Updates on the Rapid Cycling Synchrotrons studies

Fabian Batsch, *Rama Calaga,*
Heiko Damerau, Ivan Karpov

Acknowledgements: David Amorim, Scott Berg, Fulvio Boattini, Luca Bottura, Christian Carli, Antoine Chancé, Alexej Grudiev, Elias Metral, Ursula Van Rienen, Daniel Schulte, Sosoho-Abasi Udongwo

Funded by the European Union under
Grant Agreement n.101094300

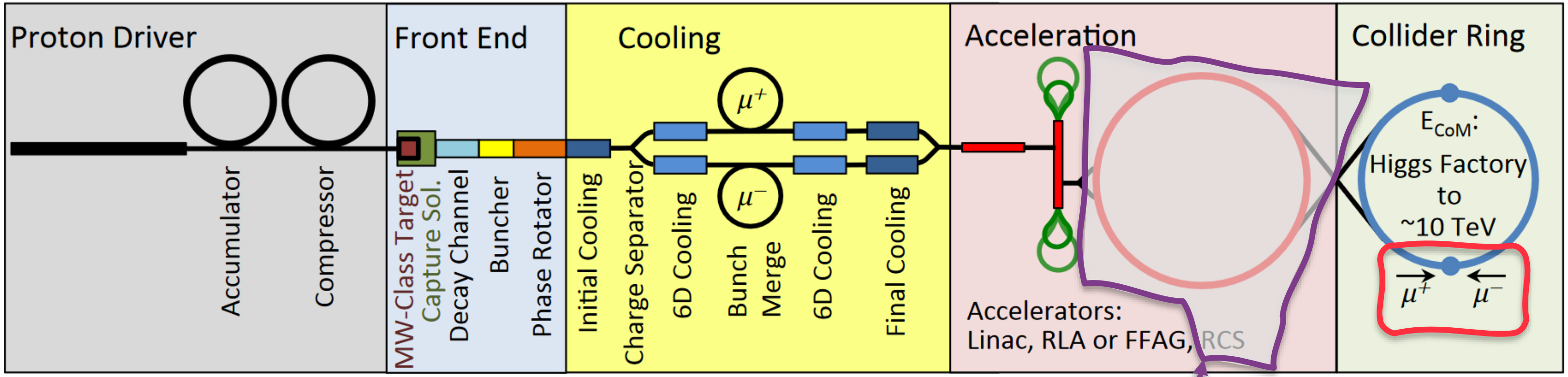
IMCC Annual Meeting, Orsay, 21/6/2023

Outline

- Design aspects of the Rapid Cycling Synchrotrons
- Magnets and RF layout
- Synchrotron tune mitigation
- Nonlinear ramping functions
- Summary and outlook on longitudinal tracking studies

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)



1 bunch per beam

Part of interest for us

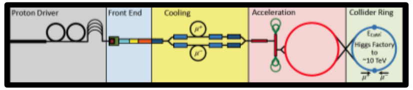
Reminder on design baselines

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

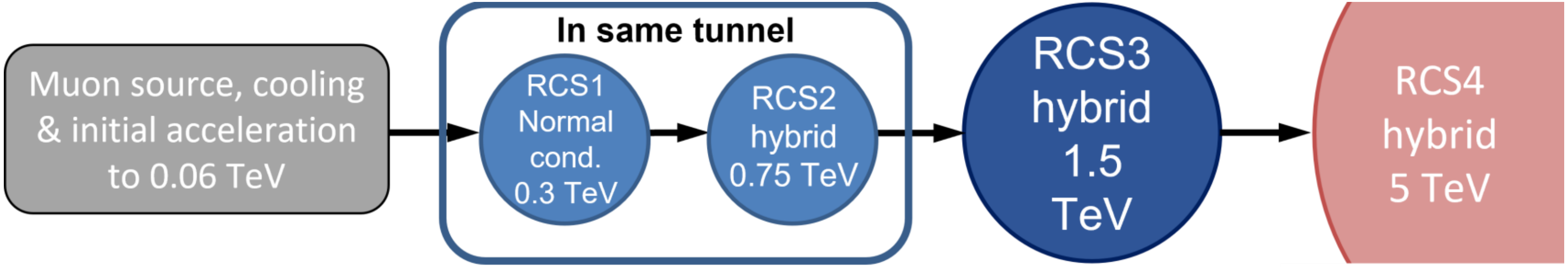
Parameter	Unit	3 TeV	10 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**
N	10^{12}	2.2	1.8
f_r	Hz	5	5
<B> (average)	T	7	10.5
ε_L (norm, $1\sigma_z\sigma_E$)	MeV m	7.5	7.5
σ_E / E	%	0.1	0.1
σ_z	mm	5	1.5

Repetition rate of 5 Hz → RCS

The high-energy complex



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



Muon source, cooling & initial acceleration to 0.06 TeV

In same tunnel

RCS1 Normal cond. 0.3 TeV

RCS2 hybrid 0.75 TeV

RCS3 hybrid 1.5 TeV

RCS4 hybrid 5 TeV

- Hybrid RCSs have interleaved normal conducting (NC) and superconducting (SC) magnets, see also talks by A. Chancé [talk1, talk2]
- This would be the first hybrid RCSs in the world!

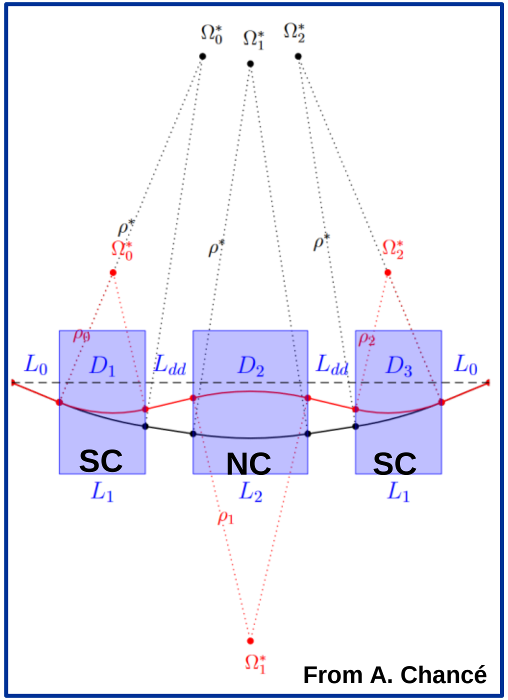
Hybrid RCS magnet layout

- SC magnets provide high average *B*, but not fast ramping → fixed-field, $B_{\mathrm{sc}} = 10$ T
- NC magnets require fast ramping within $B_{\mathrm{nc}} = \pm 1.8$ T

  Adopted achieved parameters: below saturation of both technologies
- Beam orbit not constant during acceleration

  → Orbit length and $f_{\mathrm{rev}} \neq$ const.

  → f_{RF} tuning for cavities



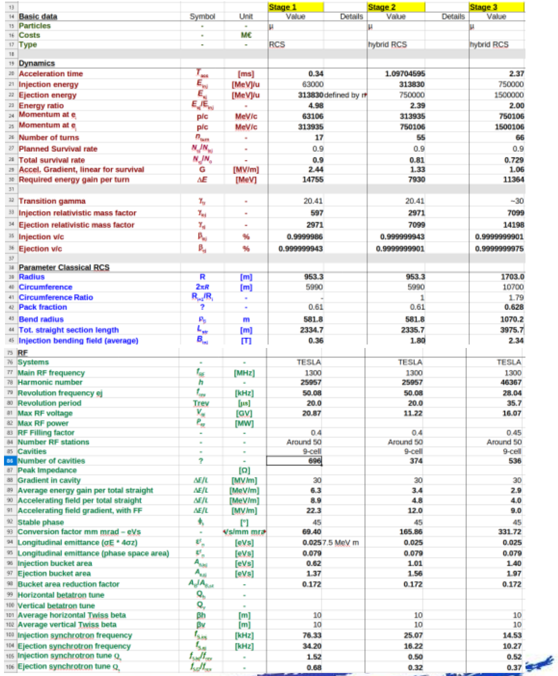
From A. Chancé

Parameters and tools:
General parameter

Details on RF requirements in presentation by H. Damerau

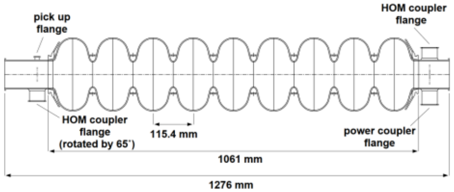
Detailed parameter table: [link]

	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, 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 (45 optimistically)	30	30



			Stage 1		Stage 2		Stage 3
Basic data	Symbol	Unit	Value	Details	Value	Details	Value
Particles	-	-	μ		μ		μ
Costs	-	M€					
Type	-	-	RCS		hybrid RCS		hybrid RCS
Dynamics							
Acceleration time	T_{acc}	[ms]	0.34		1.09704595		2.37
Injection energy	E_{inj}	[MeV]/u	63000		313830		750000
Ejection energy	E_{ej}	[MeV]/u	313830	defined by r	750000		1500000
Energy ratio	E_{ej}/E_{inj}	-	4.98		2.39		2.00
Momentum at e	p/c	MeV/c	63106		313935		750106
Momentum at e	p/c	MeV/c	313935		750106		1500106
Number of turns	n_{turn}	-	17		55		66
Planned Survival rate	N_{ej}/N_{inj}	-	0.9		0.9		0.9
Total survival rate	N_{ej}/N_0	-	0.9		0.81		0.729
Accel. Gradient, linear for survival	G	[MV/m]	2.44		1.33		1.06
Required energy gain per turn	ΔE	[MeV]	14755		7930		11364
Transition gamma	γ_{tr}	-	20.41		20.41		~30
Injection relativistic mass factor	γ_{inj}	-	597		2971		7099
Ejection relativistic mass factor	γ_{ej}	-	2971		7099		14198
Injection v/c	β_{inj}	%	0.9999986		0.999999943		0.9999999901
Ejection v/c	β_{ej}	%	0.999999943		0.9999999901		0.9999999975
Parameter Classical RCS							
Radius	R	[m]	953.3		953.3		1703.0
Circumference	$2\pi R$	[m]	5990		5990		10700
Circumference Ratio	R_{i+1}/R_i	-	-		1		1.79
Pack fraction	?	-	0.61		0.61		0.628
Bend radius	ρ_B	m	581.8		581.8		1070.2
Tot. straight section length	L_{str}	[m]	2334.7		2335.7		3975.7
Injection bending field (average)	B_{inj}	[T]	0.36		1.80		2.34
RF							
Systems	-	-	TESLA		TESLA		TESLA
Main RF frequency	f_{RF}	[MHz]	1300		1300		1300
Harmonic number	h	-	25957		25957		46367
Revolution frequency ej	f_{rev}	[kHz]	50.08		50.08		28.04
Revolution period	Trev	[µs]	20.0		20.0		35.7
Max RF voltage	V_{RF}	[GV]	20.87		11.22		16.07
Max RF power	P_{RF}	[MW]					
RF Filling factor	-	-	0.4		0.4		0.45
Number RF stations	-	-	Around 50		Around 50		Around 50
Cavities	-	-	9-cell		9-cell		9-cell
Number of cavities	?	-	696		374		536
Peak Impedance		[Ω]					
Gradient in cavity	$\Delta E/L$	[MV/m]	30		30		30
Average energy gain per total straight	$\Delta E/L$	[MeV/m]	6.3		3.4		2.9
Accelerating field per total straight	$\Delta E/L$	[MeV/m]	8.9		4.8		4.0
Accelerating field gradient, with FF	$\Delta E/L$	[MV/m]	22.3		12.0		9.0
Stable phase	ϕ_s	[°]	45		45		45
Conversion factor mm mrad – eVs	-	Vs/mm mra	69.40		165.86		331.72
Longitudinal emittance (σE * 4σz)	ε_n	[eVs]	0.025	7.5 MeV m	0.025		0.025
Longitudinal emittance (phase space area)	ε_n	[eVs]	0.079		0.079		0.079
Injection bucket area	$A_{b,inj}$	[eVs]	0.62		1.01		1.40
Ejection bucket area	$A_{b,ej}$	[eVs]	1.37		1.56		1.97
Bucket area reduction factor	$A_B/A_{B,st}$	-	0.172		0.172		0.172
Horizontal betatron tune	Q_h	-					
Vertical betatron tune	Q_v	-					
Average horizontal Twiss beta	βh	[m]	10		10		10
Average vertical Twiss beta	βv	[m]	10		10		10
Injection synchrotron frequency	$f_{S,inj}$	[kHz]	76.33		25.07		14.53
Ejection synchrotron frequency	$f_{S,ej}$	[kHz]	34.20		16.22		10.27
Injection synchrotron tune Q_s	$f_{S,inj}/f_{rev}$	-	1.52		0.50		0.52
Ejection synchrotron tune Q_s	$f_{S,ej}/f_{rev}$	-	0.68		0.32		0.37

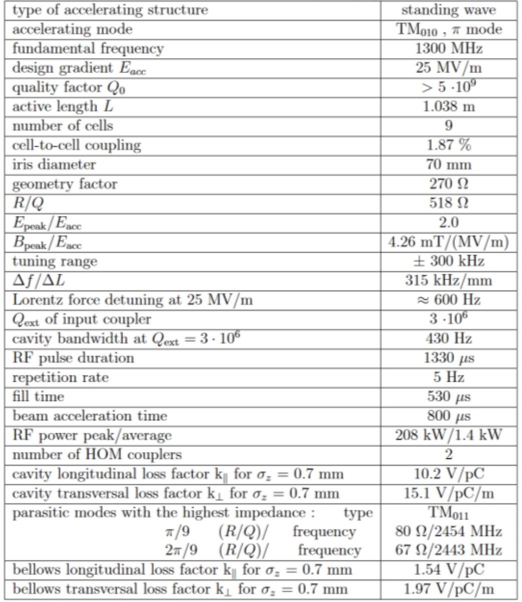
The cavity assumption: TESLA



(From design report)

- High G_{acc} and strong beam loading → SRF
- → 1.3 GHz TESLA-like cavity as assumption for muon collider RCS [Phys. Rev. ST Accel. Beams 3, 092001, 2000]
- Cavity parameter (9 cells, L=1.06 m):
  - Harmonic number h = 25957 to 46367
  - R/Q = 518 Ω, total R_s = 306 GΩ
  - Gradient of structure 30 MV/m
  - Q_L = 2.2e6 (for beam loading compensation with Δf = 320 Hz, [ref]) , probably value to high and to be corrected

Table 2: TTF cavity design parameters.[a]



type of accelerating structure	standing wave
accelerating mode	TM_{010} , π mode
fundamental frequency	1300 MHz
design gradient E_{acc}	25 MV/m
quality factor Q_0	$> 5 \cdot 10^9$
active length L	1.038 m
number of cells	9
cell-to-cell coupling	1.87 %
iris diameter	70 mm
geometry factor	270 Ω
R/Q	518 Ω
$E_{\mathrm{peak}}/E_{\mathrm{acc}}$	2.0
$B_{\mathrm{peak}}/E_{\mathrm{acc}}$	4.26 mT/(MV/m)
tuning range	± 300 kHz
$\Delta f/\Delta L$	315 kHz/mm
Lorentz force detuning at 25 MV/m	≈ 600 Hz
Q_{ext} of input coupler	$3 \cdot 10^6$
cavity bandwidth at $Q_{\mathrm{ext}} = 3 \cdot 10^6$	430 Hz
RF pulse duration	1330 μs
repetition rate	5 Hz
fill time	530 μs
beam acceleration time	800 μs
RF power peak/average	208 kW/1.4 kW
number of HOM couplers	2
cavity longitudinal loss factor $k_{\parallel}$ for $\sigma_z = 0.7$ mm	10.2 V/pC
cavity transversal loss factor $k_{\perp}$ for $\sigma_z = 0.7$ mm	15.1 V/pC/m
parasitic modes with the highest impedance : type $\pi/9$ $(R/Q)/$ frequency $2\pi/9$ $(R/Q)/$ frequency	TM_{011} 80 Ω/2454 MHz 67 Ω/2443 MHz
bellows longitudinal loss factor $k_{\parallel}$ for $\sigma_z = 0.7$ mm	1.54 V/pC
bellows transversal loss factor $k_{\perp}$ for $\sigma_z = 0.7$ mm	1.97 V/pC/m

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, ΔE [GeV]	14.8	7.9	11.4
Acc. gradient for survival [MV/m]	2.4	1.3	1.1

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

			Stage 1		Stage 2		Stage 3
Basic data	Symbol	Unit	Value	Details	Value	Details	Value
Particles	-	-	μ		μ		μ
Costs	-	M€					
Type	-	-	RCS		hybrid RCS		hybrid RCS
Dynamics							
Acceleration time	T_{acc}	[ms]	0.34		1.09704595		2.37
Injection energy	E_{inj}	[MeV]/u	63000		313830		750000
Ejection energy	E_{ej}	[MeV]/u	313830	defined by r	750000		1500000
Energy ratio	E_{ej}/E_{inj}	-	4.98		2.39		2.00
Momentum at e_i	p/c	MeV/c	63106		313935		750106
Momentum at e_j	p/c	MeV/c	313935		750106		1500106
Number of turns	n_{turn}	-	17		55		66
Planned Survival rate	N_{ej}/N_{inj}	-	0.9		0.9		0.9
Total survival rate	N_{ej}/N_0	-	0.9		0.81		0.729
Accel. Gradient, linear for survival	G	[MV/m]	2.44		1.33		1.06
Required energy gain per turn	ΔE	[MeV]	14755		7930		11364
Transition gamma	γ_{tr}	-	20.41		20.41		~30
Injection relativistic mass factor	γ_{inj}	-	597		2971		7099
Ejection relativistic mass factor	γ_{ej}	-	2971		7099		14198
Injection v/c	β_{inj}	%	0.9999986		0.999999943		0.9999999901
Ejection v/c	β_{ej}	%	0.999999943		0.9999999901		0.9999999975
Parameter Classical RCS							
Radius	R	[m]	953.3		953.3		1703.0
Circumference	$2\pi R$	[m]	5990		5990		10700
Circumference Ratio	R_{i+1}/R_i	-	-		1		1.79
Pack fraction	?	-	0.61		0.61		0.628
Bend radius	ρ_0	m	581.8		581.8		1070.2
Tot. straight section length	L_{str}	[m]	2334.7		2335.7		3975.7
Injection bending field (average)	B_{inj}	[T]	0.36		1.80		2.34
RF							
Systems	-	-	TESLA		TESLA		TESLA
Main RF frequency	f_{RF}	[MHz]	1300		1300		1300
Harmonic number	h	-	25957		25957		46367
Revolution frequency ej	f_{rev}	[kHz]	50.08		50.08		28.04
Revolution period	Trev	[µs]	20.0		20.0		35.7
Max RF voltage	V_{RF}	[GV]	20.87		11.22		16.07
Max RF power	P_{RF}	[MW]					
RF Filling factor	-	-	0.4		0.4		0.45
Number RF stations	-	-	Around 50		Around 50		Around 50
Cavities	-	-	9-cell		9-cell		9-cell
Number of cavities	?	-	696		374		536
Peak Impedance		[Ω]					
Gradient in cavity	$\Delta E/L$	[MV/m]	30		30		30
Average energy gain per total straight	$\Delta E/L$	[MeV/m]	6.3		3.4		2.9
Accelerating field per total straight	$\Delta E/L$	[MeV/m]	8.9		4.8		4.0
Accelerating field gradient, with FF	$\Delta E/L$	[MV/m]	22.3		12.0		9.0
Stable phase	ϕ_s	[°]	45		45		45
Conversion factor mm mrad – eVs	-	Vs/mm mra	69.40		165.86		331.72
Longitudinal emittance (σE * 4σz)	ε^l_n	[eVs]	0.025	7.5 MeV m	0.025		0.025
Longitudinal emittance (phase space area)	ε^l_n	[eVs]	0.079		0.079		0.079
Injection bucket area	$A_{b,inj}$	[eVs]	0.62		1.01		1.40
Ejection bucket area	$A_{b,ej}$	[eVs]	1.37		1.56		1.97
Bucket area reduction factor	$A_b/A_{b,st}$	-	0.172		0.172		0.172
Horizontal betatron tune	Q_h	-					
Vertical betatron tune	Q_v	-					
Average horizontal Twiss beta	βh	[m]	10		10		10
Average vertical Twiss beta	βv	[m]	10		10		10
Injection synchrotron frequency	$f_{S,inj}$	[kHz]	76.33		25.07		14.53
Ejection synchrotron frequency	$f_{S,ej}$	[kHz]	34.20		16.22		10.27
Injection synchrotron tune Q_s	$f_{S,inj}/f_{rev}$	-	1.52		0.50		0.52
Ejection synchrotron tune Q_s	$f_{S,ej}/f_{rev}$	-	0.68		0.32		0.37

Synchrotron tune and number of RF stations

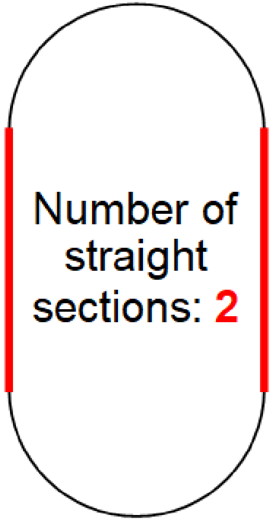
- **Number of synchrotron oscillations per turn proportional to $\sqrt{V_{\mathrm{RF}}}$:**

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

LHC: Q_s=0.005

- **Stable synchrotron oscillations and phase focusing only for $Q_s << 1/\pi$** (T. Suzuki, KEK Report 96-10)
  - → **RCSs would exceed this limit: $0.3 < Q_s < 1.5$**
  - → **Several longitudinal kicks per turn for small Q_s between stations, i.e., small Q_s/n_{RF}**
  - → **Distribute RF system over n_{RF} sections**

→ n_{RF} is an important quantity to determine!



From: H. Damerau

Synchrotron tune and number of RF stations

Why not choosing a high n_{RF} to fulfil $Q_s << 1/\pi$?

- High n_{RF} → smaller quadrupole-like oscillations caused by discrete energy steps and resulting mismatching
- **BUT:** higher n_{RF} results in higher construction / cooling / cryogenics and powering costs, even though the number of cavities is constant and defined by ΔE per turn, plus lattice restrictions

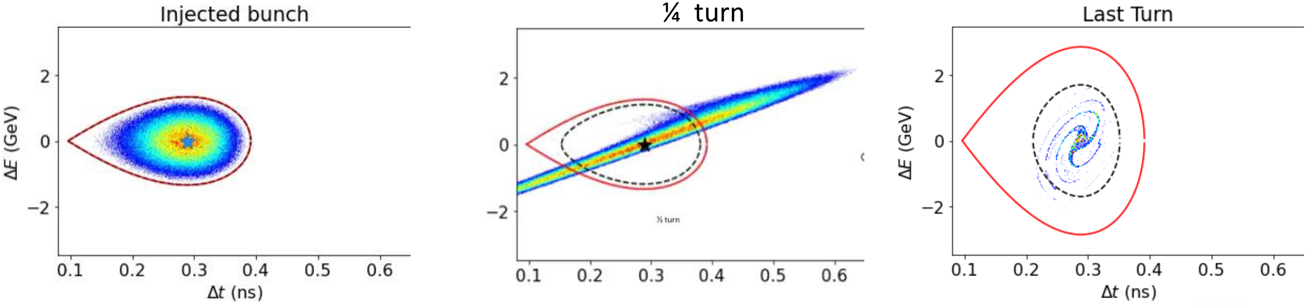
→ Determine emittance growth, also as a function of n_{RF}

Examples: $n_{RF} = 4$

RCS1, no V_{ind}, $\varepsilon_L = 0.31$ eVs

$$\frac{Q_s}{n_{RF}} = \frac{1.5}{4} = 0.38$$

High Q_s destroys bunch!

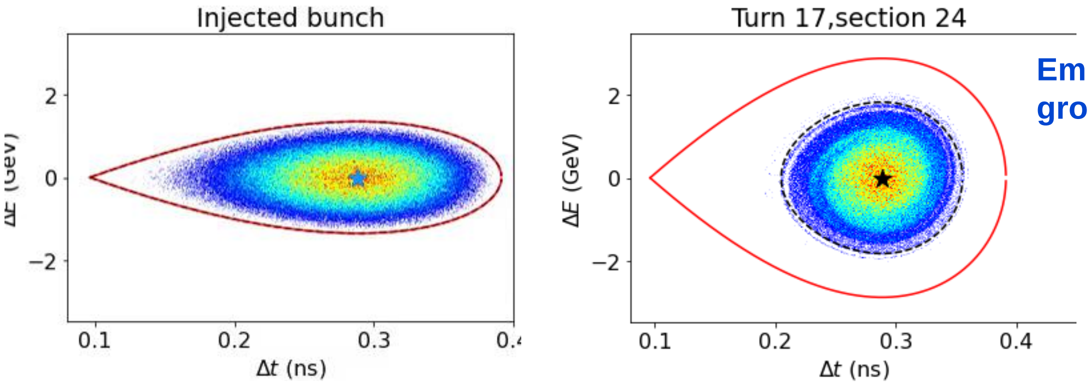


Synchrotron tune and number of RF stations

Examples: $n_{\mathrm{RF}} = 32$

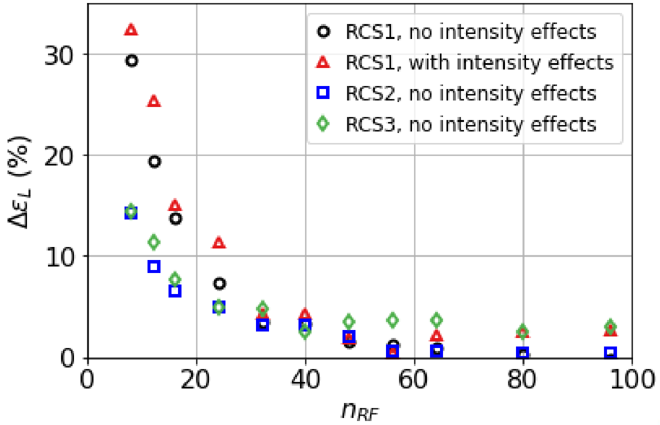
RCS1, no V_{ind}, $\varepsilon_L = 0.31$ eVs

$$\boldsymbol{\frac{Q_s}{n_{\mathrm{RF}}} = 0.05}$$



Emittance growth: 4%

- **For $n_{\mathrm{RF}} > 48$, $\Delta\varepsilon_{\mathrm{L}} = 3\%$, no further improvement**
- **For RCS1, $n_{\mathrm{RF}} \approx 32$ best candidate**
- **For RCS2 and 3, $n_{\mathrm{RF}} \approx 24$ could be enough**



Outline

- Design aspects of the Rapid Cycling Synchrotrons
- Magnets and RF layout
- Synchrotron tune mitigation
- Nonlinear ramping functions
- Summary and outlook and longitudinal studies

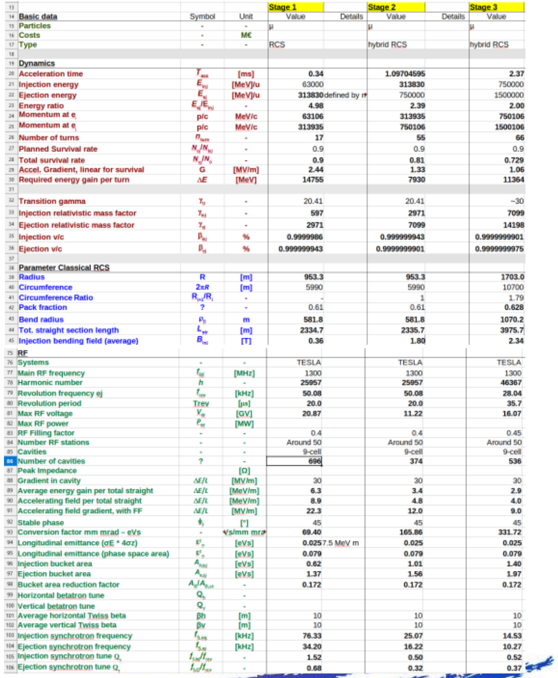
International
UON Collider
Collaboration

Parameters and tools:
General parameter

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 [ms]	0.34	1.04	2.37
Number of turns			
Energy gain per turn, ΔE [GeV]			
Acc. gradient for survival [MV/m]			
Acc. field in RF cavity [MV/m]			
Ramp rate, $\dot{B}_{nc}$ [kT/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€					
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	p/c	MeV/c	63106		313935		750106
25	Momentum at e	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

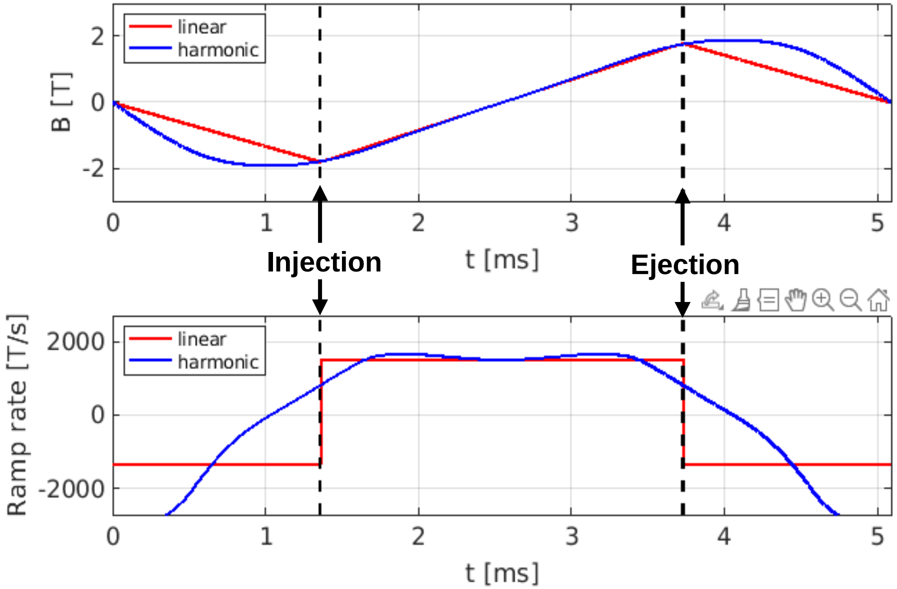
Fast ramping considerations

- **Optimization problem** between linearizing magnet ramps and installed voltage, or muon loss
- **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%

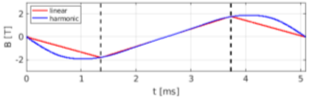
→ **Study quasi-linear ramping** by e.g. natural resonant discharge of e.g. two harmonics

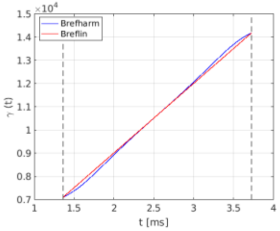
Example for RCS3

Function from F. Boattini

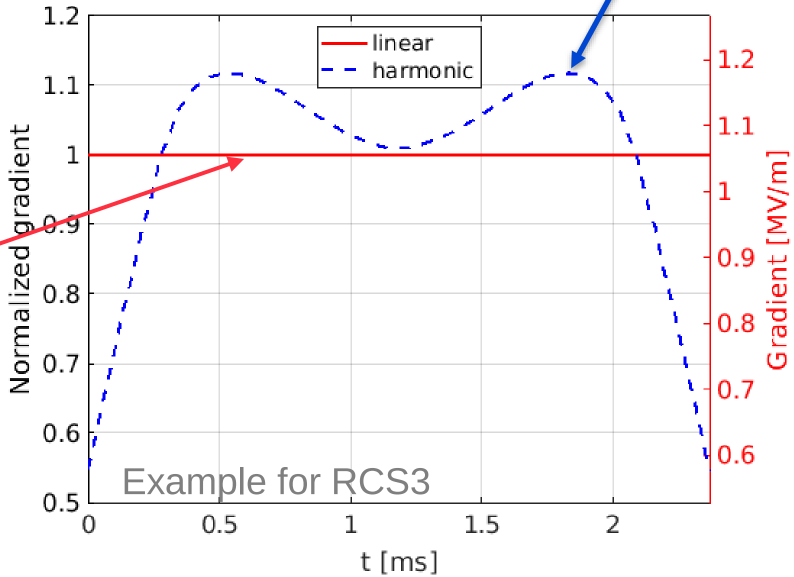


RF requirements with non-linear ramping





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



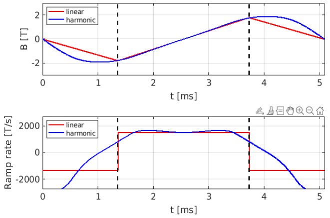
Constant gradient for linear ramp

Average gradient over ring for 90% survival

$B \propto E$ defines all dynamics!

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

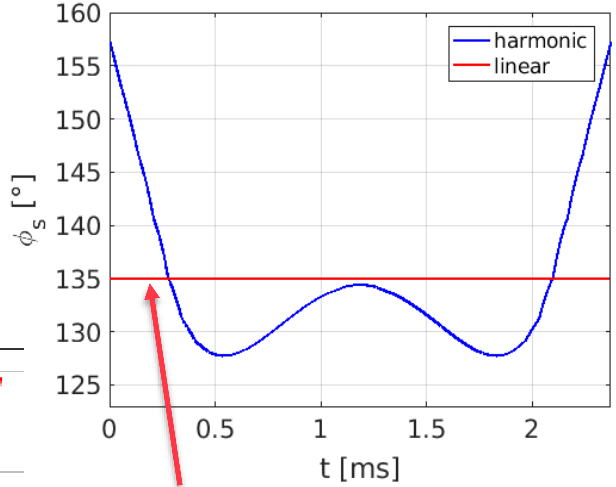
Acc. gradient with non-linear ramping



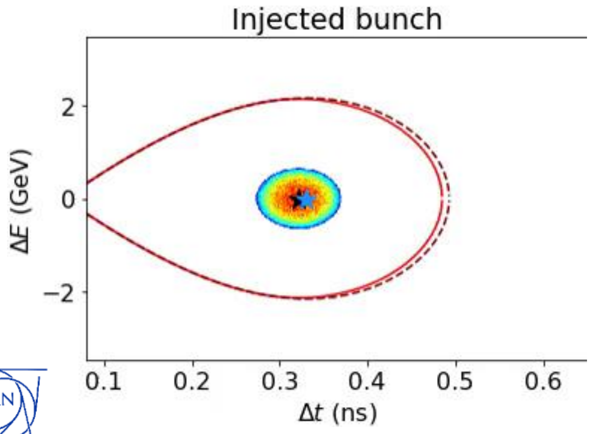
→ **Adjust the voltage by sweeping the synchrotron phase** $V(t) = V_{\mathrm{RF}} \cdot sin(\phi_s(t))$

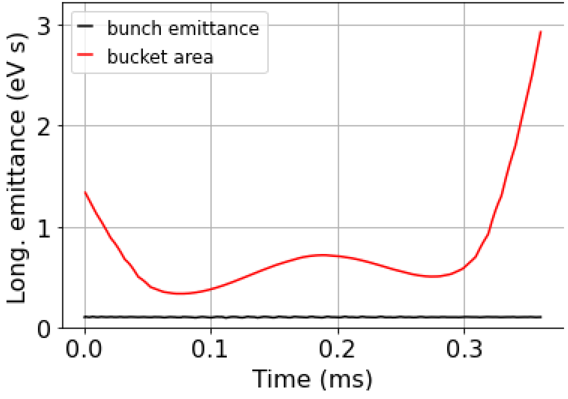
and $\phi_s(t) = \arcsin\left(\frac{\dot{B}_{harm}(t)}{\dot{B}_{lin}(t)} \cdot \sin\phi_{s,0}\right)$

- **Example for RCS3, no intensity effects:**



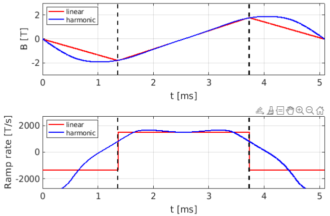
$\phi_{s,0}$ = π - 45° for linear, above transition





F. Batsch

Acc. gradient with non-linear ramping

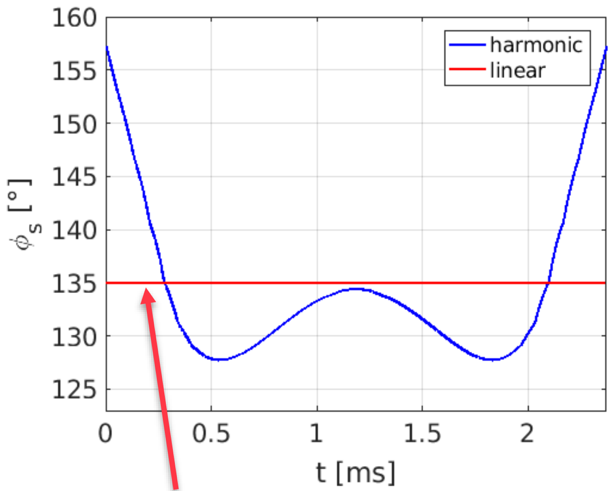


→ **Adjust the voltage by sweeping the synchrotron phase** $V(t) = V_{\mathrm{RF}} \cdot sin(\phi_s(t))$

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

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

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



$\phi_{s,0}$ = π - 45° for linear, above transition

Summary

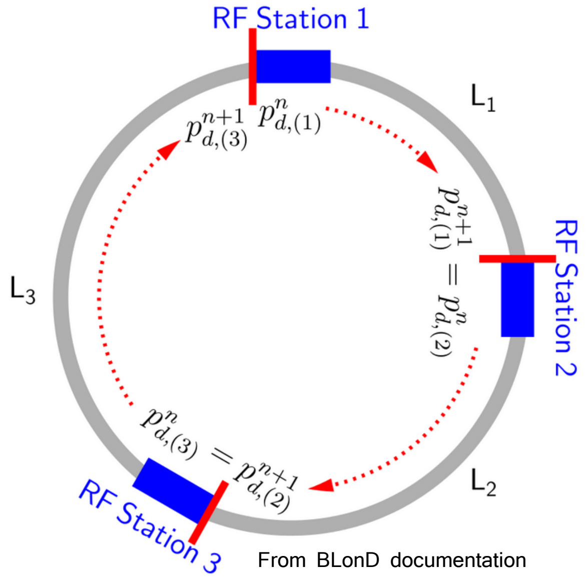
- The muon decay brings unique challenges: fast acceleration, large voltages, high intensities, high synchronous tune, small number of turns
- Fast ramping asks for RCS, high energies for hybrid magnet structure
- Developing an integrated design with respect to magnets + RF and ramping function, but also lattice (see talks by A. Chancé)
- Large, number of RF stations, e.g. 30, to mitigate extreme synchrotron tune
- Magnet ramping and RF voltages require optimization of acceleration parameters (RF voltages, synchronous phase, acceleration time = decay)

CERN

The 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
- Studies of today with only one bunch, 2nd to follow



From BLonD documentation

Studies with BLonD

(Beam Longitudinal Dynamics code)

- Using the BLonD code to observe effects of
    - Synchrotron tune Q_s
    - Choice of synchronous phase
    - Short-range wakefields
    - Beam loading at fundamental frequency
    - Induced HOM powers
    - Nonlinear ramping functions (RF and magnets)