International
MUON Collider
Collaboration

# IMCC Annual meeting
# 20 June 2023

# *RCS parameters and optimization*

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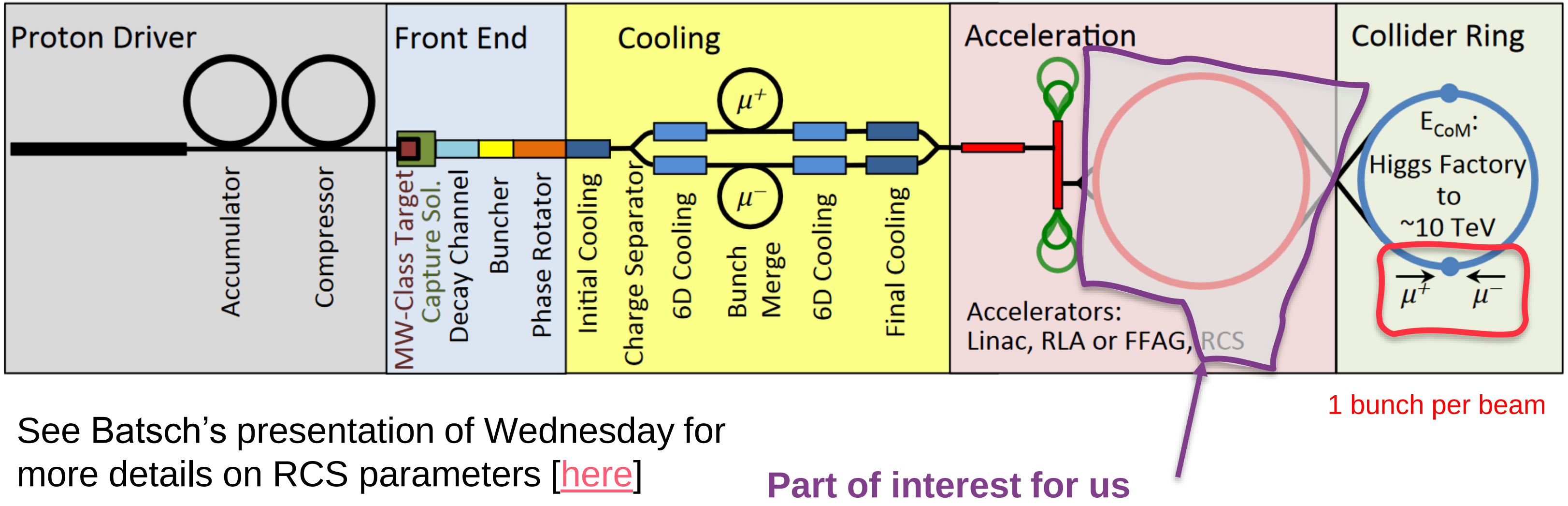
# Reminder on design baselines

- Base for the work is the US [Muon Accelerator Program] (MAP)
- High energy complex consist of a chain of rapid cycling synchrotrons (RCS)



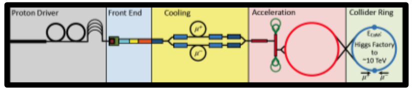

See Batsch's presentation of Wednesday for more details on RCS parameters [here]

# Reminder on design baselines

- Design oriented on reaching the performance parameter [webpage]
- The relevant target parameters are: [presentation by D. Schulte]

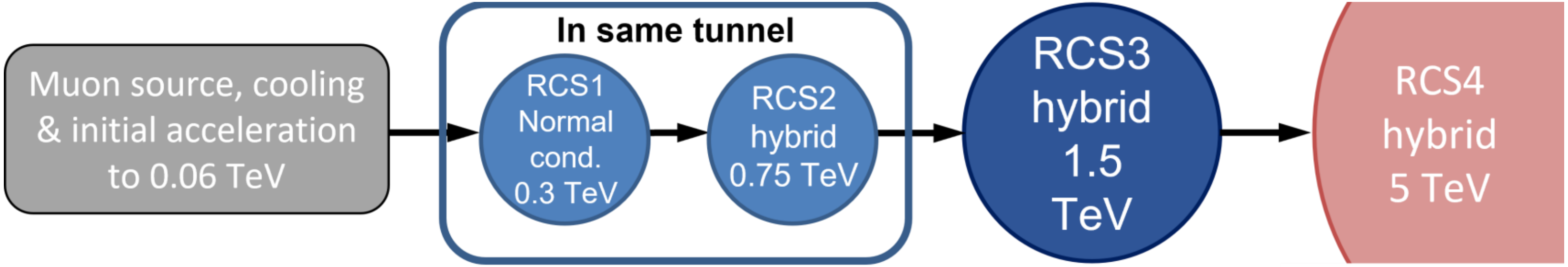
| Parameter | Unit | 3 TeV | 10 TeV |
|---|---|---|---|
| **L** | **$10^{34}$ cm$^{-2}$s$^{-1}$** | **1.8** | **20** |
| N | $10^{12}$ | 2.2 | 1.8 |
| $f_r$ | Hz | 5 | 5 |
| <B> (average) | T | 7 | 10.5 |
| $\varepsilon_L$ (norm, $1\sigma_z\sigma_E$) | MeV m | 7.5 | 7.5 |
| $\sigma_E$ / E | % | 0.1 | 0.1 |
| $\sigma_z$ | mm | 5 | 1.5 |

**Repetition rate of 5 Hz → RCS**




# The high-energy complex

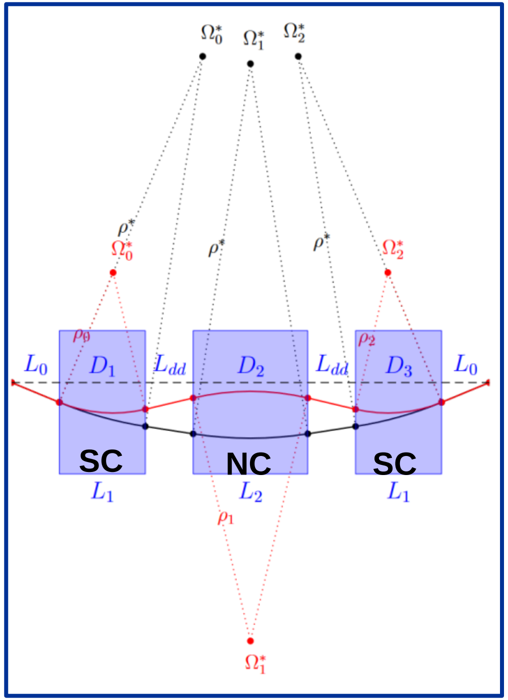
- Chain of rapid cycling synchrotrons, counter-rotating m+/m- beams
  → **60 GeV → 314 GeV → 750 GeV → 1.5 TeV → 5 TeV**




- Hybrid RCSs have interleaved normal conducting (NC) and superconducting (SC) magnets.
- This would be the first hybrid RCSs in the world!

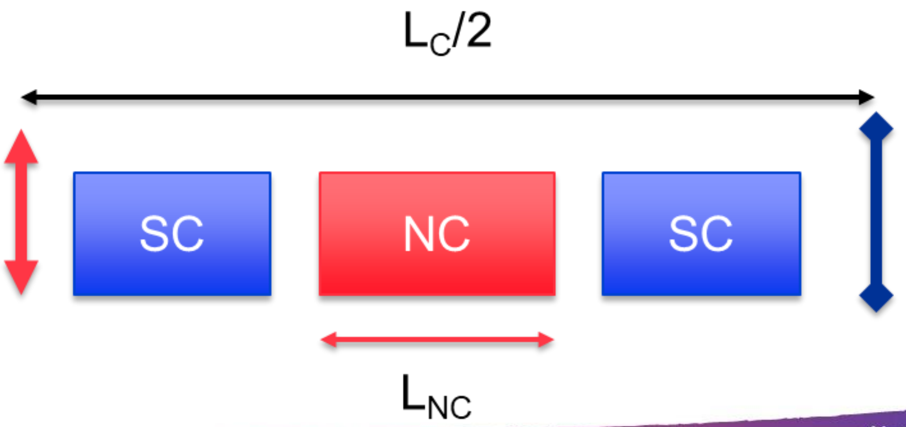
# Hybrid RCS magnet layout

- SC magnets provide high average B, but not fast ramping → fixed-field, $\boldsymbol{B_{sc} = 10}$ T
- NC magnets require fast ramping within $\boldsymbol{B_{nc} = \pm 1.8}$ T
  Decided for realistic values: below saturation of both technologies
- Beam orbit not constant during acceleration
  → Orbit length and frev ≠ const.
  → $f_{RF}$ tuning must be provided



# RCS Lattice

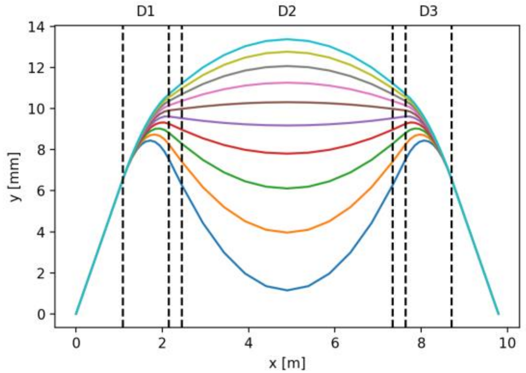
- Currently, we assume the RCS is made of FODO cells with phase advances of 90 degrees.
  - We assume we have nc cells of length Lc per arc and na arcs per RCS.
  - The muon beams run nt turns of length LRCS.
- The number of cells has been optimized to maximize the arc filling ratio.



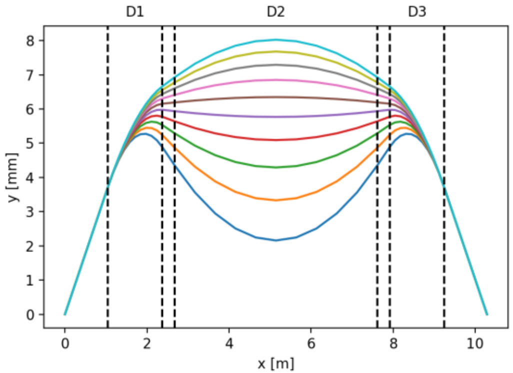
# Trajectory during ramp

- From injection to extraction the trajectory goes from the inner side to the outer side.
- The trajectory difference goes up to more than 13 mm.

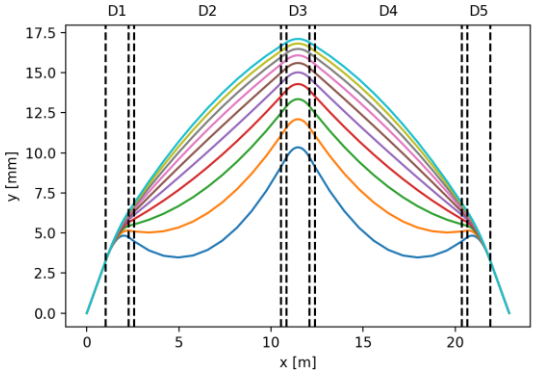
RCS2




RCS3




RCS4

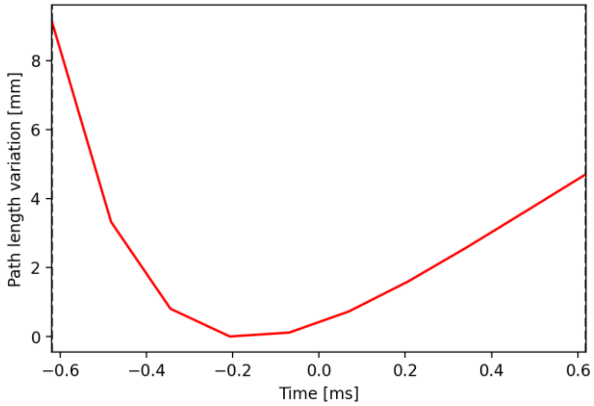


# Path lenth variation

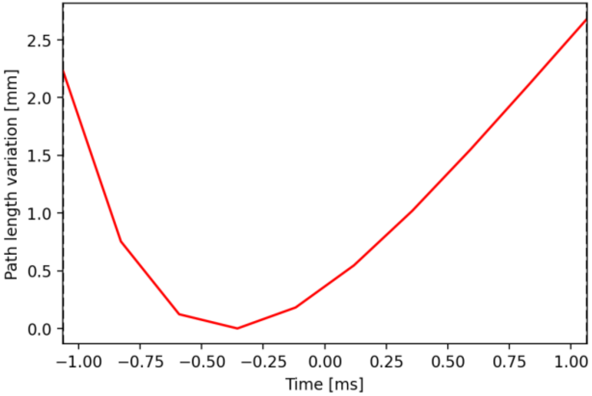
- In a hybrid RCS, the path length is not constant.

→ $f_{RF}$ **tuning to be provided**

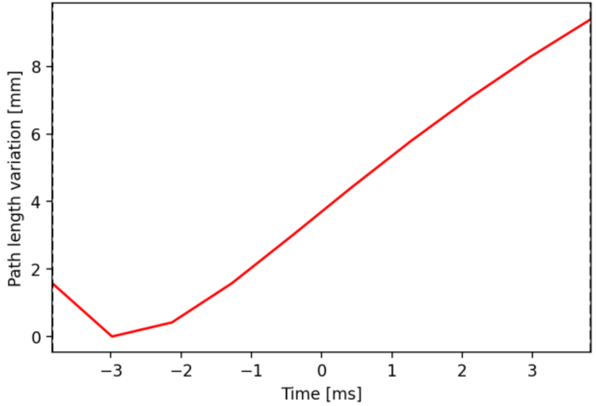
RCS2



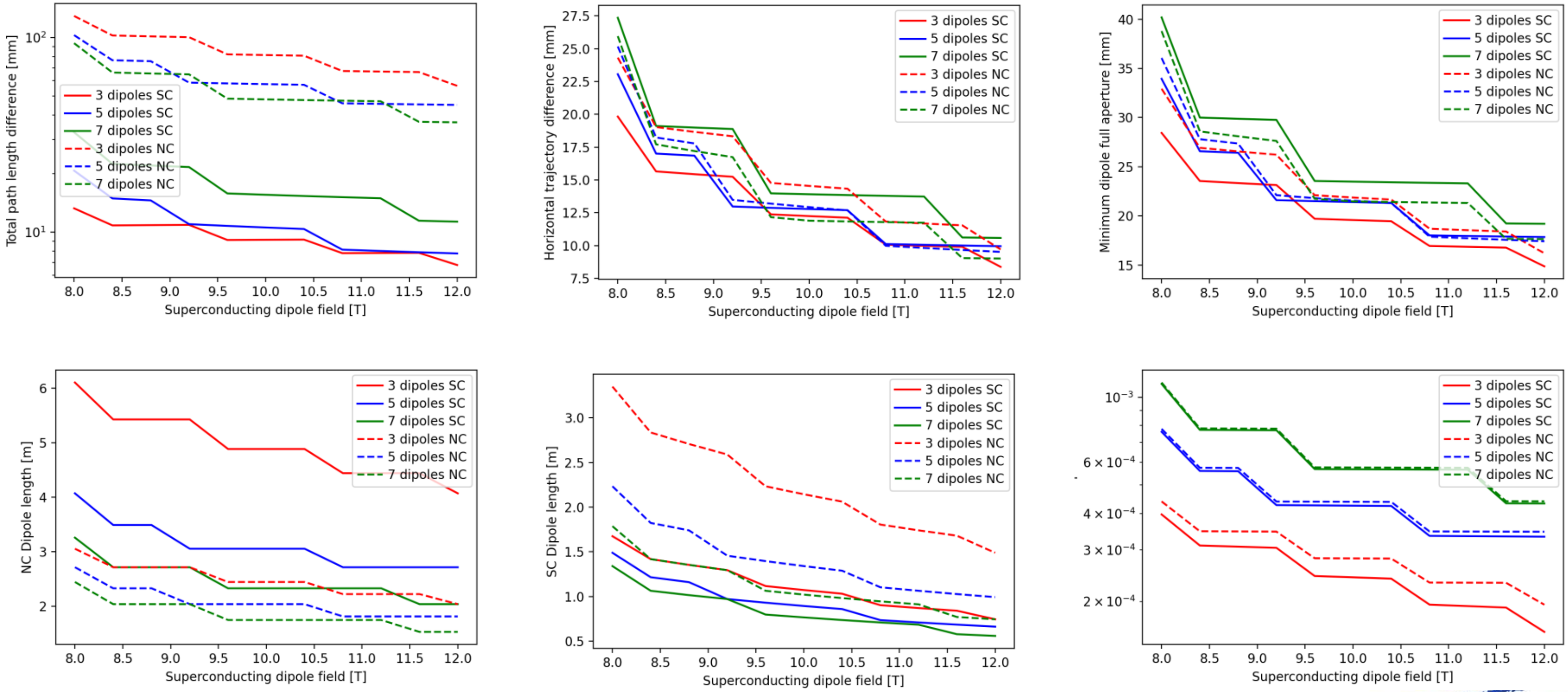

RCS3



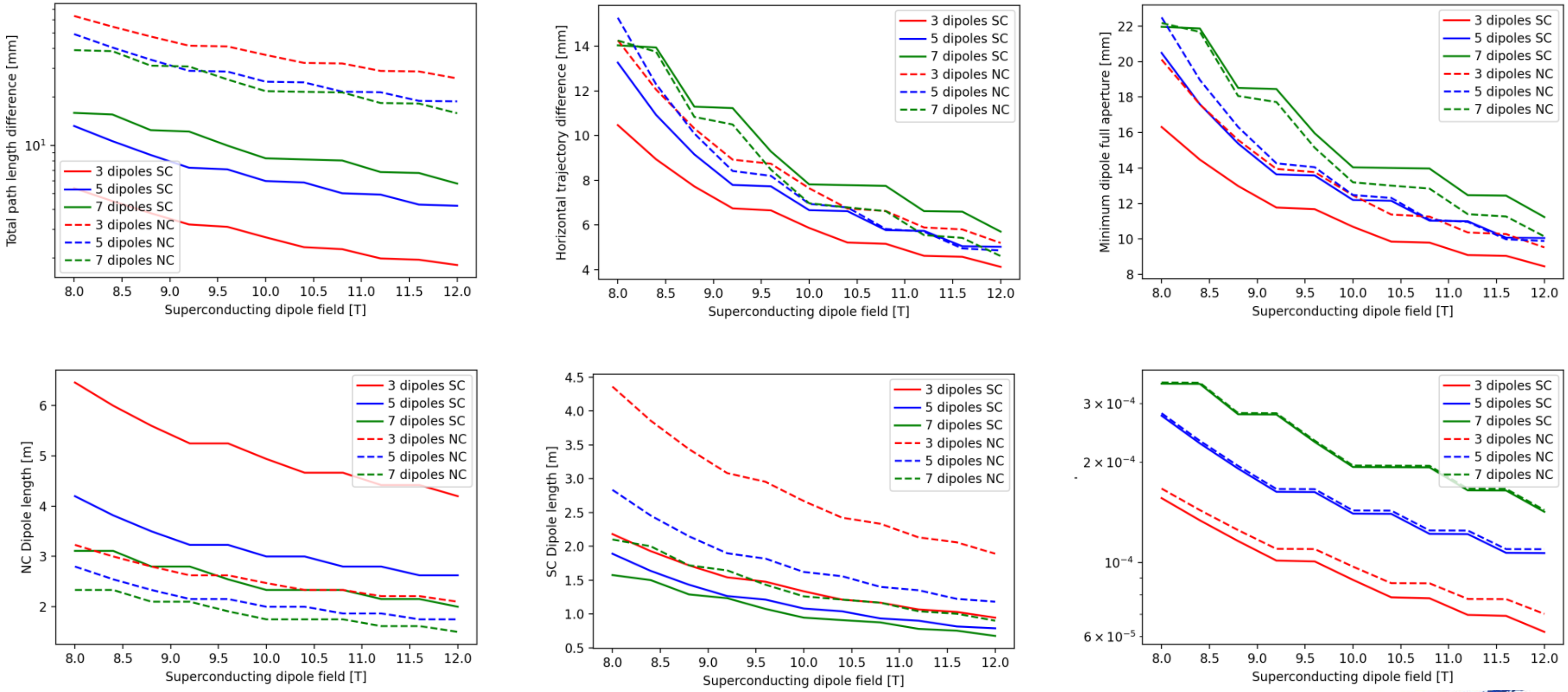

RCS4



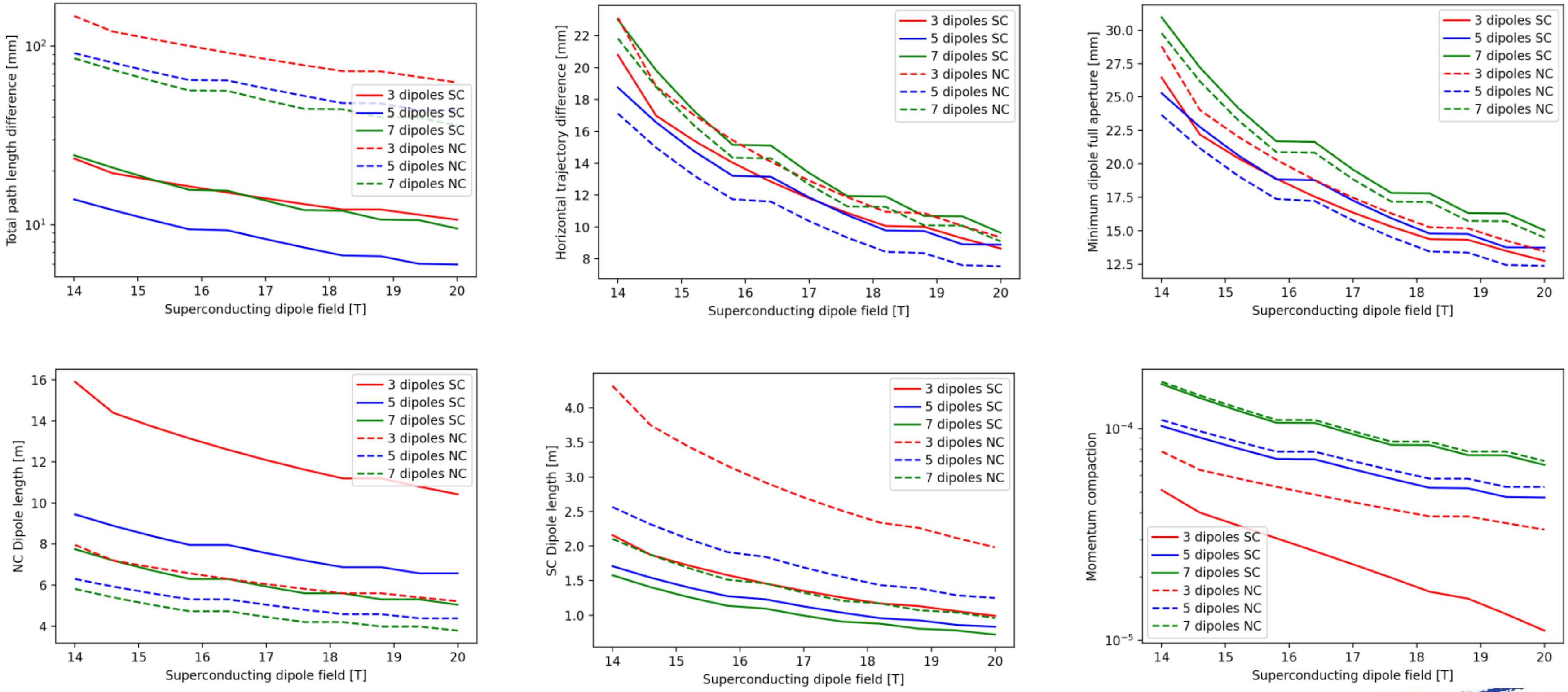
# RCS2: variation with SC dipole field



# RCS3: variation with SC dipole field



# RCS4: variation with SC dipole field



# Parameters and tools: General parameter

Details on RF requirements in presentation by H. Damerau

## Detailed parameter table: [link]

| | RCS1→314 GeV | RCS2→750GeV | RCS3→1.5TeV |
|---|---|---|---|
| Circumference, $2\pi R$ [m] | 5990 | 5590 | 10700 |
| Energy factor, $E_{ej}/E_{inj}$ | 5.0 | 2.4 | 2.0 |
| Repetition rate, $f_{rep}$ [Hz] | 5 (asym.) | 5 (asym.) | 5 (asym.) |
| Number of bunches | $1\mu^+$, $1\mu^-$ | $1\mu^+$, $1\mu^-$ | $1\mu^+$, $1\mu^-$ |
| Bunch population | >2.5E12 | >2.3E12 | 2.2E12 |
| Survival rate per ring | 90% | 90% | 90% |
| Acceleration time, $t_{acc}$ [ms] | 0.34 | 1.04 | 2.37 |
| Number of turns | 17 | 55 | 66 |
| Energy gain per turn, $\Delta E$ [GeV] | 14.8 | 7.9 | 11.4 |
| Acc. gradient for survival [MV/m] | 2.4 | 1.3 | 1.1 |
| Acc. field in RF cavity [MV/m] | 30 (45 optimistically) | 30 | 30 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 13 | | | | Stage 1 | | Stage 2 | | Stage 3 |
| 14 | Basic data | Symbol | Unit | Value | Details | Value | Details | Value |
| 15 | Particles | - | - | μ | | μ | | μ |
| 16 | Costs | - | M€ | | | | | |
| 17 | Type | - | - | RCS | | hybrid RCS | | hybrid RCS |
| 18 | | | | | | | | |
| 19 | Dynamics | | | | | | | |
| 20 | Acceleration time | $T_{acc}$ | [ms] | 0.34 | | 1.09704595 | | 2.37 |
| 21 | Injection energy | $E_{inj}$ | [MeV]/u | 63000 | | 313830 | | 750000 |
| 22 | Ejection energy | $E_{ej}$ | [MeV]/u | 313830 | defined by n | 750000 | | 1500000 |
| 23 | Energy ratio | $E_{ej}/E_{inj}$ | - | 4.98 | | 2.39 | | 2.00 |
| 24 | Momentum at $e_i$ | p/c | MeV/c | 63106 | | 313935 | | 750106 |
| 25 | Momentum at $e_j$ | p/c | MeV/c | 313935 | | 750106 | | 1500106 |
| 26 | Number of turns | $n_{turn}$ | - | 17 | | 55 | | 66 |
| 27 | Planned Survival rate | $N_{ej}/N_{inj}$ | - | 0.9 | | 0.9 | | 0.9 |
| 28 | Total survival rate | $N_{ej}/N_0$ | - | 0.9 | | 0.81 | | 0.729 |
| 29 | Accel. Gradient, linear for survival | G | [MV/m] | 2.44 | | 1.33 | | 1.06 |
| 30 | Required energy gain per turn | $\Delta E$ | [MeV] | 14755 | | 7930 | | 11364 |
| 31 | | | | | | | | |
| 32 | Transition gamma | $\gamma_{tr}$ | - | 20.41 | | 20.41 | | ~30 |
| 33 | Injection relativistic mass factor | $\gamma_{inj}$ | - | 597 | | 2971 | | 7099 |
| 34 | Ejection relativistic mass factor | $\gamma_{ej}$ | - | 2971 | | 7099 | | 14198 |
| 35 | Injection v/c | $\beta_{inj}$ | % | 0.9999986 | | 0.999999943 | | 0.9999999901 |
| 36 | Ejection v/c | $\beta_{ej}$ | % | 0.999999943 | | 0.9999999901 | | 0.9999999975 |
| 37 | | | | | | | | |
| 38 | Parameter Classical RCS | | | | | | | |
| 39 | Radius | R | [m] | 953.3 | | 953.3 | | 1703.0 |
| 40 | Circumference | $2\pi R$ | [m] | 5990 | | 5990 | | 10700 |
| 41 | Circumference Ratio | $R_{i+1}/R_i$ | - | - | | 1 | | 1.79 |
| 42 | Pack fraction | ? | - | 0.61 | | 0.61 | | 0.628 |
| 43 | Bend radius | $\rho_B$ | m | 581.8 | | 581.8 | | 1070.2 |
| 44 | Tot. straight section length | $L_{str}$ | [m] | 2334.7 | | 2335.7 | | 3975.7 |
| 45 | Injection bending field (average) | $B_{inj}$ | [T] | 0.36 | | 1.80 | | 2.34 |
| 75 | RF | | | | | | | |
| 76 | Systems | - | - | TESLA | | TESLA | | TESLA |
| 77 | Main RF frequency | $f_{RF}$ | [MHz] | 1300 | | 1300 | | 1300 |
| 78 | Harmonic number | h | - | 25957 | | 25957 | | 46367 |
| 79 | Revolution frequency ej | $f_{rev}$ | [kHz] | 50.08 | | 50.08 | | 28.04 |
| 80 | Revolution period | Trev | [μs] | 20.0 | | 20.0 | | 35.7 |
| 81 | Max RF voltage | $V_{RF}$ | [GV] | 20.87 | | 11.22 | | 16.07 |
| 82 | Max RF power | $P_{RF}$ | [MW] | | | | | |
| 83 | RF Filling factor | - | - | 0.4 | | 0.4 | | 0.45 |
| 84 | Number RF stations | - | - | Around 50 | | Around 50 | | Around 50 |
| 85 | Cavities | - | - | 9-cell | | 9-cell | | 9-cell |
| 86 | Number of cavities | ? | - | 696 | | 374 | | 536 |
| 87 | Peak Impedance | | [Ω] | | | | | |
| 88 | Gradient in cavity | $\Delta E/L$ | [MV/m] | 30 | | 30 | | 30 |
| 89 | Average energy gain per total straight | $\Delta E/L$ | [MeV/m] | 6.3 | | 3.4 | | 2.9 |
| 90 | Accelerating field per total straight | $\Delta E/L$ | [MeV/m] | 8.9 | | 4.8 | | 4.0 |
| 91 | Accelerating field gradient, with FF | $\Delta E/L$ | [MV/m] | 22.3 | | 12.0 | | 9.0 |
| 92 | Stable phase | $\phi_s$ | [°] | 45 | | 45 | | 45 |
| 93 | Conversion factor mm mrad – eVs | - | Vs/mm mra | 69.40 | | 165.86 | | 331.72 |
| 94 | Longitudinal emittance (σE * 4σz) | $\varepsilon^L_n$ | [eVs] | 0.025 | 7.5 MeV m | 0.025 | | 0.025 |
| 95 | Longitudinal emittance (phase space area) | $\varepsilon^L_n$ | [eVs] | 0.079 | | 0.079 | | 0.079 |
| 96 | Injection bucket area | $A_{b,inj}$ | [eVs] | 0.62 | | 1.01 | | 1.40 |
| 97 | Ejection bucket area | $A_{b,ej}$ | [eVs] | 1.37 | | 1.56 | | 1.97 |
| 98 | Bucket area reduction factor | $A_B/A_{B,st}$ | - | 0.172 | | 0.172 | | 0.172 |
| 99 | Horizontal betatron tune | $Q_h$ | - | | | | | |
| 100 | Vertical betatron tune | $Q_v$ | - | | | | | |
| 101 | Average horizontal Twiss beta | βh | [m] | 10 | | 10 | | 10 |
| 102 | Average vertical Twiss beta | βv | [m] | 10 | | 10 | | 10 |
| 103 | Injection synchrotron frequency | $f_{S,inj}$ | [kHz] | 76.33 | | 25.07 | | 14.53 |
| 104 | Ejection synchrotron frequency | $f_{S,ej}$ | [kHz] | 34.20 | | 16.22 | | 10.27 |
| 105 | Injection synchrotron tune $Q_s$ | $f_{S,inj}/f_{rev}$ | - | 1.52 | | 0.50 | | 0.52 |
| 106 | Ejection synchrotron tune $Q_s$ | $f_{S,ej}/f_{rev}$ | - | 0.68 | | 0.32 | | 0.37 |

# Parameters and tools: General parameter

Details on RF requirements in presentation by H. Damerau

## Detailed parameter table: [link]

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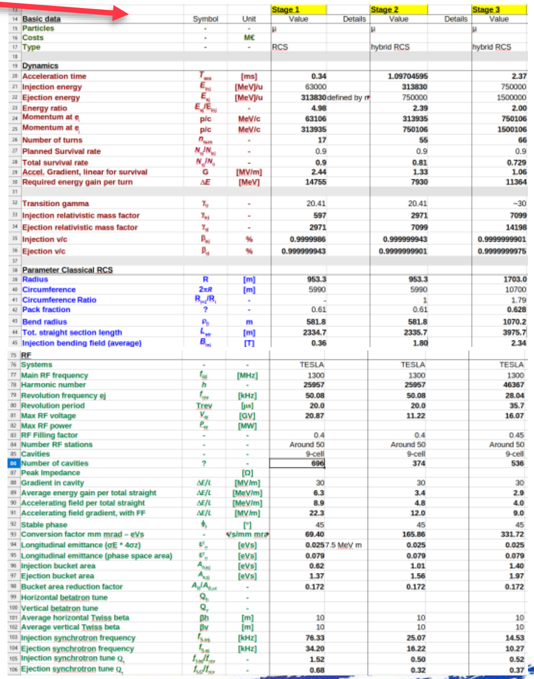


- High $\Delta E = V_{RF} \cdot cos(\phi_s)$ → Unique RF requirements such as high synchrotron tune

# Synchrotron tune and number of RF stations

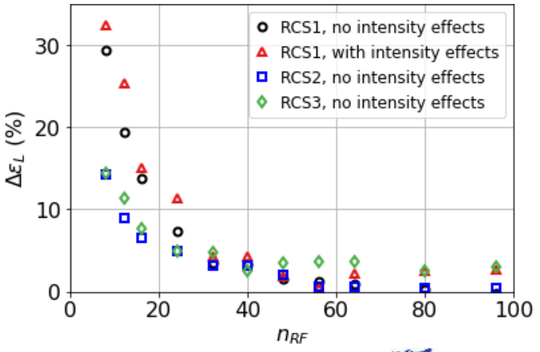
Courtesy: F. Batsch

- Number of synchrotron oscillations per turn proportional to $\sqrt{V_{\mathbf{RF}}}$:

$$Q_S = \frac{\omega_S}{\omega_0} = \sqrt{-\frac{h\eta e V_{RF}\cos\phi_S}{2\pi E\beta^2}} \propto \sqrt{V_{RF}\cos\phi_S}$$

LHC: $Q_s$=0.005

- Stable synchrotron oscillations and phase focusing only for $Q_s \ll \frac{1}{\pi}$
- RCSs would exceed this limit: 0.3 < Qs < 1.5 **(T. Suzuki, KEK Report 96-10)**
  - Several longitudinal kicks per turn for small Qs between stations, i.e., small $Qs/n_{RF}$
  - Distribute RF system over nRF sections
- **$n_{RF}$ is an important quantity to determine!**
- $n_{RF}$ gives also the minimum number of arcs.



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| Acceleration time [ms] | 0.34 | 1.04 | 2.37 |
| Number of turns | | | |
| Energy gain per turn, $\Delta E$ [GeV] | | | |
| Acc. gradient for survival [MV/m] | | | |
| Acc. field in RF cavity [MV/m] | | | |
| **Ramp rate, $\dot{B}_{nc}$ [T/s]** | 4199 | 3281 | 1518 |

**Fast ramping within $B_{nc} = \pm 1.8$ T**

| | | | | Stage 1 | | Stage 2 | | Stage 3 |
|---|---|---|---|---|---|---|---|---|
| 14 | Basic data | Symbol | Unit | Value | Details | Value | Details | Value |
| 15 | Particles | - | - | μ | | μ | | μ |
| 16 | Costs | - | M€ | | | | | |
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| 42 | Pack fraction | ? | - | 0.61 | | 0.61 | | 0.628 |
| 43 | Bend radius | $\rho_B$ | m | 581.8 | | 581.8 | | 1070.2 |
| 44 | Tot. straight section length | $L_{str}$ | [m] | 2334.7 | | 2335.7 | | 3975.7 |
| 45 | Injection bending field (average) | $B_{inj}$ | [T] | 0.36 | | 1.80 | | 2.34 |
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| 76 | Systems | - | - | TESLA | | TESLA | | TESLA |
| 77 | Main RF frequency | $f_{RF}$ | [MHz] | 1300 | | 1300 | | 1300 |
| 78 | Harmonic number | h | - | 25957 | | 25957 | | 46367 |
| 79 | Revolution frequency ej | $f_{rev}$ | [kHz] | 50.08 | | 50.08 | | 28.04 |
| 80 | Revolution period | Trev | [μs] | 20.0 | | 20.0 | | 35.7 |
| 81 | Max RF voltage | $V_{RF}$ | [GV] | 20.87 | | 11.22 | | 16.07 |
| 82 | Max RF power | $P_{RF}$ | [MW] | | | | | |
| 83 | RF Filling factor | - | - | 0.4 | | 0.4 | | 0.45 |
| 84 | Number RF stations | - | - | Around 50 | | Around 50 | | Around 50 |
| 85 | Cavities | - | - | 9-cell | | 9-cell | | 9-cell |
| 86 | Number of cavities | ? | - | 696 | | 374 | | 536 |
| 87 | Peak Impedance | | [Ω] | | | | | |
| 88 | Gradient in cavity | $\Delta E/L$ | [MV/m] | 30 | | 30 | | 30 |
| 89 | Average energy gain per total straight | $\Delta E/L$ | [MeV/m] | 6.3 | | 3.4 | | 2.9 |
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| 92 | Stable phase | $\phi_s$ | [°] | 45 | | 45 | | 45 |
| 93 | Conversion factor mm mrad – eVs | - | Vs/mm mra | 69.40 | | 165.86 | | 331.72 |
| 94 | Longitudinal emittance (σE * 4σz) | $\varepsilon^l_n$ | [eVs] | 0.025 | 7.5 MeV m | 0.025 | | 0.025 |
| 95 | Longitudinal emittance (phase space area) | $\varepsilon^l_n$ | [eVs] | 0.079 | | 0.079 | | 0.079 |
| 96 | Injection bucket area | $A_{b,inj}$ | [eVs] | 0.62 | | 1.01 | | 1.40 |
| 97 | Ejection bucket area | $A_{b,ej}$ | [eVs] | 1.37 | | 1.56 | | 1.97 |
| 98 | Bucket area reduction factor | $A_B/A_{B,st}$ | - | 0.172 | | 0.172 | | 0.172 |
| 99 | Horizontal betatron tune | $Q_h$ | - | | | | | |
| 100 | Vertical betatron tune | $Q_v$ | - | | | | | |
| 101 | Average horizontal Twiss beta | βh | [m] | 10 | | 10 | | 10 |
| 102 | Average vertical Twiss beta | βv | [m] | 10 | | 10 | | 10 |
| 103 | Injection synchrotron frequency | $f_{S,inj}$ | [kHz] | 76.33 | | 25.07 | | 14.53 |
| 104 | Ejection synchrotron frequency | $f_{S,ej}$ | [kHz] | 34.20 | | 16.22 | | 10.27 |
| 105 | Injection synchrotron tune $Q_s$ | $f_{S,inj}/f_{rev}$ | - | 1.52 | | 0.50 | | 0.52 |
| 106 | Ejection synchrotron tune $Q_s$ | $f_{S,ej}/f_{rev}$ | - | 0.68 | | 0.32 | | 0.37 |

# Fast ramping considerations

International MUON Collider Collaboration

**Courtesy: F. Batsch**

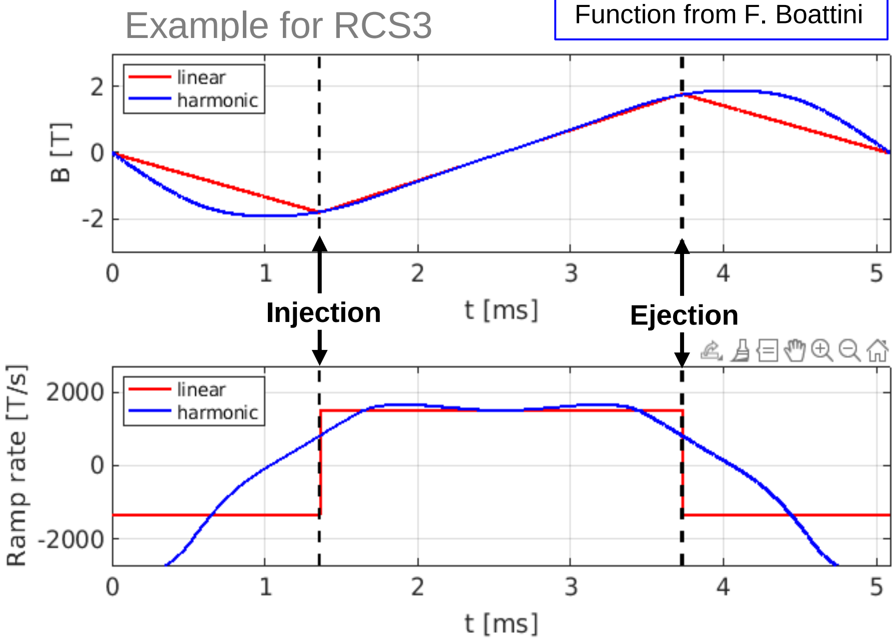
- Ramping times ≈ cavity filling time:

$$t_{\mathrm{acc}} = 0.3\ \mathrm{ms} \approx \frac{Q_L}{\omega} = 0.27\ \mathrm{ms}$$

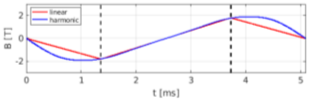
- **Optimization problem** between magnet powering and RF
- **Linear ramping** → constant $V_{RF}$ → simplest RF solution, best for μ
- **Non-linear ramping** → decrease peak power ≙ magnet powering costs significantly (see talk by F. Boattini)
- **Sinusoidal ramp function** → performance decrease of 50%

→ **Study quasi-linear ramping** by e.g. natural resonant discharge of e.g. two harmonics

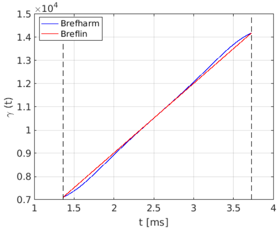
Function from F. Boattini



# RF requirements with non-linear ramping

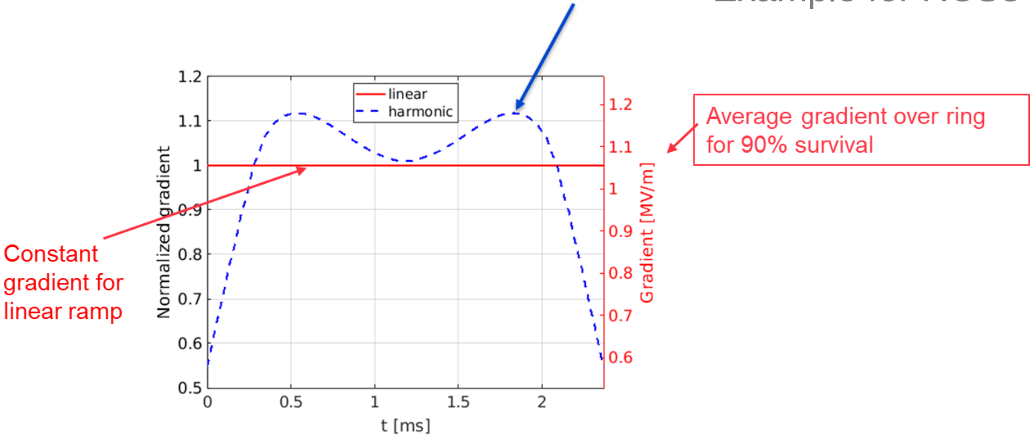


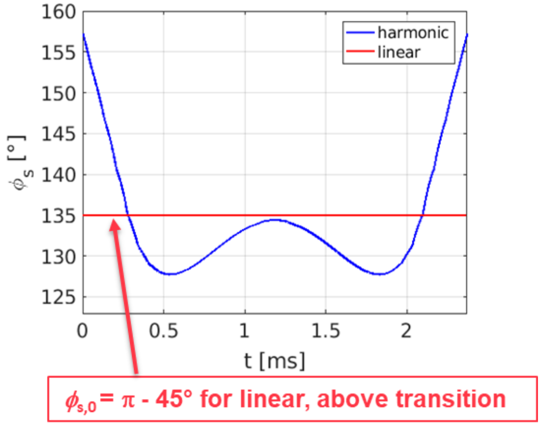

**Courtesy: F. Batsch**




- **$V_{acc}$ and $G_{acc}$ must be increased by 12% to achieve the same $\tau_{acc}$ ⇔ ≠ 200% as for a sine-like ramp!**

Example for RCS3

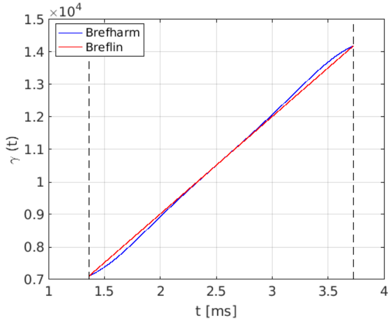


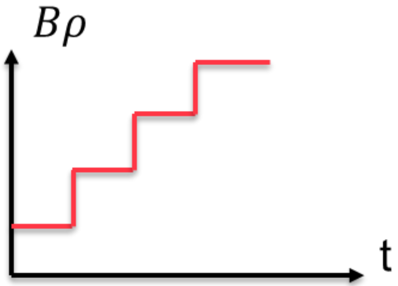




- Powering and ramping function optimization ongoing, combined with synchronous phase and RF voltage optimization (see talk by F. Batsch and talk by F. Boattini).

# Energy against magnetic variation

- The magnetic field is varying quasi-linearly.
- The beam energy has a step-wise shape: energy bump at RF stations.




- If we consider RCS1: acceleration 60 → 314 GeV in 17 turns and 32 RF stations.
- In the first arc: energy of 60 GeV but relative variation of the field of $\frac{314-60}{17\times 32\times 60} = 0.8\%$!
- μ+ and μ- are propagating in 2 opposite directions: impact of this variation to be discussed.

# Summary and outlook

- The muon decay brings unique challenges: fast acceleration, large voltages, high intensities, high synchronous tune, small number of turns.
- The synchrotron tune mitigation implies a large number of RF stations and thus arcs (about 30).
- We still need to optimize several acceleration parameters: RF voltages, synchronous phase, acceleration time = decay.
- Still a lot of remaining questions: impact of power supply errors on the orbits, required reproducibility? Beam trajectory with quickly varying dipole fields? Field quality to be discussed this afternoon.
- **That is crucial to discuss between RF, magnet, beam dynamics, shielding, and optics people!**

# Tentative RCS parameters

- **Detailed parameter table (by F. Batsch):** https://cernbox.cern.ch/index.php/s/l9VplTncUeCBtiz
- Parameters of the 4th RCS under study.

Example parameters for the muon RCSs

| | RCS1 | RCS2 | RCS3 | RCS4 |
|---|---|---|---|---|
| Hybrid RCS | No | Yes | Yes | Yes |
| Circumference [m] | 5990 | 5990 | 10700 | 26659 |
| Injection/extraction energy [TeV] | 0.06/0.314 | 0.314/0.75 | 0.75/1.5 | 1.5/4.2 |
| Survival rate [%] | 90 | 90 | 90 | 90 |
| **Acceleration time [ms]** | **0.34** | **1.10** | **2.37** | **5.75** |
| Number of turns | 17 | 55 | 66 | 65 |
| Energy gain/turn [GeV] | 14.8 | 7.9 | 11.4 | 41.5 |
| **NC dipole field [T]** | **0.36/1.8** | **-1.8/1.8** | **-1.8/1.8** | **-1.8/1.8** |
| **SC dipole field [T]** | **-** | **10** | **10** | **16** |
| NC/SC dipole length [m] | 2.6/- | 4.9/1.1 | 4.9/1.3 | 8.0/1.3 |
| Number of arcs | 34 | 26 | 26 | 26 |
| Number of cells/arc | 7 | 10 | 17 | 19 |
| Cell length [m] | 21.4 | 19.6 | 20.6 | 45.9 |
| **Path length diff. [mm]** | **0** | **9.1** | **2.7** | **9.4** |
| **Orbit difference [mm]** | **0** | **12.2** | **5.9** | **13.2** |
| **Min. dipole width [mm]** | **17.4** | **19.6** | **10.7** | **18.8** |
| **Min. dipole height [mm]** | **14.8** | **6.4** | **4.2** | **4.4** |

Collective effects and shielding not included

# Thank you to Fabian Batsch for providing most of the slides

International MUON Collider Collaboration

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*Thank you for your attention*