RF parameters and longitudinal beam dynamics considerations

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Overview

- Introduction
- Trading bending field ramp with RF voltage
- RF and longitudinal beam parameters during the acceleration cycle
- Baseline RCS parameter assumptions
- Summary and outlook

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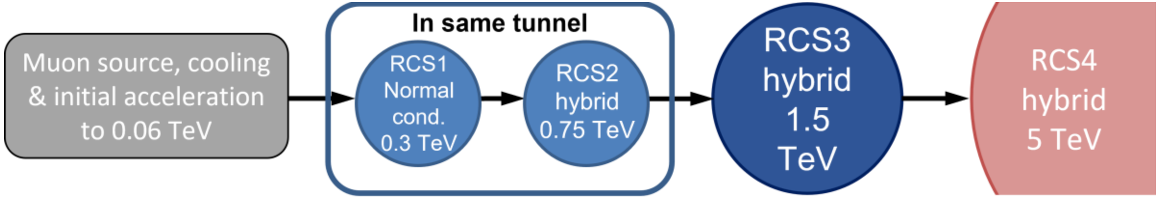
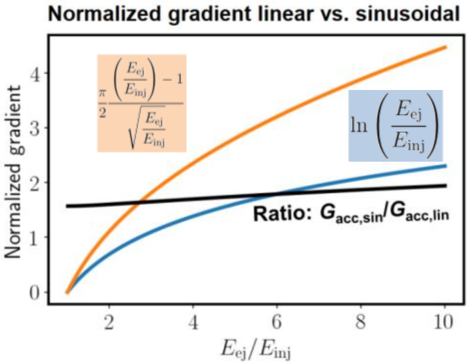
The Rapid Cycling Synchrotrons (RCSs)

- **Working hypothesis: 60 GeV → 310 GeV → 750 GeV → 1.5 TeV → 5 TeV**



- Optimization problem for ramp function between **sinusoidal optimum for magnet powering** and **linear optimum for RF**
- **Linear ramp** → constant V_{RF}, ideal RF solution
  → unfavorable for magnet powering
- **Non-linear ramp** → reduced peak power **and** magnet powering costs, but required more RF voltage

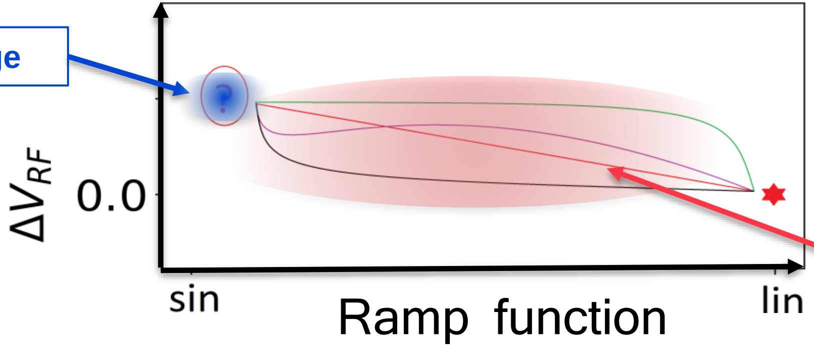


The optimization problem

- **Goal: cost-optimized compromise with quasi-linear magnet and RF ramping**

50% extra RF voltage

Extra voltage for the 4 RCS



Parameter space for optimization

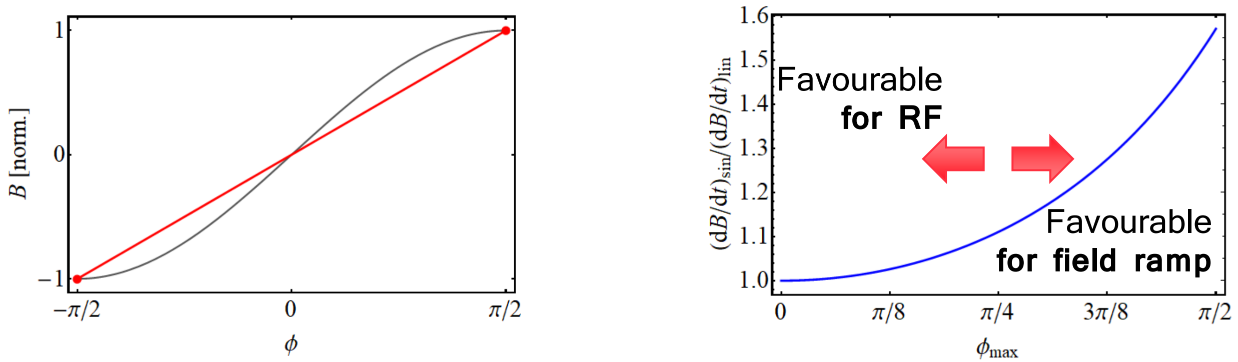
- **The required extra voltage is the sum**
  - → **Gradient reduction due to nonlinear ramping**
  - → **Change in the synchronous phase**

Mini-workshops on RCS ramp shape

- **20/09/23: https://indico.cern.ch/event/1309172/**
- **17/01/24: https://indico.cern.ch/event/1356899/**

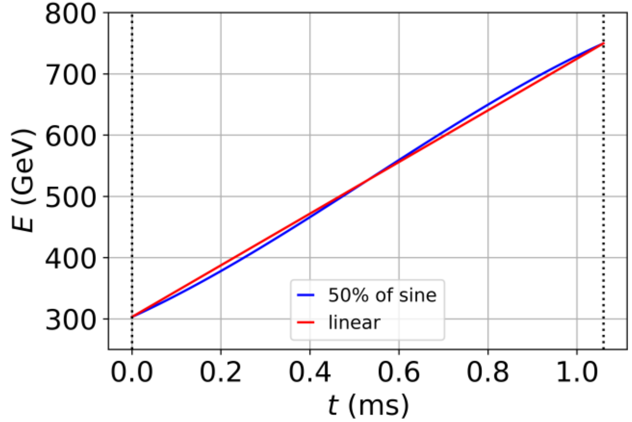
Reminders

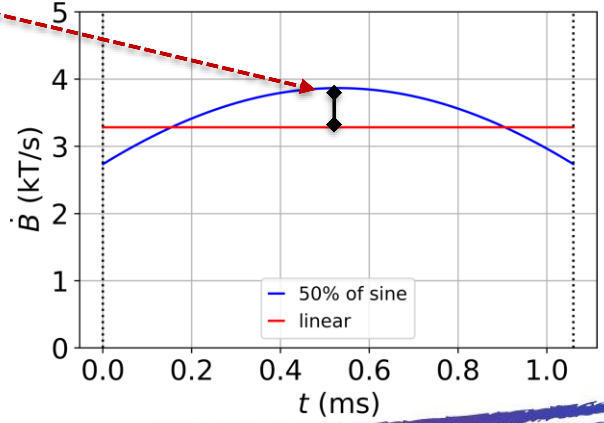
- Initial **focus on RCS2** as test case → **highest ramp rate d*B*/d*t* of the hybrid RCS**
- Ramp shape assumption: fraction of sinusoidal function



Reminders

- Initial **focus on RCS2** as test case → **highest ramp rate $\dot{B}$ of the hybrid RCS**
- Ramp shape assumption: fraction of sinusoidal
- Example of central half of sine → almost 20% extra RF voltage required
- That maxima defines the extra costs as the magnet ramp shape defines the voltage shape / RF requirements!





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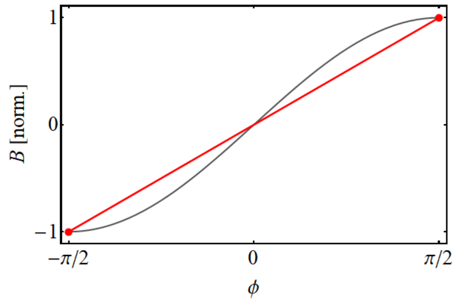
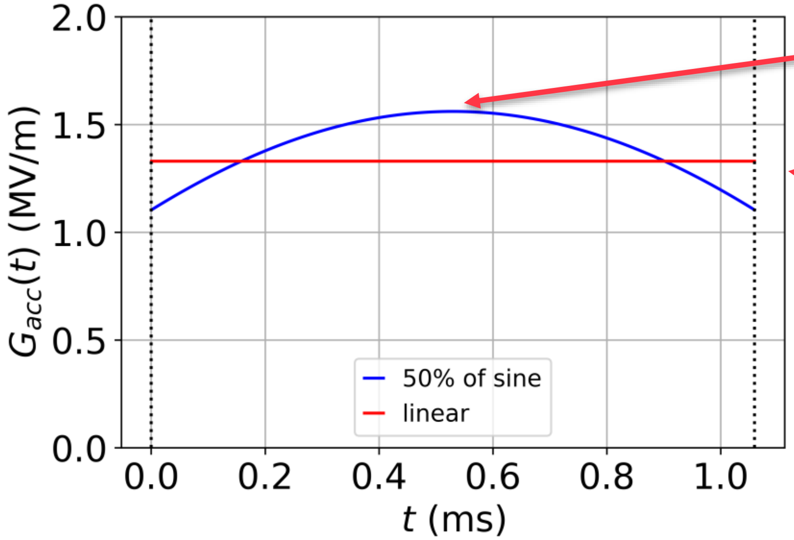
Accelerating gradient

- $G_{acc}(t)$ and $V_{acc}(t)$ follow the shape of $B(t)$ and define the additional gradient / voltage / number of cavities to achieve the same τ_{acc}





Maxima that defines extra RF costs!

Average gradient for linear ramp and 90% survival

$$G_{harm}(t) = \frac{(\gamma_{ej} - \gamma_{inj})}{2} \cdot \frac{m_\mu}{c} \left(\frac{\dot{B}_{harm}(t)}{B_{ej}} \right)$$

Synchronous phase

→ Additional voltage requirement can be partly compensated by a larger synchronous phase

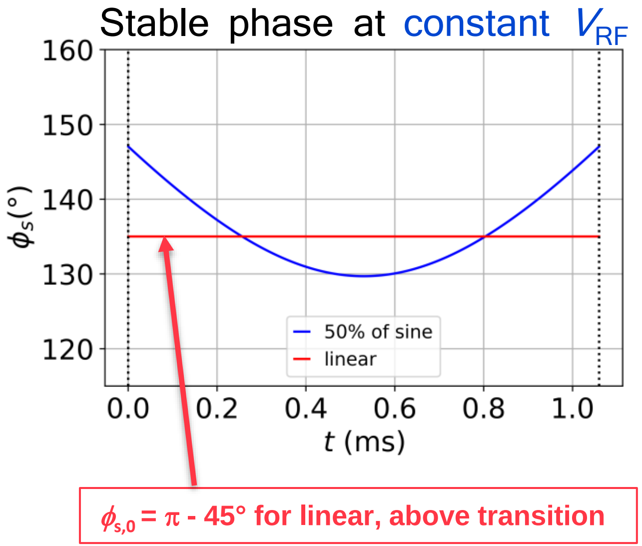
→ Results in reduction in bucket area

→ Adjust the energy gain by changing the synchronous phase during acceleration

$$\Delta E(t) = e\, V_{\mathrm{RF}} \cdot \sin[\phi_s(t)] \propto dB/dt$$

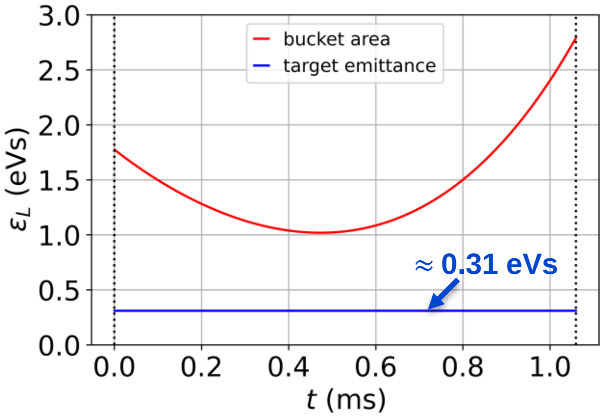
and $\phi_s(t) = \arcsin\left(\frac{\dot{B}_{harm}(t)}{\dot{B}_{lin}(t)} \cdot \sin\phi_{s,0}\right)$

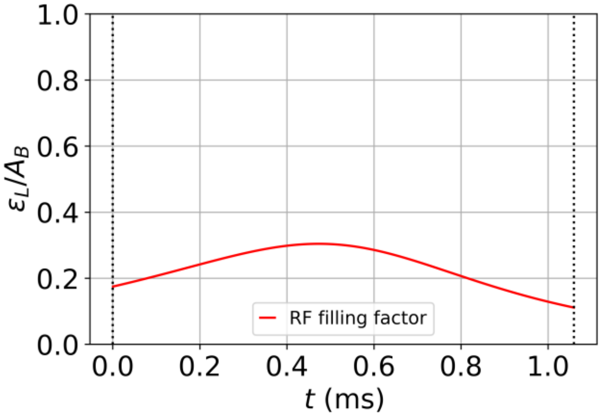
- Time scale of RF voltage changes is given by cavity filling time $2Q_L/\omega$ = 0.5 ms

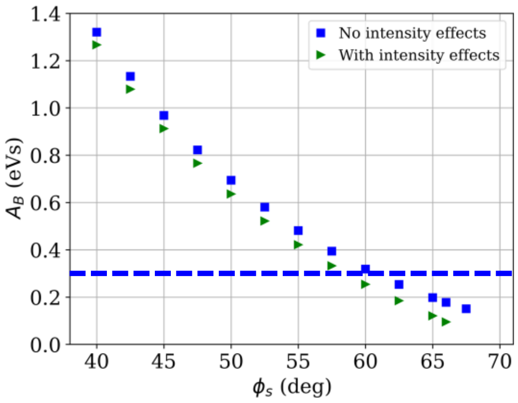


Bucket area and RF filling factor

→ $V(t)$ and $\phi_s(t)$ are the most important parameters that define available bucket area $A_B(t)$ and RF filling factor → Important for optimization efforts







Example of $\phi_s = 60°$: low filling factor, not ideal, room for optimization → Too large

Example for RF calculations

Overall flow:

$$\gamma_{harm}(t) = \gamma_{inj} + (\gamma_{ej} - \gamma_{inj}) \cdot \frac{1}{2}\left(\frac{B_{harm}(t)}{B_{ej}} + 1\right)$$

$$G_{harm}(t) = \frac{(\gamma_{ej} - \gamma_{inj})}{2} \cdot \frac{m_\mu}{c}\left(\frac{\dot{B}_{harm}(t)}{B_{ej}}\right)$$

$$\phi_s(t) = \arcsin\left(\frac{\dot{B}_{harm}(t)}{\dot{B}_{lin}(t)} \cdot \sin\phi_{s,0}\right)$$

$B(t)$, $\dot{B}(t)$ (and higher-level parameters)

↓

$\gamma(t)$, $E(t)$, $G_{acc}(t)$ → Max. gradient & number of cavities for costs

↓

$\phi_s(t)$, $V_{acc}(t)$

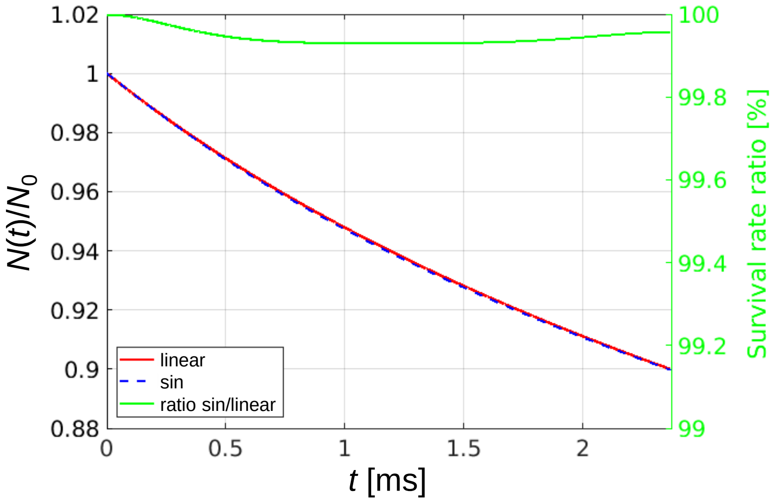
↓

Bucket area $A_B(t)$, RF filling factor and other criteria

→ Details in next talk by L. Thiele

Survival rate

- **The survival rate is not affected by quasi-linear ramping as long as the deviations from linear are not too large. Example for 11% extra voltage requirement:**



$$\frac{N(t)}{N_0} = \exp\left(-\frac{1}{\tau_\mu}\int_0^{\tau_{acc}} \frac{dt}{\gamma(t)}\right)$$

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RCS1/2/3 optimization parameters

Parameters to be optimized:

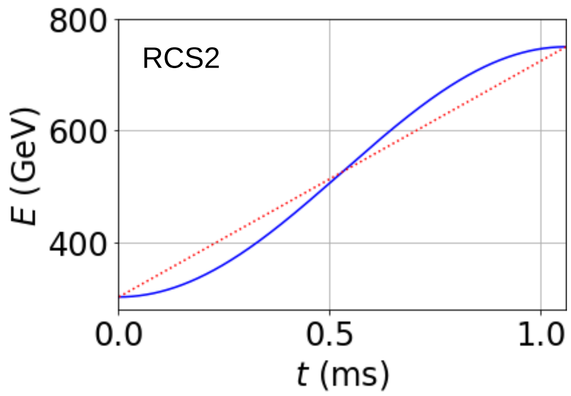
- Circumference
- Survival rate and acceleration time
- Number of RF stations, n_{RF}
- Synchronous phase
- Minimal required bucket area and RF filling factor
- Inj. and ejection *B* fields
- **Maximum ramp rate, d*B*/dt?**

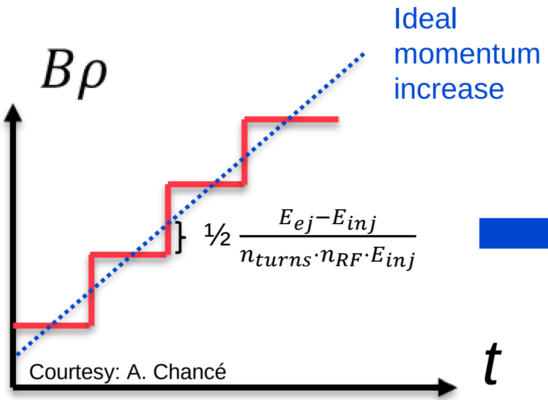
	RCS1→314 GeV	RCS2→750GeV	RCS3→1.5TeV
Circumference, $2\pi R$ [m]	5990	5990	10700
Bunch population [10^{12}]	<2.7	<2.43	<2.2
Survival rate per ring [%]	~90	~90	~90
Acceleration time, t_{acc} [ms]	0.34	1.04	2.37
Number of turns	17	55	66
Energy gain per turn [GeV]	14.8	7.9	11.4
Avg. acc. gradient [MV/m]	2.4	1.3	1.1
Acc. field in RF cavity [MV/m]	30 (45 optimistically)	30	30
Synchronous phase [°]	45	45	45
Minimal bucket area [eVs]	0.6?	0.6?	0.8?
Injection B field [T] (warm m.)	0.36	-1.8	-1.8
Ejection B field [T] (warm m.)	1.8	1.8	1.8

Energy and magnetic field synchronization

2nd order impact on optimization

- Continuous magnet ramp and discrete energy steps causes a relative field variation / error **for both linear and nonlinear ramping**





RCS1	< 0.36%
RCS2	< 0.13%
RCS3	< 0.09%
RCS	< 0.21%

→ μ^+ and μ^- are propagating in opposite directions: impact of this variation to be discussed

→ **Novel issue** for muon RCS

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Summary and outlook

- Close interaction RF voltage and bending field
- Fraction of sinusoidal function for linearization, ideally well below 50%
- RF power requirement ($P \propto V_{RF}^2$) given by maximum RF voltage during cycle
- **Outlook**
  - Complete calculations for entire RCS chain
  - Optimize transfer energies between accelerators

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