RF cycling considerations

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Acknowledgements*: David Amorim, Fulvio Boattini, Luca Bottura, Christian Carli, Antoine Chancé, Alexej Grudiev, Elias Metral, Daniel Schulte

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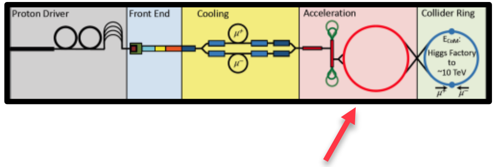
Outline

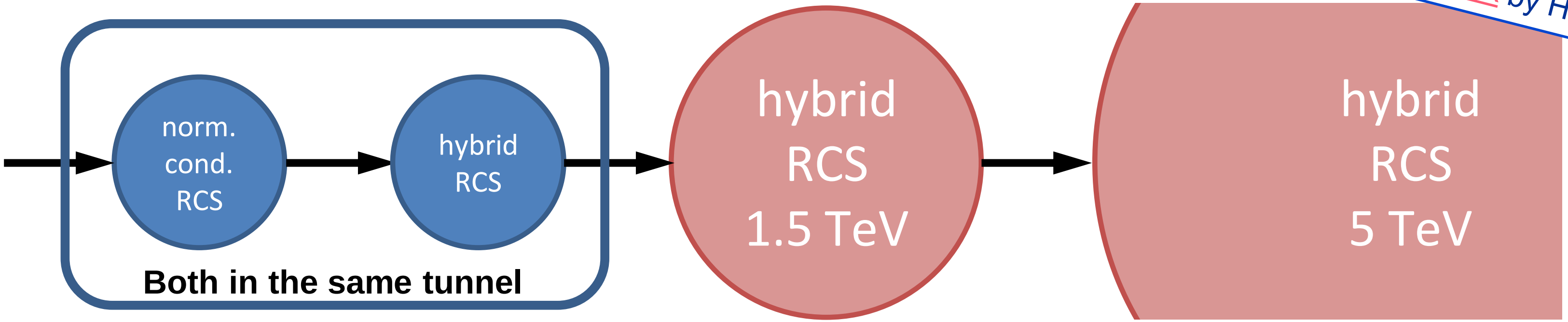
- **RCS and magnet parameter**
- **Linear and non-linear ramping considerations**
- **Consequences of non-linear ramping on the accelerator performance (decay rates, RF requirements)**
- **Simulations of muon acceleration with nonlinear ramping**
- **Summary**

Introduction



- **Chain of rapid cycling synchrotrons, counter-rotating μ^+/μ^- beams**
  $\rightarrow$ 63 GeV $\rightarrow$ 314 GeV $\rightarrow$ 750 GeV $\rightarrow$ 1.5 TeV ($\rightarrow$ 5 TeV)

Details on RCS & RF:
See talk by H. Damerau



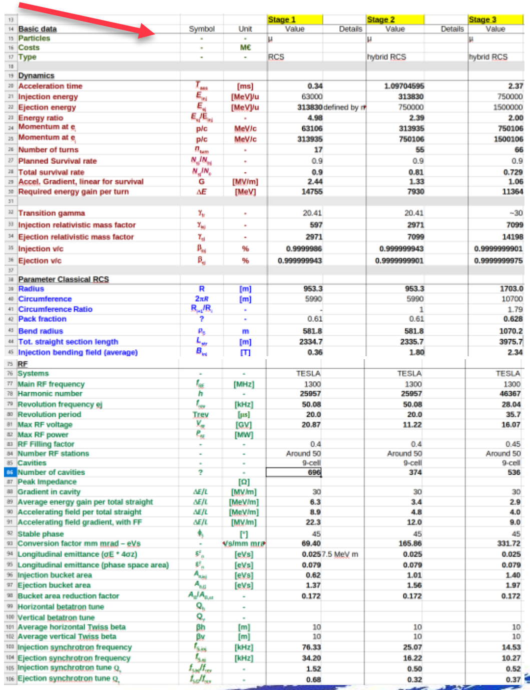
- **Hybrid RCSs have intersecting normal conducting (NC) and superconducting (SC) magnets**

H. Damerau

Parameters and tools:
General parameter

Detailed parameter table: https://cernbox.cern.ch/index.php/s/I9VpITncUeCBtiz

	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 [ms]	0.34	1.04	2.37
Number of turns	17	55	66
Energy gain per turn, ΔE [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 (TESLA)	30	30
Ramp rate $\dot{B}_{nc}$ [kT/s]	4199	3281	1518



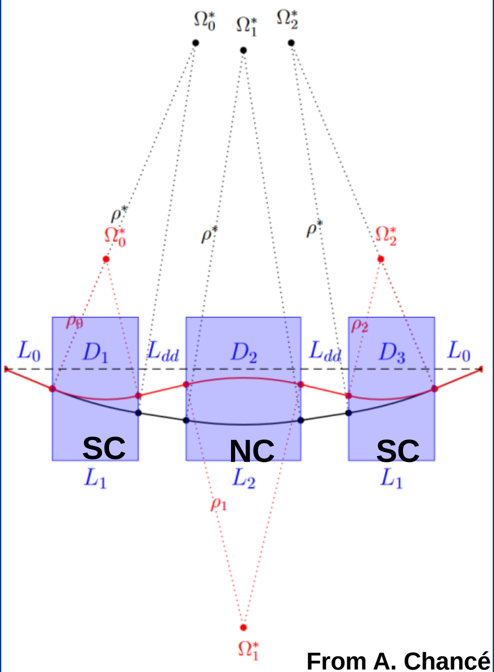
		Symbol	Unit	Stage 1 Value	Details	Stage 2 Value	Details	Stage 3 Value
14	Basic data							
15	Particles	-	-	μ		μ		μ
16	Costs	-	M€					
17	Type	-	-	RCS		hybrid RCS		hybrid RCS
18								
19	Dynamics							
20	Acceleration time	T_{acc}	[ms]	0.34		1.09704595		2.37
21	Injection energy	E_{inj}	[MeV]/u	63000		313830		750000
22	Ejection energy	E_{ej}	[MeV]/u	313830	defined by r	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	ΔE	[MeV]	14755		7930		11364
31								
32	Transition gamma	γ_{tr}	-	20.41		20.41		~30
33	Injection relativistic mass factor	γ_{inj}	-	597		2971		7099
34	Ejection relativistic mass factor	γ_{ej}	-	2971		7099		14198
35	Injection v/c	β_{inj}	%	0.9999986		0.999999943		0.9999999901
36	Ejection v/c	β_{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	ρ_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	ϕ_s	[°]	45		45		45
93	Conversion factor mm mrad – eVs	-	Vs/mm mra	69.40		165.86		331.72
94	Longitudinal emittance (σE * 4σz)	ε^l_n	[eVs]	0.025	7.5 MeV m	0.025		0.025
95	Longitudinal emittance (phase space area)	ε^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

Hybrid RCS magnet layout

- SC magnets provide high average B_{sc}, but not fast ramping → fixed-field
- NC magnets required for fast ramping within ± B_{nc}
- Large ramp rates of kT/s
- Beam orbit not constant during acceleration

→ $f_{rev} \neq$ const. → f_{RF} tuning to be provided

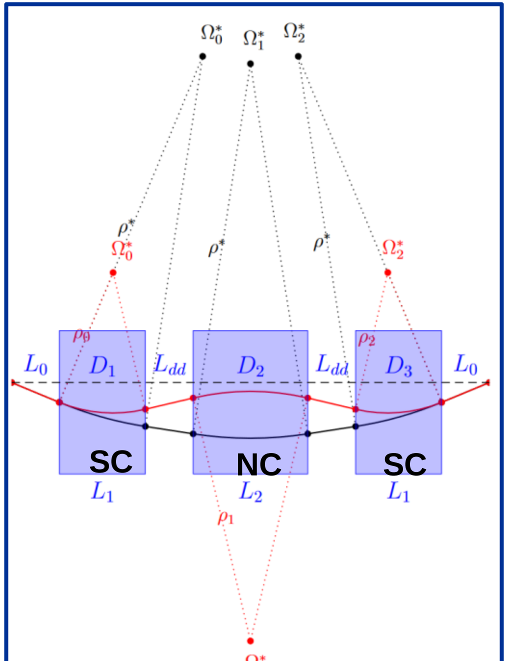
see e.g. talk by A. Chancé



From A. Chancé

Hybrid RCS magnet layout

- **<u>Choice of field strengths:</u>**
  - **B_{nc}= ± 1.8 T, feasible with current technique, 2.0+ T would be beyond saturation and require special materials**
  - **B_{sc} = 10 T: limit of current niobium-titanium technologies, 16 T only reachable with niobium-tin (Nb3Sn), significantly more expensive, 16 T can be kept as option**



From A. Chancé

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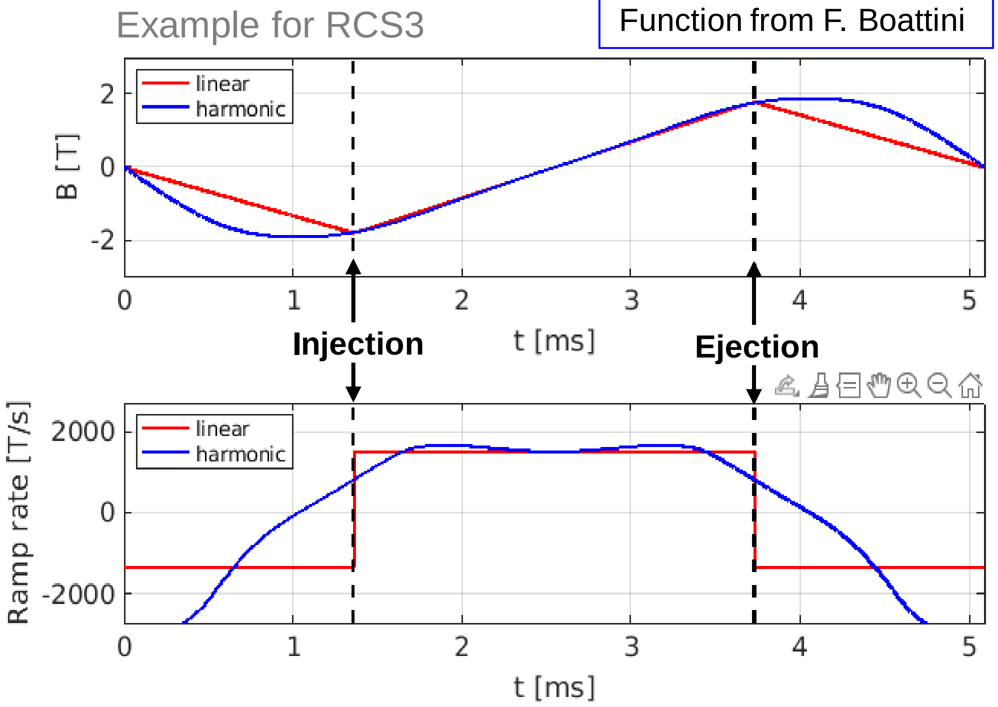
Ramping considerations

- → Optimization problem between magnet powering and RF
- **Linear ramping** → constant V_{RF} → simplest RF solution, best for μ
- **However: <u>no</u> RF requirement for beam transport!**
- **Non-linear ramping** → decrease peak power ≙ magnet powering costs significantly (see G. Brauchli, D. Aguglia, F. Boattini here)
- ***B*** **∝** ***E*** **defines all dynamics!**

$$G_{acc} = -\frac{1}{\tau_\mu} m_\mu c \ln\left(\frac{E_{ej}}{E_{inj}}\right) / \ln\left(\frac{N_{ej}}{N_{inj}}\right)$$



Non-linear ramping

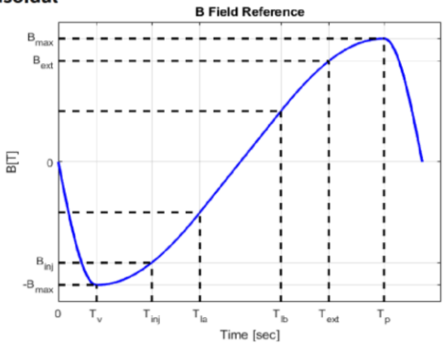
- **Sinusoidal ramp function** → performance decrease of 50%, see H. Damerau, I. Karpov, MC RF WG meeting #3
- **Optimum**: near linear ramp with reasonable technical effort
- → **Approximated linear ramping** by e.g. natural resonant discharge of two harmonics and active filter

→ Peak power lowered, see talk by F. Boattini

Magnetic Field reference design

- **Compromise between pure lineal and pure sinusoidal**
- **Decreasing Magnetic Field**
  - No beam in accelerator
  - Circuits resonates naturally
  - Active Filter is short-circuited
- **Increasing Magnetic Field**
  - AF controls the current in the magnet
  - Piecewise reference:

$$B_{max}(t) = \begin{cases} -B_{max}\cos(\omega_a(t-t_v)) & t_v < t \leq t_{la} \\ a\,t + b \text{ or } at^3 + bt^2 + ct + d & t_{la} < t \leq t_{lb} \\ B_{max}\cos\left(\omega_b(t-t_p)\right) & t_p < t \leq t_{end} \end{cases}$$



Slide by G. Brauchli, D. Aguglia, F. Boattini

Non-linear ramping

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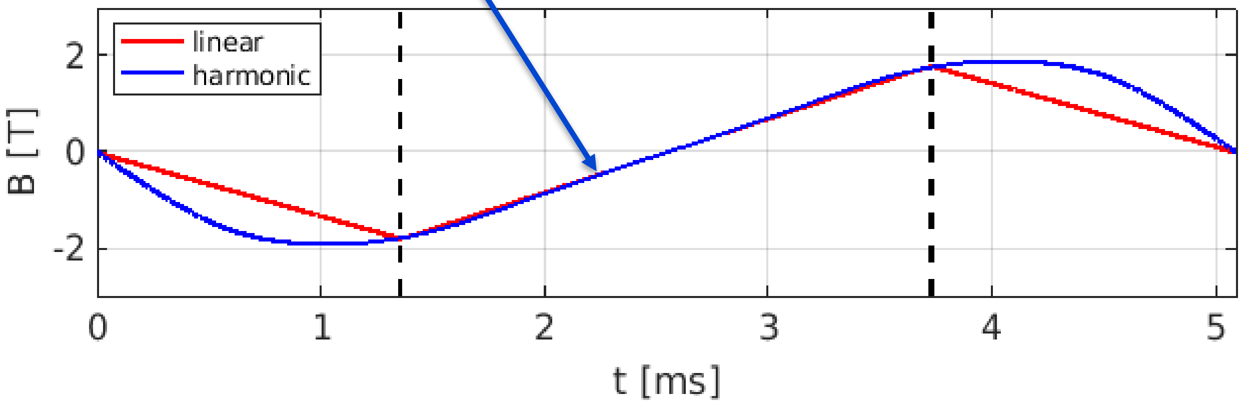
- **Optimum**: near linear ramp with reasonable technical effort
- → **Approximated linear ramping** by e.g. natural resonant discharge of two harmonics and active filter

→ **Studied possible ramping function**



Example for RCS3, ±1.8 T normal conducting, 2.4 ms acceleration time, but equal trend line for the other RCSs

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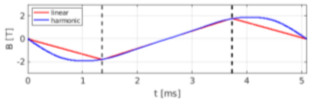
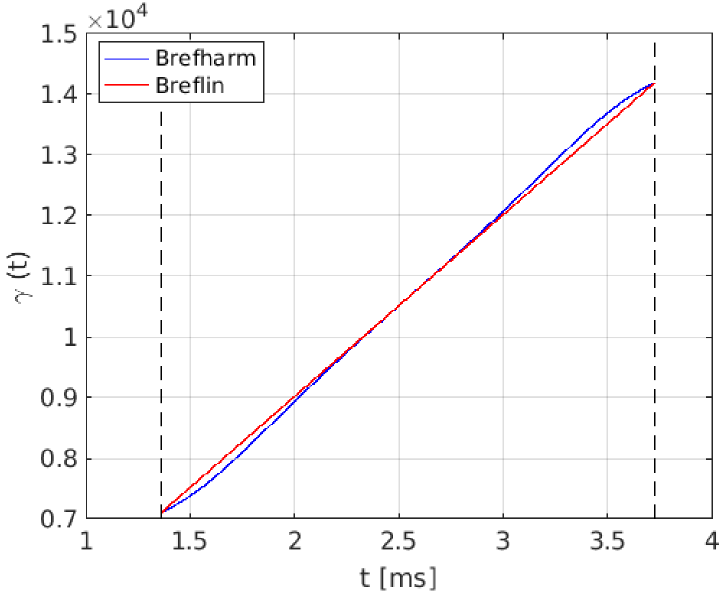
Acceleration with non-linear ramping



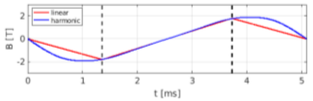
- **Bunch energies over time** for RCS3, expressed by their γ functions:

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



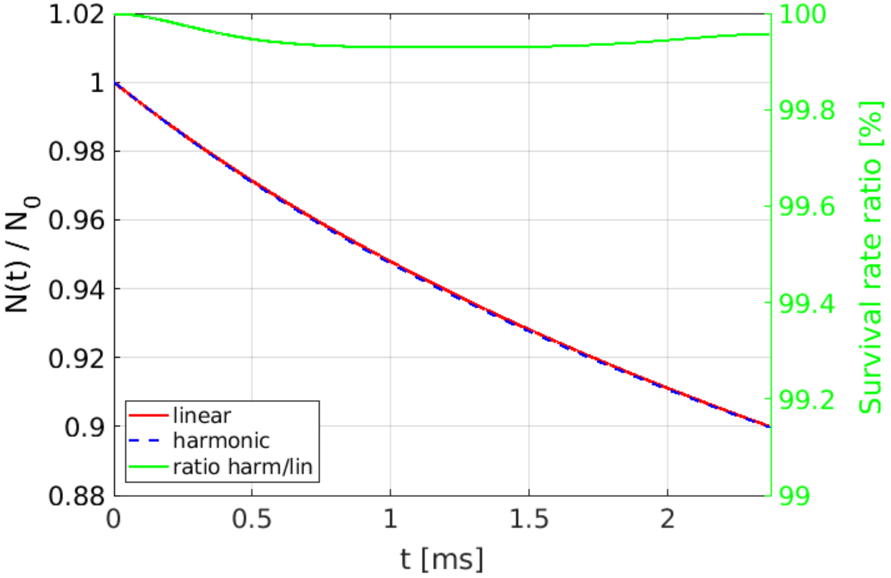
***γ*(t) follow the same trend as *B*(t)!**

Acceleration with non-linear ramping

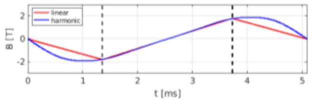


- **Ramping does not influence survival rate:**

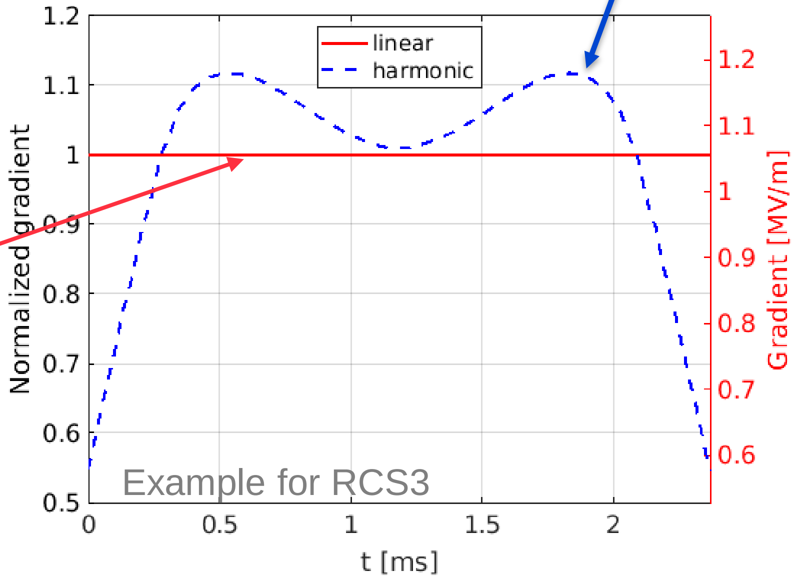
$$\frac{N(t)}{N_0} = \exp\left(-\frac{1}{\tau_\mu}\int_0^{\tau_{acc}} \frac{dt}{\gamma(t)}\right)$$



Acc. gradient with non-linear ramping



- V_{acc} and G_{acc} must be increased by 12% to achieve the same acceleration time ⇔ ≠ factor of two as for a sine-like ramp:

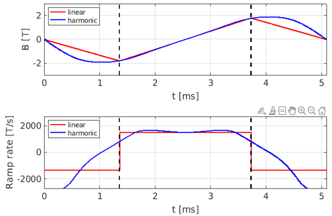


Constant gradient for linear ramp

Average gradient over ring for survival

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

Acc. gradient with non-linear ramping



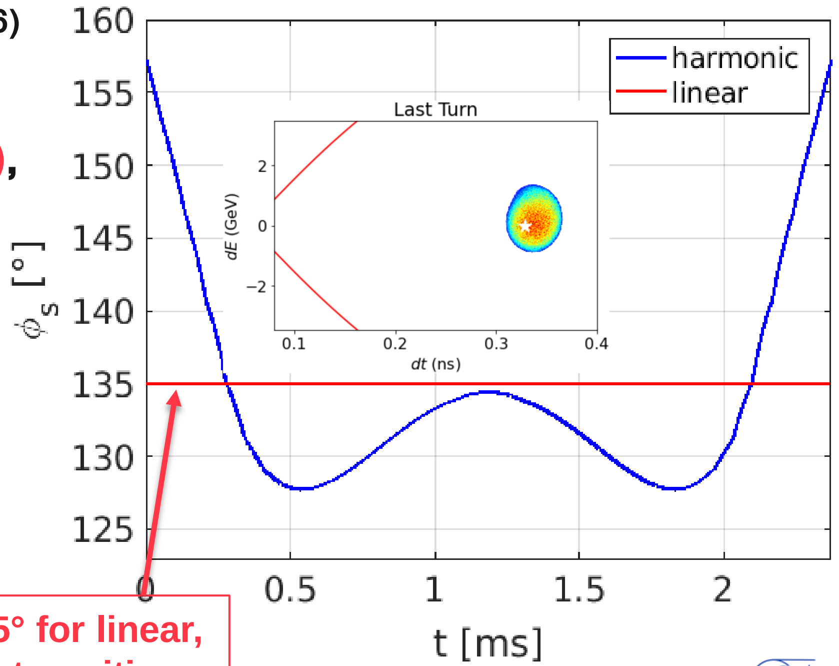
- **Cavity filling time $(2Q_L/\omega)$ = 0.5 ms similar to t_{acc} < 2.4 ms** (f = 1.3 GHz, Q_L = 2.2e6)

→ **Sweep synchrotron phase $V = V_{RF} \cdot \sin(f_s)$, demonstrated in simulations with fixed V_{RF} for different G_{acc}**

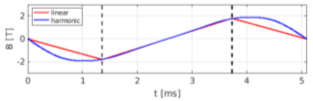
→ **Example for RCS3, no intensity effects**

→ **Bunch transported!**

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



ϕ_s = 45° for linear, above transition



Limitations on the ramping function

- **Sweeping of ϕ_s or G_{acc} raises the question of limitations in ramping B**

→ **Consider bucket area deformation and longitudinal emittance budget**

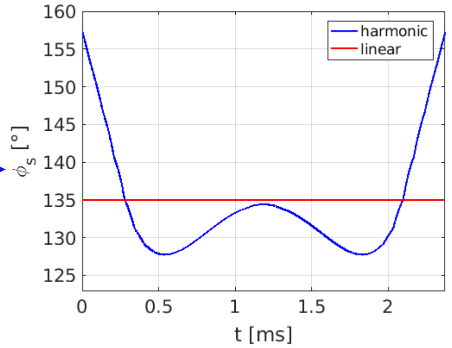
- The **adiabaticity factor ε must fulfil:**

$$\varepsilon = \left| \frac{1}{\omega_s \alpha_b} \frac{\mathrm{d}\alpha_b}{\mathrm{d}t} + \frac{1}{\omega_s^2} \frac{\mathrm{d}\omega_s}{\mathrm{d}t} \right| \ll 1$$

$$\frac{1}{2\omega_s} \left| \frac{\dot{B}_{harm}}{B_{harm}} + \frac{\tan(\phi_s)}{\cos(\phi_s)} \cdot \frac{\ddot{B}_{harm}}{\dot{B}_{lin}} \cdot \sin(\phi_{s,0}) \right| \ll 1$$

$$[1-\sin(\phi_s(t))]/[1+\sin(\phi_s(t))]$$

$$\omega_s(t) = \sqrt{\frac{2\pi\eta h f_{rev}^2 V_{RF} \cos(\phi_s(t))}{E_s(t)}}$$



→ **Evaluation with BLonD simulations**

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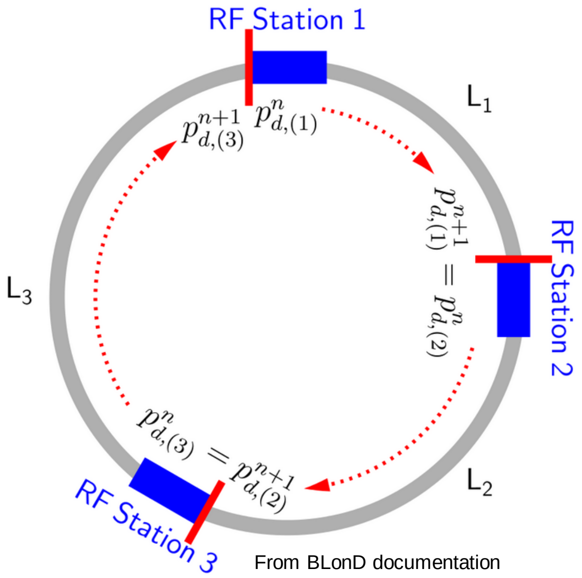
Studies & BLonD code

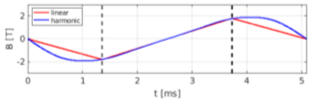
(Beam Longitudinal Dynamics code)

- BLonD: macro-particle tracking code, developed at CERN since 2014
- Links: documentation and github
- MuC-specific to multiple RF stations & muon decay
- First studies with only one bunch, 2nd to follow



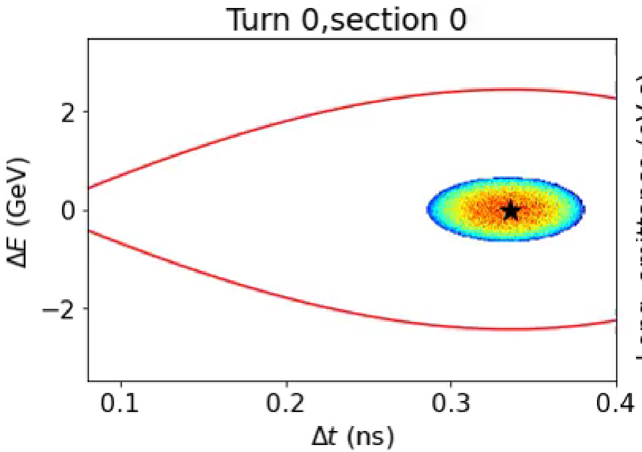
From BLonD documentation

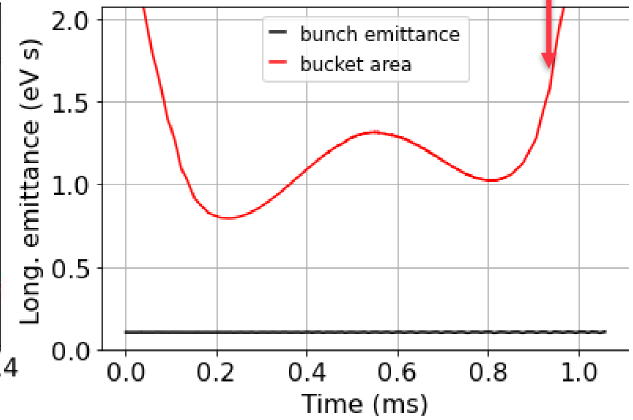
Limitations on the ramping function



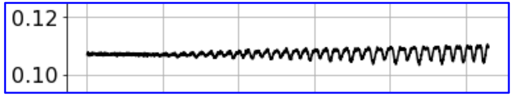
- **BLonD simulation for RCS1 (63→314 GeV), n_{RF} = 48 RF, no intensity effects stations to observe effect of ramping**

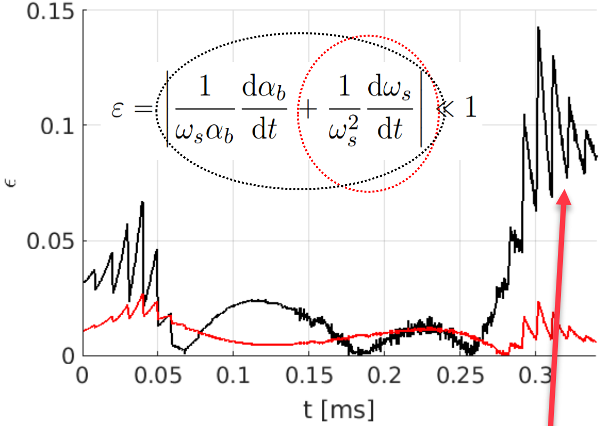
$$A_B(t) = \frac{8\sqrt{2}}{2\pi h f_{ref}} \cdot \sqrt{\frac{E(t)V_{RF}(t)}{\pi h \eta}} \cdot \alpha_B(t)$$





Zoomed:

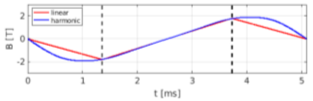




Peaks not physical, caused by B(t)!

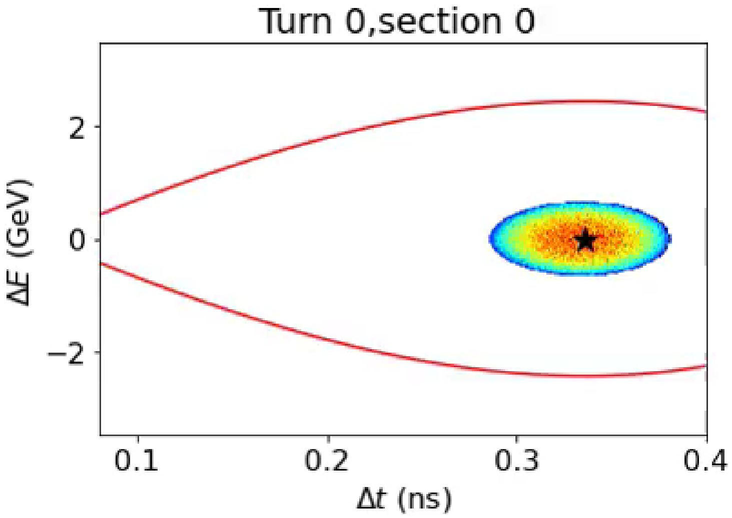
- **Beam transported with approx. 3% emittance growth!**

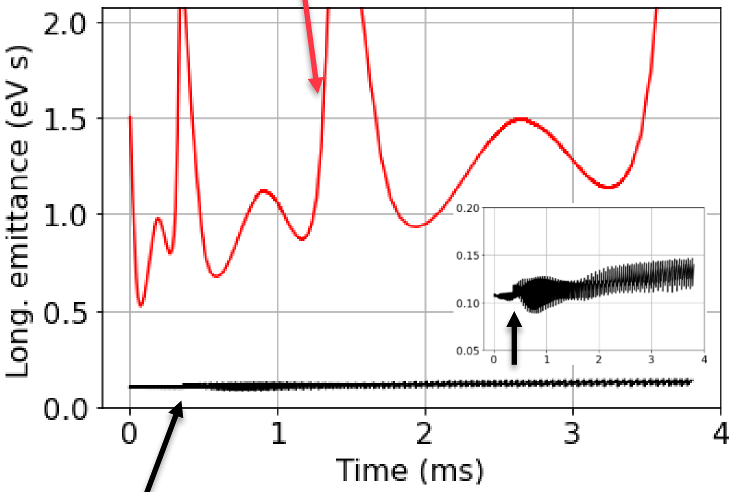
Transport trough all RCS



- **BLonD simulation for all RCS (63→1500 GeV), n_{RF}=48 RF, no intensity effects stations to observe effect of ramping**

$$A_B(t) = \frac{8\sqrt{2}}{2\pi h f_{ref}} \cdot \sqrt{\frac{E(t)V_{RF}(t)}{\pi h \eta}} \cdot \alpha_B(t)$$





- **The beam suffers from mismatch, as seen for linear ramping (see presentation** "RF parameter choices and longitudinal stability")

Consequences & Follow up

- Observed small effect of nonlinear ramping on bunch

→ Careful design of ramping function and RF voltage for matching between RCS required

- Bucket area and longitudinal emittance budget mainly question in RCS1
- Adiabaticity factor only an indication, final evaluation through simulations

→ **Equations for bucket area and emittance allow to re-write requirements for optimized non-linear ramping functions (see talk by F. Boattini just before)**

E.g.

$$\varepsilon(t) = \frac{1}{2\omega_s}\left| \frac{\dot{B}_{harm}}{B_{harm}} + \frac{\frac{\dot{B}_{harm}(t)}{\dot{B}_{lin}(t)} \cdot \sin\phi_{s,0} - 4}{1 - \left(\frac{\dot{B}_{harm}(t)}{\dot{B}_{lin}(t)} \cdot \sin\phi_{s,0}\right)^2} \cdot \frac{\ddot{B}_{harm}}{\dot{B}_{lin}} \cdot \sin(\phi_{s,0}) \right| \ll 1$$

Function of *B(t)!*

Summary

- **Linear** ramping not required for optimal beam transport

- **Non-linear** ramping preserves accelerator performance while keeping the cavity voltage constant and sweeping ϕ_s to increase gradient G_{acc} by ≈12%

- Beam transported with %-like emittance growth in one RCS (without intensity effects)

- To follow: Implications for matching, bucket area and longitudinal emittance budget as a function of B with optimized ramping functions

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