Accelerator design meeting
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Parameters: high-energy complex

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On behalf of WP5.2

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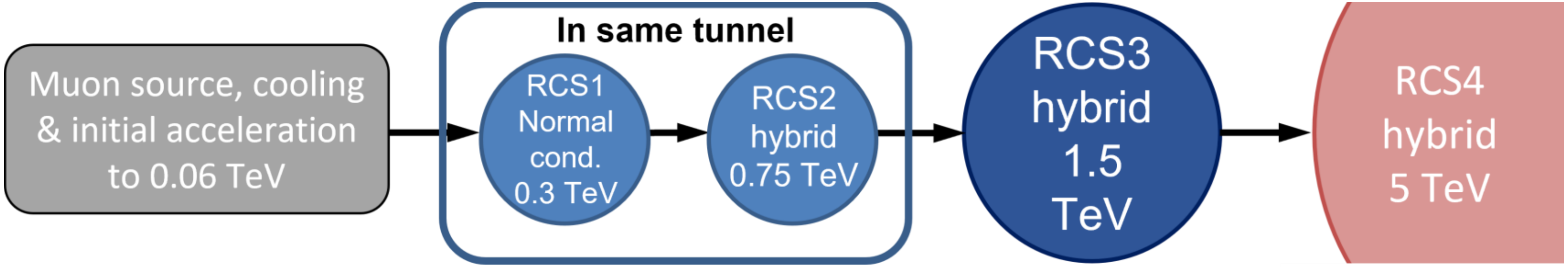
The RCSs

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



- Hybrid RCSs have interleaved normal conducting (NC) and superconducting (SC) magnets
- Cryogenics around the entire RCS2/3/4

General parameters

Key points & parameters [link]

- RF dictated through muon decay:
- The survival rate $\frac{N(\tau_{acc})}{N_0} = \exp\left(-\frac{1}{\tau_\mu}\int_0^{\tau_{acc}} \frac{dt}{\gamma(t)}\right)$

and energy swing $(\gamma_{\text{inj}}, \gamma_{ej})$ define acceleration time

$$\tau_{acc} = -\tau_\mu(\gamma_{ej} - \gamma_{inj}) \ln\left(\frac{N_{ej}}{N_{inj}}\right) / \ln\left(\frac{\gamma_{ej}}{\gamma_{inj}}\right)$$

and average RF gradient

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

and number of required cavities.

Table 7.1: Summary table of the acceleration chain.

Parameter	Symbol	Unit	RCS1	RCS2	RCS3	RCS4
Hybrid RCS	-	-	No	Yes	Yes	Yes
Number of bunches/species		-	1	1	1	1
Repetition rate	f_{rep}	[Hz]	5	5	5	5
Circumference	$2\pi R$	[m]	5990	5990	10700	26659
Bunch population	N_{inj}	$[1 \times 10^{12}]$	2.54	2.43	2.2	2.22
Injection energy	E_{inj}	[GeV/u]	63	313.83	750	1500
Ejection energy	E_{ej}	[GeV/u]	313.830	750	1500	5000
Energy ratio	$E_{\text{ej}}/E_{\text{inj}}$	-	4.98	2.39	2.00	3.33
Planned Survival rate	$N_{\text{ej}}/N_{\text{inj}}$	-	0.9	0.9	0.9	0.9
Acceleration time	τ_{acc}	[ms]	0.343	1.097	2.37	6.37
Number of turns	n_{turn}	-	17	55	66	72
Average Accel. Gradient	G	[MV/m]	2.44	1.33	1.06	1.83
Required energy gain per turn	ΔE	[GeV]	14.755	7.930	11.364	48.611
Tot. straight section length	L_{str}	[m]	2334.7	2335.7	3975.7	4063.3
Vertical norm. Emittance	$\epsilon_{v,n}$	[μm]	25	25	25	25
Horiz. norm. Emittance	$\epsilon_{h,n}$	[μm]	25	25	25	25
Long. norm. emittance	$\epsilon_{z,n}$	[eVs]	0.025	0.025	0.025	0.025
Total NC dipole length	L_{NC}	[m]	3655.3	2539.26	4366.29	18338.42
Total SC dipole length	L_{SC}	[m]	0	1115.02	2358.02	4257.27
Max. NC dipole field	$B_{NC,inj}$	[T]	1.80	1.80	1.80	2.00
Max. SC dipole field	B_{SC}	[T]	-	10	10	16
Ramp rate	$\dot{B}$	[T/s]	4198.9	3281.5	1518.5	628.0
Main RF frequency	f_{RF}	[MHz]	1300	1300	1300	1300
Max RF voltage	V_{RF}	[GV]	20.87	11.22	16.07	68.75
Number of cavities		-	696	374	536	2292

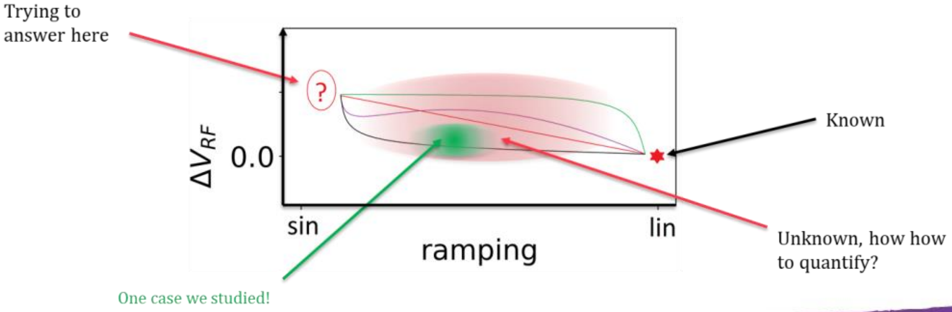
Courtesy: F. Batsch

Ramp parameters

- Currently, the ramp is assumed to be quasi-linear.
- Ramp parameres need to be refined:
  - RF considerations
  - Powering considerations.
  - Cost considerations.
- Which basis to define the ramp?

Table 7.2: Tentative ramp parameters for the acceleration chain.

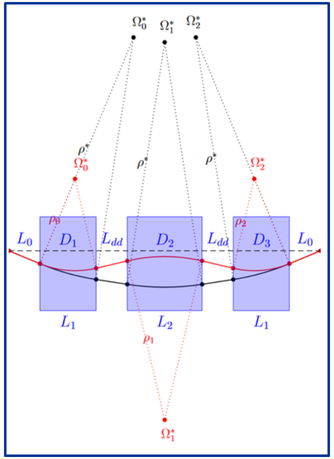
Data	Symbol	Unit	RCS1	RCS2	RCS3	RCS4
Acceleration time	τ_{acc}	[ms]	0.343	1.097	2.37	6.37
Injection energy	E_{inj}	[GeV/u]	63	313.83	750	1500
Ejection energy	E_{ej}	[GeV/u]	313.830	750	1500	5000
Energy ratio	E_{ej}/E_{inj}	-	4.98	2.39	2.00	3.33
Number of turns	n_{turn}	-	17	55	66	72
Ramp shape			Quasi-Linear			
Planned Survival rate	N_{ej}/N_{inj}	-	0.9	0.9	0.9	0.9
Total survival rate	N_{ej}/N_0	-	0.9	0.81	0.729	0.6561
Average Accel. Gradient	G	[MV/m]	2.44	1.33	1.06	1.83
Required energy gain per turn	ΔE	[GeV]	14.755	7.930	11.364	48.611
Injection Lorentz factor	γ_{inj}	-	597	2971	7099	14198
Ejection Lorentz factor	γ_{ej}	-	2971	7099	14198	47323
Ramp rate	$\dot{B}$	[T/s]	4198.9	3281.5	1518.5	628.0
Repetition rate		[Hz]	5	5	5	5



Courtesy: F. Batsch and H. Damerau

Machine and lattice parameters

- Most RCS are hybrid.
- Total dipole length determined by injection/ejection energies and maximum dipole field.
- Path length and orbit differences depend on the number of cells.



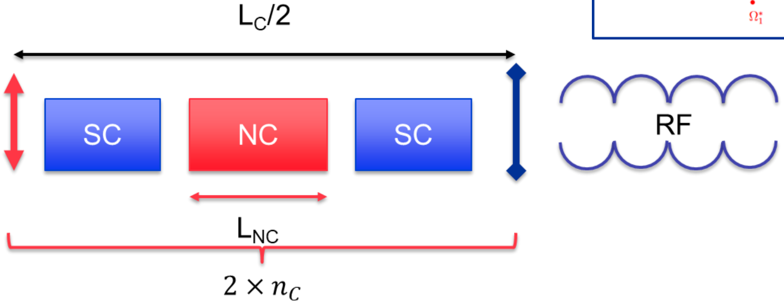


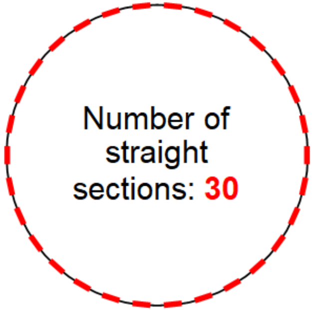
Table 7.3: Tentative machine and lattice parameters for the acceleration chain. The acceleration ramp is assumed to be linear. The minimum dipole width and height do not include the required shielding and limitations coming from collective effects studies.

Data	Symbol	Unit	RCS1	RCS2	RCS3	RCS4
Hybrid RCS	-	-	No	Yes	Yes	Yes
Radius	R	[m]	953.3	953.3	1703.0	4242.9
Circumference	$2\pi R$	[m]	5990	5990	10700	26659
Pack fraction		[%]	61	61	62.8	84.8
Bend radius	ρ_B	[m]	581.8	581.8	1070.2	3596.2
Tot. straight section length	L_{str}	[m]	2334.7	2335.7	3975.7	4063.3
Average Injection dipole field	B_{inj}	[T]	0.36	1.80	2.34	1.39
Average ejection dipole field	B_{ej}	[T]	1.8	4.30	4.68	4.64
Ramp rate	$\dot{B}$	[T/s]	4198.9	3281.5	1518.5	628.0
Repetition rate		[Hz]	5	5	5	5
Total NC dipole length	L_{NC}	[m]	3655.3	2539.26	4366.29	18338.42
Total SC length	L_{SC}	[m]	0	1115.02	2358.02	4257.27
Injection NC dipole field	$B_{NC,inj}$	[T]	0.36	-1.80	-1.80	-2.00
Ejection NC dipole field	$B_{NC,inj}$	[T]	1.80	1.80	1.80	2.00
SC dipole field	B_{SC}	[T]	-	10	10	16
Number of cells/arc	n_c		7	10	17	19
Cell length	L_c	[m]	21.4	19.6	20.6	45.9
Path length diff.	ΔC	[mm]	0	9.1	2.7	9.4
Orbit difference	$\Delta \bar{x}$	[mm]	0	12.2	5.9	13.2
Min. dipole width	w_d	[mm]	17.4	19.6	10.7	18.8
Min. dipole height	h_d	[mm]	14.8	6.4	4.2	4.4
Transition gamma	γ_{tr}	-	20.41	20.41	30.9	30.9

RF parameters

Further key points:

- Consequences are unique longitudinal dynamics due to fast acceleration and high intensities (>2.2×10^{12})
- Large synchrotron tune requires a distribute SRF system: → Up to 30 RF stations
- Synchronous phase defines number of cavities, RF voltage and bucket area, i.e., beam dynamics



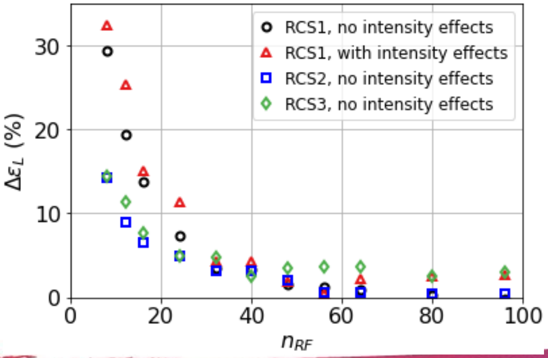


Table 7.5: Tentative RF parameters for the acceleration chain. The acceleration ramp is assumed to be linear. The minimum required cavity gradient assumed that all the allocable space is filled with cavities by assuming an RF filling factor of the straight sections (to included the interconnections inside and between the cryomodules).

Data	Symbol	Unit	RCS1	RCS2	RCS3	RCS4
Main RF frequency	f_{RF}	[MHz]	1300	1300	1300	1300
Harmonic number	h	-	25957	25957	46367	115522
Revolution frequency	f_{rev}	[kHz]	50.08	50.08	28.04	11.25
Revolution period	T_{rev}	[ms]	20.0	20.0	35.7	88.9
Max RF voltage	V_{RF}	[GV]	20.87	11.22	16.07	68.75
Max RF power	P_{RF}	[kW]	850.6	437.4	317.6	550.3
max RF Filling factor	–	-	0.4	0.4	0.45	0.45
Current RF Filling factor	–	-	0.38	0.21	0.17	0.45
Minimum Number RF stations	-	-	32	24	24	24
Number of cavities		-	696	374	536	2292
Assumed Gradient in cavity	$\Delta E/L$	[MV/m]	30	30	30	45
Min. Required gradient in cavity	$\Delta E/L$	[MV/m]	22.3	12.0	9.0	37.6
Stable phase	ϕ_S	[°]	135	135	135	135
Longitudinal emittance $\sigma_E \times \sigma_z$	$\epsilon_{z,n}$	[eVs]	0.025	0.025	0.025	0.025
Injection bucket area	$A_{B,\mathrm{inj}}$	[eVs]	0.62	1.01	2.11	3.91
Ejection bucket area	$A_{B,\mathrm{ej}}$	[eVs]	1.37	1.56	2.99	7.15
Bucket area reduction factor	$A_B/A_{B,st}$	-	0.172	0.172	0.172	0.172
Injection synchrotron frequency	$f_{S,\mathrm{inj}}$	[kHz]	76.33	25.07	9.59	8.89
Ejection synchrotron frequency	$f_{S,\mathrm{ej}}$	[kHz]	34.20	16.22	6.78	4.87
Injection synchrotron tune	$Q_{s,\mathrm{inj}}$	-	1.52	0.50	0.34	0.79
Ejection synchrotron tune	$Q_{s,\mathrm{ej}}$	-	0.68	0.32	0.24	0.43
Momentum compaction factor	α_p	-	0.0024	0.0024	0.0010	0.0010

Courtesy: F. Batsch

Summary

- A first parameter table is proposed for the high-energy acceleration.
  - The RCS4 is the most preliminary and needs more studies to be consolidated.
  - The needed total dipole length and RF voltage are evaluated and can be a first step for costing considerations.
  - The optics is based on FODO cells and should be reviewed.
  - The acceleration ramp is quasi-linear and may evolve.
- Future versions of the parameter table should include also an FFA alternative.
- We need to continue the discussions to see how to marry RF, magnet, powering, costing, vacuum, collective effects, and optics considerations.

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Thank you for your attention