high energy particle accelerators', Chp12

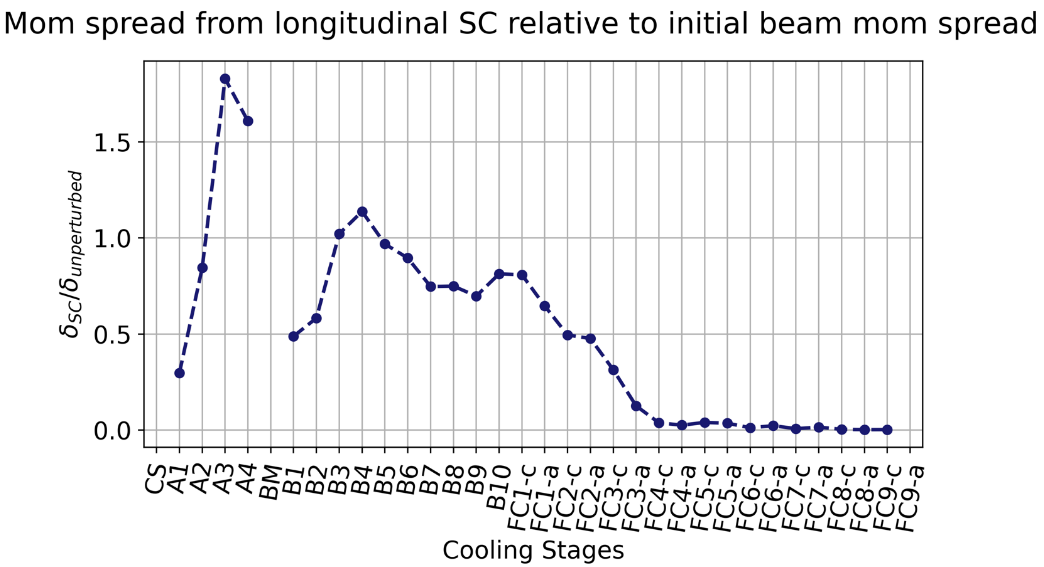
Longitudinal space charge – Results 1/2



- Momentum spread caused by longitudinal space charge mostly affected by
  1. **Intensity** of the beam
  2. **Energy** of the beam

  } higher SC mom spread at beginning of cooling line

Longitudinal space charge – Results 2/2



- The space charge induced momentum spread is in the **same order of magnitude** as the beam's initial momentum spread **in RC** where the beam intensity is higher
  - Potential impact on lattice design
  - Need for RF track simulations
- In **FC no problem** from longitudinal SC, thanks to low beam intensity and long bunch size

Beam loading - theory

Theory

- When passing in RF cavity – beam's EM field interacts with cavity → additional voltage
- **Beam induced voltage V_{ind}** resonates in cavity at ω_{res} frequency → head and tail of bunch see different voltages
- Expect **energy spread** caused by beam loading

$$V_{ind} = N_q q \frac{R}{Q} \omega_{res}$$

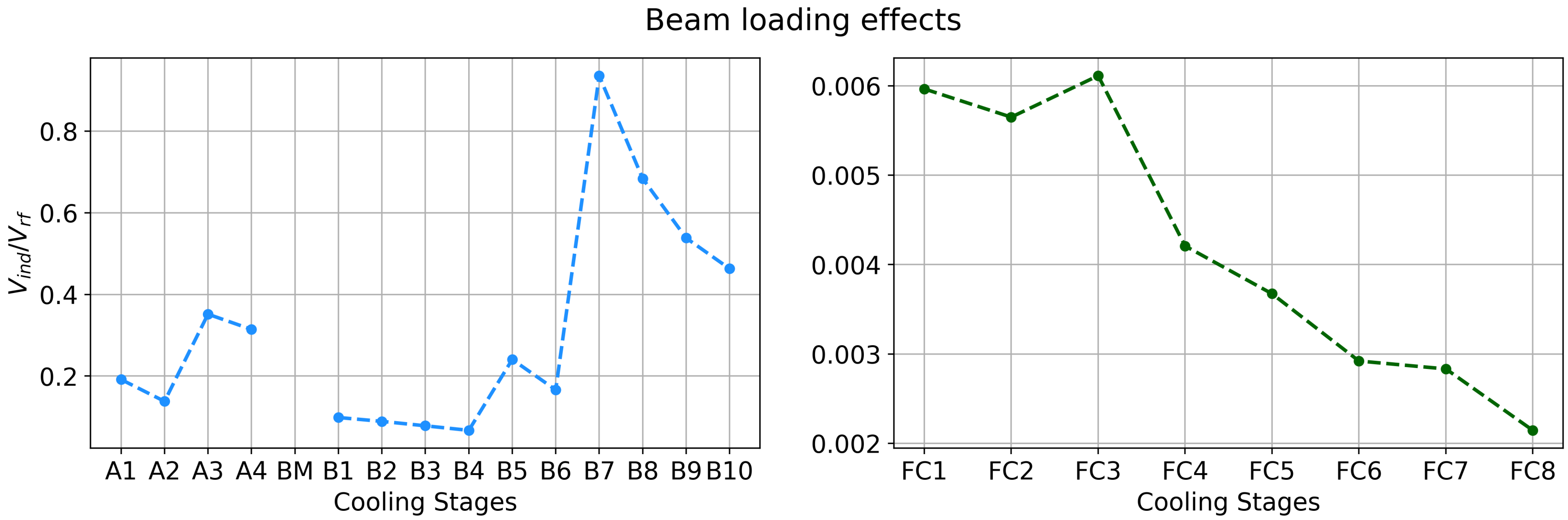
Approximation

- Geometric factor R/Q taken from presentations @ the 'MuCol WP8 Cooling Cell Workshop
  - D.A.Giove, 'Status of 650 MHZ cavity design'
  - C.Barbagallo, 'Status of 704 MHz cavity design'
  - G.S.Mauro, '3 GHZ RF for the RFMTF'

R/Q	Real RF frequency of design [MHz]	Line RF frequency [MHz]
194.73	704	704
200.00	-	24-86
223.00	650	352
466.00	3000	1056

From 'Proceedings of the General CAS course on Introduction to Particle Accelerators', on *Radio-Frequency (RF) Systems*

Beam loading - results



- **BL important in RC** where
  - Charge density is high (starts at Nq ~ 1e14)
  - RF frequency is high (325MHz → 1056MHz)
  - Beam induced voltage atteins almost 90% of the RF voltage in B7 (where RF cavity goes from 704MHz to 1054MHz
  - ➢ BL is unacceptable with high frequency RF → revise RF choices and design
  - ➢ BL must be added / considered for RF track simulations
- **BL not a problem in FC**

Beam break-up – 1/2

Theory

- Due to transverse wake force, beams' **tails betatron oscillations may resonate** with the wake leading to a transverse break-up of the beam
- Oscillation amplitude of the tail relative to the head characterised by **growth parameter** Υ

Approximation

- Look only at dipolar beam break-up here
- 2 macroparticle model ✅
- Neglect BNS damping ❌
- Use only **resistive wall** wake of relativistic beam at low frequency → classical thick wall of copper

[1]
$$\Upsilon = -\frac{N_q r_0 W_1(z) L_0}{4 k_\beta \gamma L} 4\pi\epsilon_0$$

[2]
$$W^{\perp}_{m=1}(t>0) = \frac{cL}{\pi^{\frac{3}{2}} a^3} \sqrt{\frac{\mu_0 \mu_r}{\sigma_c}} \frac{1}{\sqrt{|t|}}$$

Evaluate the wake at $z = -\sigma_z$

- Classical muon radius r_0
- Transverse wake for one cavity period W_1
- Cavity period L
- LINAC length L_0
- Betatron wavenumber $k_\beta = \frac{2\pi}{\beta}$

- Time $t = z/v$
- Beam pipe radius $a = 5\sigma_z$
- Cell length L
- Relative permeability μ_r
- Conductivity σ_c

[1] From Chao, 'Physics of collective beam instabilities in high energy accelerators', Chp3

[2] From A. Koschik et al., 'Transverse resistive wall impedance and wake function witj "inductive bypass"'

Beam break-up 2/2

Results

- Resistive wall wake equation of a relativistic beam with big pipe size results **does not seem to increase the tail's betatrons motion** → negative growth parameter of **less than 10^{-3}**
- Moreover, with BNS damping, which will probably be strong (**→to include in theory & RF track simulations**) resistive wall wake will certainly not be a problem
- Need to evaluate ϒ for all transverse wake of non-relativistic beams
  - Wake in matter
  - Wake at transition
  - Plasma wake

  → **First step evaluate wake function – Non trivial**

❖ V. M. Malkin and N. J. Fisch and S. Ahmed et al. found that plasma waves are not important limiting factors in ionization cooling

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Conclusion & next steps

- Few critical items were identified based on coarse models on collective effetcs
  - Transverse SC in FC and its impact on DA → Theory of fully coupled beam with SC + RF track simulation including SC
  - Longitudinal SC in RC and its impact on momentum spread → RF track simulation including SC
  - Beam loading in end of RC (high frequency cavities) → improve design (R/Q, frequency)

- No clear issues with wake were identified at this point but significant studies needed to quantify wakes in *unusual* setup of ionisation cooling
  - Wake in material
  - Wake at interface
  - Plasma from ionisation cooling

International
MUON Collider
Collaboration

CERN

Thank you
for attention

Back-up slides

Parameters of the cooling line 1/2

- **Parameters stages Charge separation (CS), Bunch merge (BM), final muon numbers Nq = 4e12** → *Grant Agreement No: 101094300, MuCoL, "A Design Study for a Muon Collider complex at 10 TeV centre of mass", "TENTATIVE PARAMETERS AVAILABLE"*

- **A-stages** → *Diktys Stratakis et al., "Rectilinear six-dimensional ionization cooling channel for a muon collider: A theoretical and numerical study"*

- **B-stages** → *Ruihu Zhu, Muon Cooling, https://indico.cern.ch/event/1372773/*

- **Final cooling FC-stages** → Results p10 of *Elena Fol, Muon Cooling https://indico.cern.ch/event/1351066/*, and the github parameters *https://github.com/MuonCollider-WG4/muon_final_cooling/blob/main/FCchannel_025m_RFcav (parameters)*
  - Separate FC cells between cooling part (solenoid + absorber) and acceleration part (drift + RF acceleration + RF rotation)
  - Approximate beam sizes and emittances, at the cooling part (missing) to be the same as the accelerating part & likewise for Nq, i.e. the number of particles stays constant during the whole FC cell and the transmission percentage is applied after the cell

- **Momentum** → A/B-stages momentum is chosen to be the one after RF acceleration

- **Minimum beta transverse A-stage anf FC-stages** → 2*(Pz)/(10*0.3*B)[cm] from *https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.091001* for momentum approximately having 30MeV/c less than after RF acceleration for A-stages (Pz-30MeV)

- **Beta longitudinal** → from https://www.researchgate.net/publication/259106391_Comments_on_Ionization_Cooling_Channel_Characteristics where lambda rf is approximated to be one of the rotation RF cavity for the FC-stages (for longitudinal focusing) where V' is the average voltage gradient

$$\beta_L = \sqrt{\frac{\lambda_{rf}\beta^3\gamma\, m_\mu c^2 \alpha_p}{2\pi e V' \cos(\phi_s)}}$$

Parameters of the cooling line 2/2

- **RF phases** → A/B-stages are given. FC-stages rotational are given and acceleration phase are on crest – 0 degrees
- **Number of bunches** → A-stages – 21, B-stages – 1, FC-stages – 1
- **Transmission** → A/B-stages: each cell's transmission. FC-stages: cumulative transmission
  Made such that in each cell there is the maximum muon intensity i.e. the transmission is applied at the end of the cell
- **Configuration of the cells** →
  A1-2 W+D+3xRF+D+W+D+3xRF+D+W
  A3-4 W+D+nxRF+D+W
  A4 W+D+4xRF+D+W
  B1-9 W+D+nxRF+D+W
  FC1-5 4m of entry sol, main sol + absorber, exit sol, drift, n x RF rot, m x RF acc
  FC6-8 4m of entry sol, main sol + absorber, exit sol, n x RF acc, drift, m x RF acc

  D = Drift
  W = Wedge
- **Number of cells** → A/B-stages have a lot of cells in each stage
  FC-stages are each composed of one cell only
- **R/Q ratio chosen** → 223 Ohm for 650MHz as WP8 https://indico.cern.ch/event/1335151/contributions/5727257/ → for A/B-stages with RF 352MHz
  194.73 Ohm for 704MHz as WP8 https://indico.cern.ch/event/1335151/contributions/5727258/ → for B5-B6-stages with RF 704MHz
  466.4 Ohm for 3GHz as WP8 https://indico.cern.ch/event/1335151/contributions/5727256/ → for B7-B10-stages with RF 1056MHz
  As RF frequency is lower for FC stages → try R/Q ratio of 200 Ohm

Parameters of the RC line

	Beam sizeı[cm]	Beam size⊥[cm]	Betaı[cm]	Beta⊥[cm]	Emitı[mm]	Emit⊥[mm]	Length cell[m]	Momentum spread	Momentum[MeV/c]	Nq	Peak field[T]	Transmission[%]
CS	NaN	9.910712	NaN	57.777778	46.000	17.0000	NaN	NaN	238.0	1.028698e+14	2.4	90.0
A1	9.592434	6.023657	63.546123	57.777778	14.480	6.2800	2.00	0.150952	238.0	9.258286e+13	2.4	70.6
A2	5.460106	3.589933	64.251636	37.904762	4.640	3.4000	1.32	0.084980	229.0	6.536350e+13	3.5	87.5
A3	3.340354	2.337199	42.915261	26.388889	2.600	2.0700	1.00	0.077836	220.0	5.719306e+13	4.8	88.8
A4	3.185342	1.729841	43.176177	20.218579	2.350	1.4800	0.80	0.073775	215.0	5.078744e+13	6.1	94.6
BM	NaN	4.330686	NaN	36.559140	9.910	5.1300	NaN	NaN	200.0	4.804492e+13	3.1	78.0
B1	7.453510	3.184808	64.726565	35.000000	8.583	2.8980	2.30	0.115154	200.0	3.747503e+13	3.1	86.1
B2	6.175193	2.433516	65.162359	30.000000	5.852	1.9740	1.80	0.094766	200.0	3.226600e+13	4.1	91.1
B3	4.492381	1.702351	62.077770	20.000000	3.251	1.4490	1.40	0.072367	200.0	2.939433e+13	4.8	88.8
B4	3.865832	1.264516	63.137557	15.000000	2.367	1.0660	1.10	0.061229	200.0	2.610217e+13	6.2	91.7
B5	3.138860	0.852702	43.136779	10.000000	2.284	0.7271	0.80	0.072765	200.0	2.393569e+13	8.8	91.3
B6	2.883467	0.545307	38.689542	6.000000	2.149	0.4956	0.70	0.074528	200.0	2.185328e+13	11.7	88.2
B7	2.704872	0.376776	35.259445	4.000000	2.075	0.3549	0.60	0.076713	200.0	1.927459e+13	15.0	87.7
B8	2.595608	0.284077	35.627604	3.000000	1.891	0.2690	0.60	0.072854	200.0	1.690382e+13	16.8	88.4
B9	2.637226	0.213951	39.360283	2.500000	1.767	0.1831	0.60	0.067002	200.0	1.494298e+13	18.1	82.2
B10	2.103449	0.167511	28.307722	2.000000	1.563	0.1403	0.60	0.074307	200.0	1.228313e+13	19.0	83.5

Parameters of the FC line

	Beam size∥[mm]	Beam size⊥[cm]	Beta∥[cm]	Beta⊥[cm]	Emit∥[mm]	Emit⊥[um]	Length cell[m]	Momentum spread	Momentum[MeV/c]	Nq	Peak field[T]	Transmission[%]
FC1-acc	229.0	0.779499	132.069547	27.619048	4.90	220.0	4.860	0.012800	145	1.025641e+13	3.500	97.0
FC2-acc	245.0	0.762573	193.881049	31.264368	7.30	186.0	5.200	0.018623	136	9.948718e+12	2.900	94.0
FC3-acc	236.0	0.854454	154.520537	42.201835	8.10	173.0	2.147	0.029205	138	9.641026e+12	2.180	91.0
FC4-acc	643.0	0.826265	223.619384	52.923602	21.00	129.0	3.978	0.045559	124	9.333333e+12	1.562	86.0
FC5-acc	801.0	0.675781	278.011717	45.667947	25.00	100.0	5.019	0.036776	107	8.820513e+12	1.562	81.0
FC6-acc	1142.0	0.625201	387.928256	56.648778	25.00	69.0	9.650	0.069273	95	8.307692e+12	1.118	74.0
FC7-acc	1300.0	0.541205	427.052245	55.264689	16.50	53.0	9.350	0.070847	95	7.589744e+12	1.146	62.0
FC8-acc	1693.0	0.417547	500.366368	47.120419	19.90	37.0	2.515	0.091314	81	6.358974e+12	1.146	51.0
FC9-acc	2068.0	0.387585	NaN	57.777778	26.53	26.0	NaN	0.129191	65	5.230769e+12	0.750	39.0

	Beam size∥[mm]	Beam size⊥[cm]	Beta∥[cm]	Beta⊥[cm]	Emit∥[mm]	Emit⊥[um]	Length cell[m]	Momentum spread	Momentum[MeV/c]	Nq	Peak field[T]	Transmission[%]
FC1-cool	229.0	0.191485	132.069547	1.666667	4.90	220.0	4.0	0.021822	100	1.025641e+13	40.0	97.0
FC2-cool	245.0	0.179555	193.881049	1.733333	7.30	186.0	4.0	0.027414	104	9.948718e+12	40.0	94.0
FC3-cool	236.0	0.175646	154.520537	1.783333	8.10	173.0	4.0	0.042030	107	9.641026e+12	40.0	91.0
FC4-cool	643.0	0.134387	223.619384	1.400000	21.00	129.0	4.0	0.082259	84	9.333333e+12	40.0	86.0
FC5-cool	801.0	0.108012	278.011717	1.166667	25.00	100.0	4.0	0.072425	70	8.820513e+12	40.0	81.0
FC6-cool	1142.0	0.087778	387.928256	1.116667	25.00	69.0	4.0	0.122632	67	8.307692e+12	40.0	74.0
FC7-cool	1300.0	0.083006	427.052245	1.300000	16.50	53.0	4.0	0.097139	78	7.589744e+12	40.0	62.0
FC8-cool	1693.0	0.063311	500.366368	1.083333	19.90	37.0	4.0	0.132127	65	6.358974e+12	40.0	51.0
FC9-cool	2068.0	0.047011	NaN	0.850000	26.53	26.0	4.0	0.198473	51	5.230769e+12	40.0	39.0

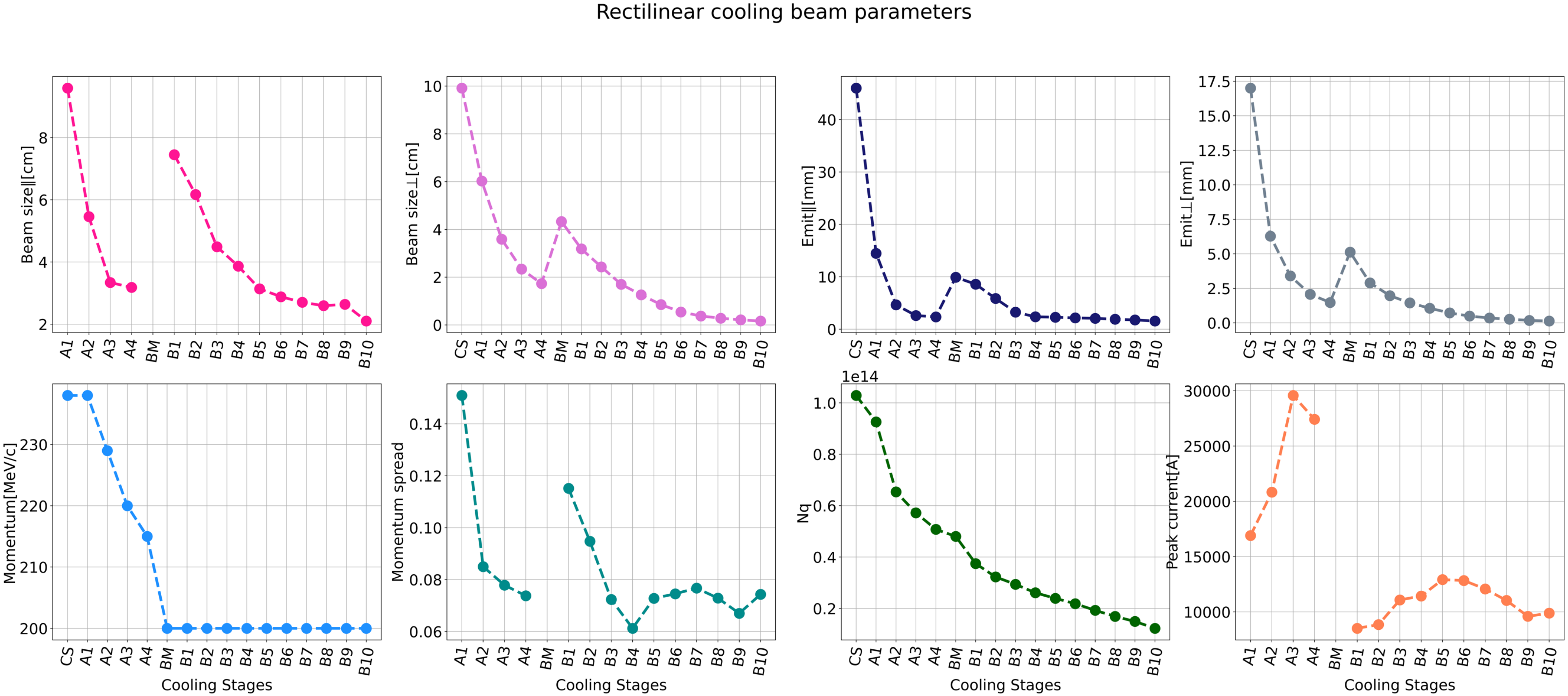
Parameters of the cooling RF system 1/2

	R/Q[Ω]	RF frequency[MHz]	RF gradiant[MV/m]	RF phase[deg]	RF length[cm]	RFs number
CS	NaN	NaN	NaN	NaN	NaN	NaN
A1	223.00	325.0	22.0	45.0	25.50	6.0
A2	223.00	325.0	22.0	45.0	25.00	4.0
A3	223.00	650.0	28.0	45.0	13.49	5.0
A4	223.00	650.0	28.0	45.0	13.40	4.0
BM	NaN	NaN	NaN	NaN	NaN	NaN
B1	223.00	352.0	25.2	27.9	19.00	6.0
B2	223.00	352.0	24.0	30.7	19.00	5.0
B3	223.00	352.0	24.9	27.4	19.00	4.0
B4	223.00	352.0	25.8	29.8	19.00	3.0
B5	194.73	704.0	23.0	24.5	9.50	5.0
B6	194.73	704.0	30.4	20.6	9.50	4.0
B7	466.40	1056.0	25.0	23.7	6.50	5.0
B8	466.40	1056.0	30.0	20.9	6.50	4.0
B9	466.40	1056.0	33.7	24.7	6.50	3.0
B10	466.40	1056.0	32.2	23.2	6.50	6.0

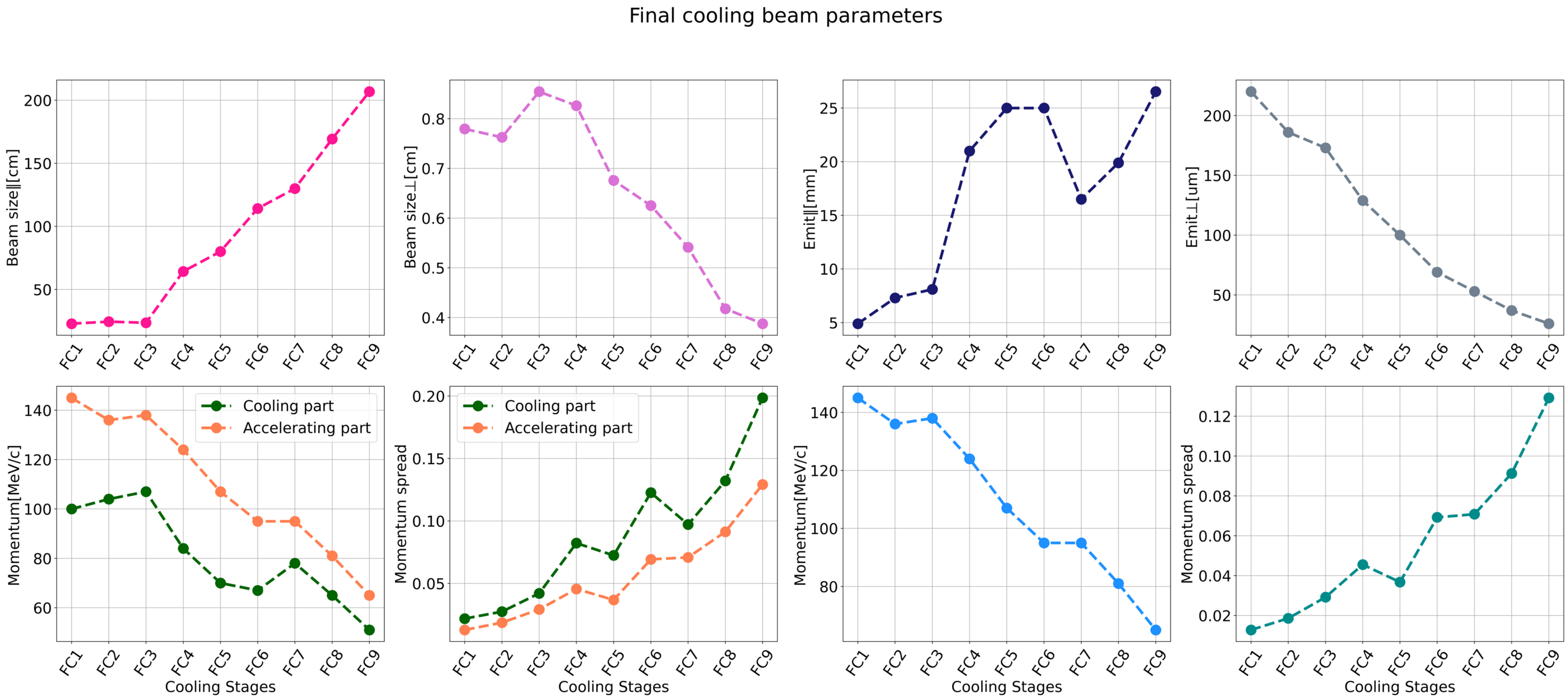
Parameters of the cooling RF system 2/2

	R/Q[Ω]	RF frequency[MHz]	RF gradiant[MV/m]	RF phase[deg]	RF length[m]	RF rot frequency[MHz]	RF rot gradiant[MV/m]	RF rot phase[deg]	RFs number	RFs rot number
FC1-acc	200	72.8000	16.041	90.0	0.25	117.0000	20.3400	180.0	12.0	3.0
FC2-acc	200	69.4000	15.662	90.0	0.25	72.8000	16.0400	180.0	10.0	2.0
FC3-acc	200	86.5140	17.486	90.0	0.25	86.5100	17.4900	180.0	5.0	1.0
FC4-acc	200	43.7575	12.436	90.0	0.25	43.7575	12.4336	180.0	12.0	1.0
FC5-acc	200	37.3350	11.487	90.0	0.25	37.3350	11.4870	180.0	10.0	1.0
FC6-acc	200	26.5900	9.690	90.0	0.25	26.5900	9.6900	180.0	10.0	5.0
FC7-acc	200	30.0000	10.300	90.0	0.25	30.0000	10.3000	180.0	9.0	1.0
FC8-acc	200	24.5080	9.307	90.0	0.25	24.5080	9.3070	0.0	1.0	1.0
FC9-acc	200	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

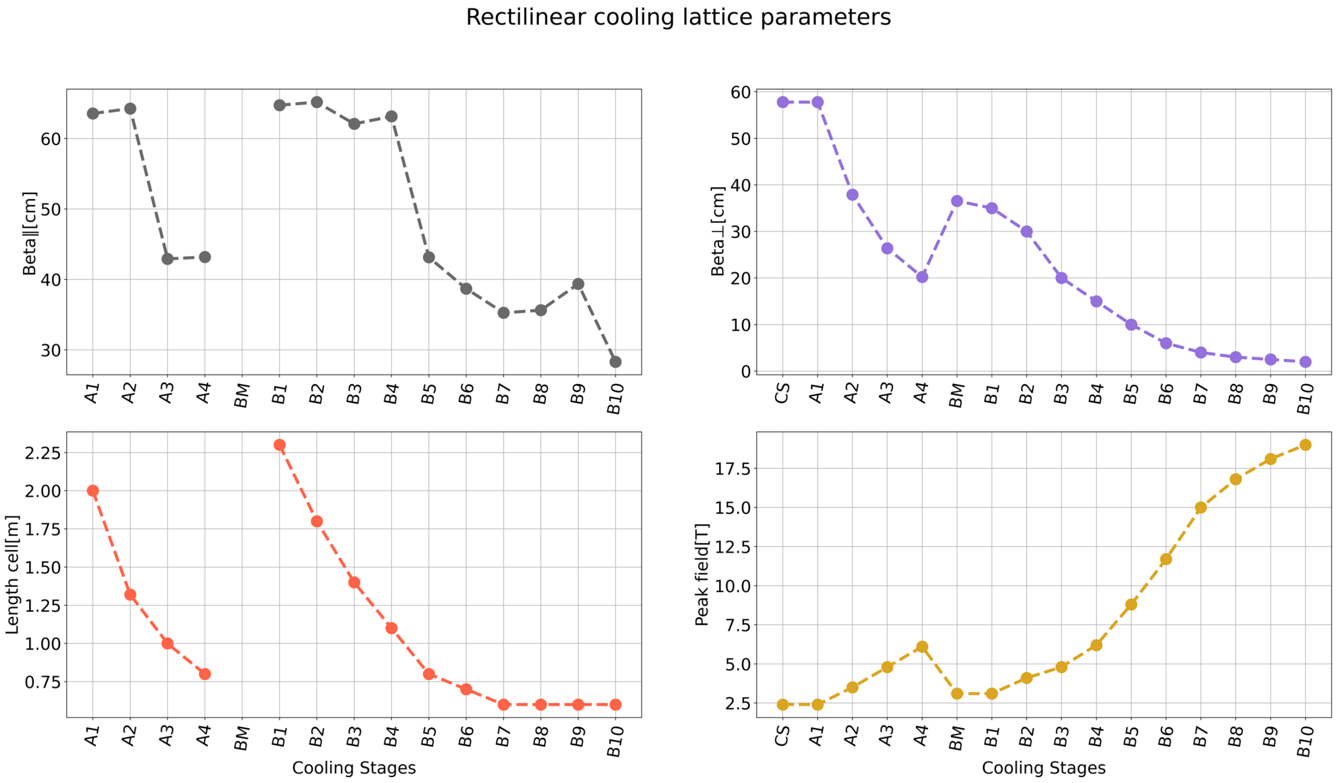
Rectilinear cooling beam parameters



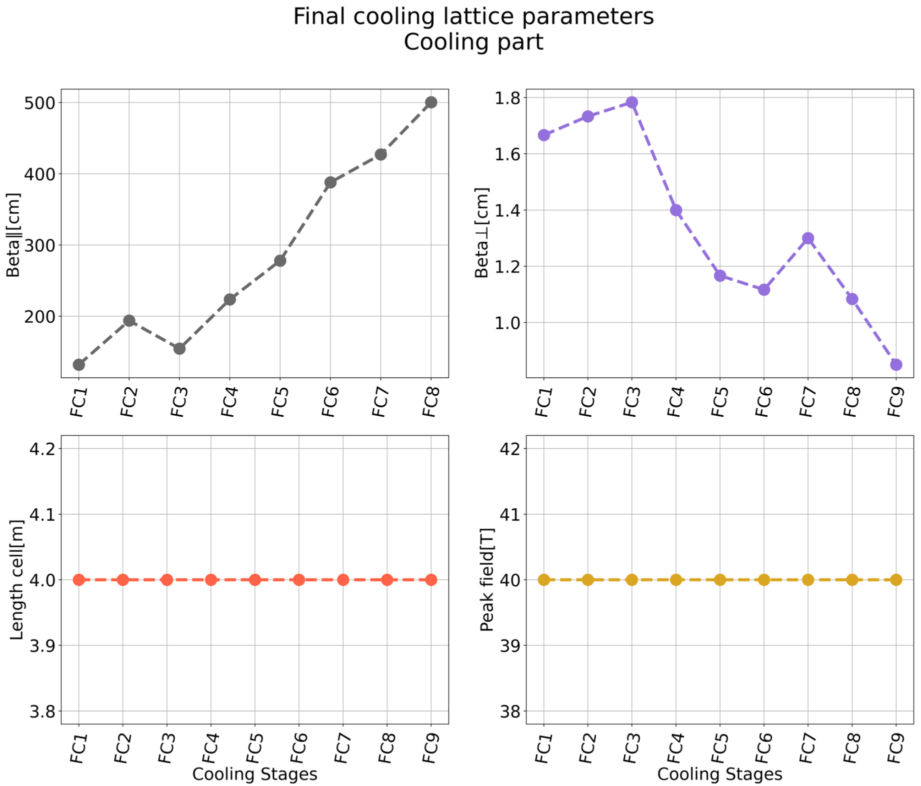
Final cooling beam parameters

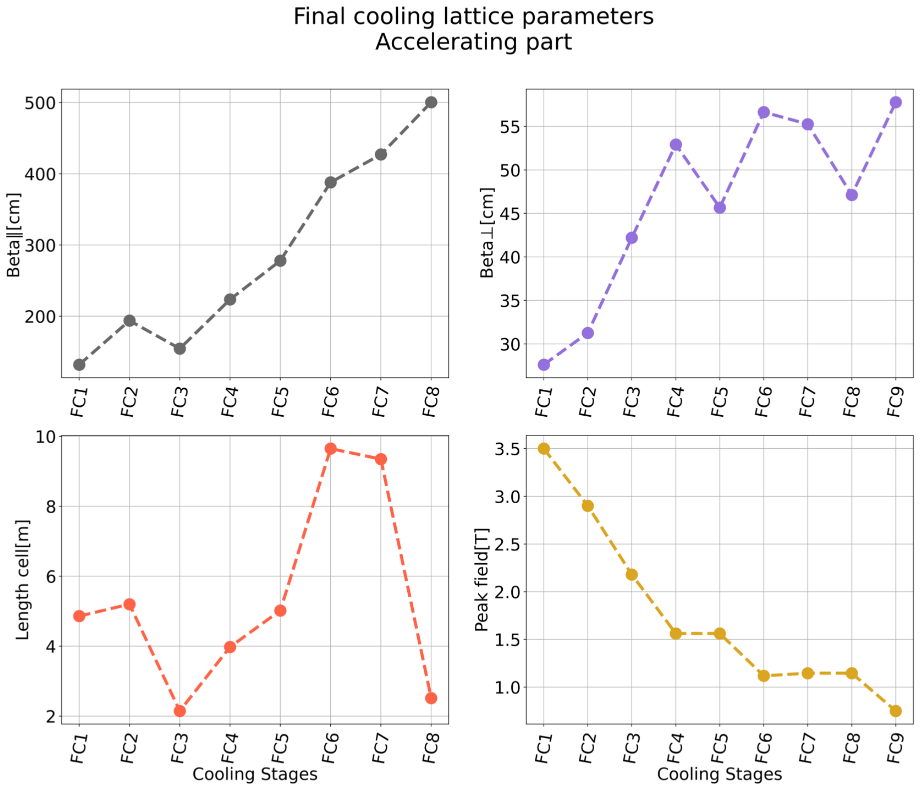


Rectilinear cooling lattice parameters



Final cooling lattice parameters





Beam break-up - results