Parameter options for the RCS chain in SPS and LHC

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RCS chain options for CERN-based scenarios

Start points:

- **SPS with 6912m circumference, LHC with 26659m**
- **Kept the magnet strengths of 1.8T and 10T**
- **Filling factors match those of the real tunnels**
- **Optimization tool minimizes the four linear gradients times length**
- **The energy reach of RCS 4 is to be maximized (for the optimization tool, see appendix)**

Possible scenarios:

- **3 RCS: 1x normal conducting in SPS tunnel, 2x (NC + hybrid) in LHC tunnel**
- **3 RCS: 2x (NC + hybrid) in SPS tunnel, 1x hybrid in LHC tunnel**
- **2 RCS: NC in SPS tunnel and hybrid in LHC tunnel**

Common case: the normal conducting SPS

<u>This RCS is common in all three scenarios:</u>

→ **The ejection energy is set by the maximum reach defined by B_{nc}**

→ **400 GeV ejection energy**

Parameter	Symbol	Unit	RCS 1
RCS type	–	[-]	Normal
Injection energy	E_{inj}	[eV]	63.000G
Ejection energy	E_{ej}	[eV]	400.000G
Energy ratio	$E_{\mathrm{ej}}/E_{\mathrm{inj}}$	[-]	6.349
Injection Lorentz factor	γ_{inj}	[-]	597.261
Ejection Lorentz factor	γ_{ej}	[-]	3.787k
Survival rate	$N_{\mathrm{ej}}/N_{\mathrm{inj}}$	[-]	0.90
Acceleration time	τ_{acc}	[s]	399.748u
Average accel. gradient	G_{avg}	[V/m]	2.814M
Ramp rate	$\dot{B}_{\mathrm{NC}}$	[T/s]	3.793k
Machine radius	R	[m]	1.100k
Circumference	$2\pi R$	[m]	6.910k
Pack fraction	-	[-]	0.67
Bend radius	ρ_B	[m]	741.440
Total NC dipole length	L_{NC}	[m]	4.659k
Total SC dipole length	L_{SC}	[m]	0.000
SC dipole field	B_{SC}	[T]	10.000
Average injection dipole field	B_{inj}	[T]	283.900m
Average ejection dipole field	B_{ej}	[T]	1.800
Injection NC dipole field	$B_{\mathrm{NC,inj}}$	[T]	283.900m
Ejection NC dipole field	$B_{\mathrm{NC,ej}}$	[T]	1.800
Number of RF cavities	n_{RF}	[-]	883

Example values

Example table created with D. Amorim's online tool

Scenario 2xSPS, 1x LHC

Table 5: General properties of: 2xSPS (normal + hybrid), 1x LHC hybrid

Parameter	Symbol	Unit	RCS SPS 1	RCS SPS 2	RCS LHC
Injection energy	E_{inj}	[GeV]	63	394	936
Ejection energy	E_{ej}	[GeV]	394	936	3950
Energy ratio	$E_{\text{ej}}/E_{\text{inj}}$	[-]	6.3	2.4	4.2
Injection Lorentz factor	γ_{inj}	[-]	597	3730	8864
Ejection Lorentz factor	γ_{ej}	[-]	3730	8864	37362
Survival rate	$N_{\text{ej}}/N_{\text{inj}}$	[-]	0.88	0.87	0.92
Acceleration time	τ_{acc}	[ms]	0.48	1.89	3.54
Number of turns	N_{turns}	[-]	21	79	41
Average accel. gradient	G_{avg}	[MV/m]	2.32	0.96	2.84
Energy gain per turn	ΔE	[GeV]	15.8	6.87	73.4
Total RF voltage	V_{RF}	[GV]	22.3	9.7	103.8
Number of cavities	N_{cav}	[-]	740	294	2308
Ramp rate	$\dot{B}_{\text{NC}}$	[T/s]	3170	1907	1017
Machine radius	R	[m]	1100	1100	4243
Pack fraction	-	[-]	0.66	0.66	0.85
Bend radius	ρ_B	[m]	730	724	3604
Total straight length	L_{str}	[m]	2323	2359	4015
Total NC dipole length	L_{NC}	[m]	4589	3158	17529
Total SC dipole length	L_{SC}	[m]	-	1394	5118
SC dipole field	B_{SC}	[T]	-	10	10
Average Injection dipole field	B_{inj}	[T]	0.29	1.80	0.87
Average ejection dipole field	B_{ej}	[T]	1.80	4.31	3.65
Injection NC dipole field	$B_{\text{NC,inj}}$	[T]	0.29	-1.80	-1.80
Ejection NC dipole field	$B_{\text{NC,ej}}$	[T]	1.80	1.80	1.80

→ **RF not yet optimized as `Bref` for RCS1 is not determined**

Scenario 1xSPS, 2x LHC

Table 1: General properties of: 1xSPS, 2x LHC (normal + hybrid)

Parameter	Symbol	Unit	RCS SPS	RCS LHC 1	RCS LHC 2
Injection energy	E_{inj}	[GeV]	63	386	1943
Ejection energy	E_{ej}	[GeV]	386	1943	4648
Energy ratio	$E_{\mathrm{ej}}/E_{\mathrm{inj}}$	[-]	6.1	5.0	2.3
Injection Lorentz factor	γ_{inj}	[-]	597	3653	18387
Ejection Lorentz factor	γ_{ej}	[-]	3653	18387	43993
Survival rate	$N_{\mathrm{ej}}/N_{\mathrm{inj}}$	[-]	0.88	0.90	0.92
Acceleration time	τ_{acc}	[ms]	0.46	2.17	5.70
Number of turns	-	[-]	20	24	64
Average accel. gradient	G_{avg}	[MV/m]	2.36	2.39	1.58
Energy gain per turn	ΔE	[GeV]	16.1	64.9	42.3
Total RF voltage	V_{RF}	[GV]	22.8	91.8	59.8
Number of cavities	N_{cav}	[-]	760	3060	1870
Ramp rate	$\dot{B}_{\mathrm{NC}}$	[T/s]	3290	664	632
Machine radius	R	[m]	1100	4243	4243
Pack fraction	-	[-]	0.65	0.85	0.85
Bend radius	ρ_B	[m]	715	3600	3600
Total straight length	L_{str}	[m]	2418	4040	4004
Total NC dipole length	L_{NC}	[m]	4494	22621	15750
Total SC dipole length	L_{SC}	[m]	-	-	6907
SC dipole field	B_{SC}	[T]	-	-	10
Average Injection dipole field	B_{inj}	[T]	0.29	0.36	1.80
Average ejection dipole field	B_{ej}	[T]	1.80	1.80	4.30
Injection NC dipole field	$B_{\mathrm{NC,inj}}$	[T]	0.29	0.36	-1.80
Ejection NC dipole field	$B_{\mathrm{NC,ej}}$	[T]	1.80	1.80	1.80

=> 9 TeV collider

Large number of cavities

Note: using 16T would allow to reach 5 TeV

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Scenario 1xSPS, 1x LHC

Table 7: General properties of the RCS chain: 1 SPS, 1 LHC

Parameter	Symbol	Unit	RCS SPS	RCS LHC
Injection energy	E_{inj}	[GeV]	63	397
Ejection energy	E_{ej}	[GeV]	397	3580
Energy ratio	$E_{\mathrm{ej}}/E_{\mathrm{inj}}$	[-]	6.3	9.0
Injection Lorentz factor	γ_{inj}	[-]	597	3756
Ejection Lorentz factor	γ_{ej}	[-]	3756	33824
Survival rate	$N_{\mathrm{ej}}/N_{\mathrm{inj}}$	[-]	0.91	0.80
Acceleration time	τ_{acc}	[ms]	0.36	6.7
Number of turns	N_{turns}	[-]	16	75
Average accel. gradient	G_{avg}	[MV/m]	3.07	1.58
Energy gain per turn	ΔE	[GeV]	20.9	42.4
Total RF voltage	V_{RF}	[GV]	29.5	59.9
Number of cavities	N_{cavities}	[-]	980	1865
Ramp rate	$\dot{B}_{\mathrm{NC}}$	[T/s]	4176	537
Machine radius	R	[m]	1100	4243
Pack fraction	-	[-]	0.67	0.85
Bend radius	ρ_B	[m]	735	3600
Total straight length	L_{str}	[m]	2291	4001
Total NC dipole length	L_{NC}	[m]	4621	18495
Total SC dipole length	L_{SC}	[m]	-	4161
SC dipole field	B_{SC}	[T]	-	10
Average Injection dipole field	B_{inj}	[T]	0.29	0.37
Average ejection dipole field	B_{ej}	[T]	1.80	3.31
Injection NC dipole field	$B_{\mathrm{NC,inj}}$	[T]	0.29	-1.80
Ejection NC dipole field	$B_{\mathrm{NC,ej}}$	[T]	1.80	1.80

=> 7 TeV collider

Much less cavities

1 RCS per tunnel optimal at CERN!

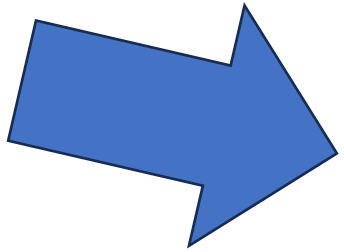
Energy swings in hybrid RCS

What is the difference to the green field (GF) study???

The energy swing of a second hybrid RCS is given by

- $\frac{E_{ej}}{E_{inj}} = \frac{\frac{B_{sc}}{B_{nc}} * L_{sc,2} + L_{nc,2}}{2 * \pi * \rho_{b,1}}$ **for the case of NC RCS as pre-injector**

  with $L_{sc,2} + L_{nc,2} = 2 * \pi * \rho_{b,2}$



RCS@LHC: $\frac{E_{ej}}{E_{inj}} = \frac{\frac{10}{1.8} * 4160 + 18495}{2 * \pi * 735} = 9.0$

RCS2 GF: $\frac{E_{ej}}{E_{inj}} = \frac{\frac{10}{1.8} * 1115 + 2539}{2 * \pi * 581} = 2.39$

and by

- $\frac{E_{ej}}{E_{inj}} = \frac{\frac{B_{sc}}{B_{nc}} * L_{sc,2} + L_{nc,2}}{\frac{B_{sc}}{B_{nc}} * L_{sc,1} + L_{nc,1}}$ **for a hybrid RCS as pre-injector**

Conclusion

- In summery

Scenario	# RCS	Final Energy [TeV]	V_{RF} [V]	N_{cav}	Survival rate
2x SPS, 1x LHC	3	3.95	135.8	3342	0.7
1x SPS, 2x LHC	3	4.65	174.4	5690	0.7
1x SPS, 1x LHC	2	3.58	89.4	2845	0.7

- The fine-tuned RF optimization will be done for the selected scenario
- Real cost analysis requires a defined magnetic ramp of RCS1
- The CERN complex has a beneficial machine radius ratio such that 1 RCS per ring is optimal and large energy swings are also possible in hybrid RCSs


CERN

Scenario 1xSPS, 2x LHC for 16T SC magnets

Table 3: General properties of: 1xSPS, 2x LHC (normal + hybrid)

Parameter	Symbol	Unit	RCS SPS	RCS LHC 1	RCS LHC 2
Injection energy	E_{inj}	[GeV]	63	383	1945
Ejection energy	E_{ej}	[GeV]	383	1945	5046
Energy ratio	$E_{\mathrm{ej}}/E_{\mathrm{inj}}$	[-]	6.1	5.1	2.6
Injection Lorentz factor	γ_{inj}	[-]	597	3627	18410
Ejection Lorentz factor	γ_{ej}	[-]	3627	18410	47757
Survival rate	$N_{\mathrm{ej}}/N_{\mathrm{inj}}$	[-]	0.94	0.87	0.90
Acceleration time	τ_{acc}	[ms]	0.246	2.83	7.40
Number of turns	-	[-]	11	32	83
Average accel. gradient	G_{avg}	[MV/m]	4.3	1.8	1.4
Energy gain per turn	ΔE	[GeV]	29.3	48.7	32.6
Total RF voltage	V_{RF}	[GV]	41.1	69.0	46
Number of cavities	N_{cav}	[-]	1370	2300	1023
Ramp rate	$\dot{B}_{\mathrm{NC}}$	[T/s]	6112	511	486
Machine radius	R	[m]	1100	4243	4243
Pack fraction	-	[-]	0.65	0.85	0.85
Bend radius	ρ_B	[m]	710	3605	3602
Total straight length	L_{str}	[m]	2418	4040	6605
Total NC dipole length	L_{NC}	[m]	4462	22649	18052
Total SC dipole length	L_{SC}	[m]	-	-	4579
SC dipole field	B_{SC}	[T]	-	-	16
Average Injection dipole field	B_{inj}	[T]	0.30	0.35	1.80
Average ejection dipole field	B_{ej}	[T]	1.80	1.80	4.67
Injection NC dipole field	$B_{\mathrm{NC,inj}}$	[T]	0.30	0.35	-1.80
Ejection NC dipole field	$B_{\mathrm{NC,ej}}$	[T]	1.80	1.80	1.80

= 10 TeV collider

Limit to be applied

Length does not fit 8*540m

Scenario 1xSPS, 1x LHC, 16T

Table 9: General properties for 1 SPS, 1 LHC with 16T SC magnets

Parameter	Symbol	Unit	RCS SPS	RCS LHC
Injection energy	E_{inj}	[GeV]	63	397
Ejection energy	E_{ej}	[GeV]	397	3815
Energy ratio	$E_{\mathrm{ej}}/E_{\mathrm{inj}}$	[-]	6.3	9.6
Injection Lorentz factor	γ_{inj}	[-]	597	3757
Ejection Lorentz factor	γ_{ej}	[-]	3757	36108
Survival rate	$N_{\mathrm{ej}}/N_{\mathrm{inj}}$	[-]	0.89	0.80
Acceleration time	τ_{acc}	[ms]	0.44	7.01
Number of turns	N_{turns}	[-]	16	75
Average accel. gradient	G_{avg}	[MV/m]	2.51	1.63
Energy gain per turn	ΔE	[GeV]	20.9	42.4
Ramp rate	$\dot{B}_{\mathrm{NC}}$	[T/s]	3407	513
Machine radius	R	[m]	1100	4243
Circumference	$2\pi R$	[m]	6912	26659
Pack fraction	-	[-]	0.67	0.85
Bend radius	ρ_B	[m]	736	3606
Total NC dipole length	L_{NC}	[m]	4622	19.889
Total SC dipole length	L_{SC}	[m]	0	2.759
SC dipole field	B_{SC}	[T]	-	16
Average Injection dipole field	B_{inj}	[T]	0.29	0.37
Average ejection dipole field	B_{ej}	[T]	1.81	3.53
Injection NC dipole field	$B_{\mathrm{NC,inj}}$	[T]	0.29	-1.80
Ejection NC dipole field	$B_{\mathrm{NC,ej}}$	[T]	1.80	1.80

= 7.5 TeV collider

Greenfield scenario with 1 RCS per tunnel

Table 10: General properties of the RCS chain

Parameter	Symbol	Unit	RCS 1	RCS 2	RCS 3
Injection energy	E_{inj}	[GeV]	63	333	1232
Ejection energy	E_{ej}	[GeV]	333	1.232	4219
Energy ratio	$E_{\mathrm{ej}}/E_{\mathrm{inj}}$	[-]	5.3	3.7	3.4
Injection Lorentz factor	γ_{inj}	[-]	597	3149	11663
Ejection Lorentz factor	γ_{ej}	[-]	3149	11663	39928
Survival rate	$N_{\mathrm{ej}}/N_{\mathrm{inj}}$	[-]	0.89	0.80	0.94
Acceleration time	τ_{acc}	[ms]	0.41	3.12	3.14
Average accel. gradient	G_{avg}	[MV/m]	2.21	0.96	3.17
Ramp rate	$\dot{B}_{\mathrm{NC}}$	[T/s]	3582	1153	1146
Circumference	$2\pi R$	[m]	5990	10700	35000
Pack fraction	-	[-]	0.65	0.64	0.66
Bend radius	ρ_B	[m]	617	1095	3676
Total NC dipole length	L_{NC}	[m]	3874	5237	17386
Total SC dipole length	L_{SC}	[m]	0	1640	5712
SC dipole field	B_{SC}	[T]	-	10	10
Average Injection dipole field	B_{inj}	[T]	0.34	1.01	1.12
Average ejection dipole field	B_{ej}	[T]	1.80	3.76	3.83
Injection NC dipole field	$B_{\mathrm{NC,inj}}$	[T]	0.34	-1.80	-1.80
Ejection NC dipole field	$B_{\mathrm{NC,ej}}$	[T]	1.80	1.80	1.80

Parameter optimization using David's python script

- **Use this as input for the optimization tool by David Amorim, Leonard Thiele, Marco Gast, ...**

Example of an optimization: try to fit the RCS in the CERN tunnels

7 variables

- the four transmission rates in RCS 1/2/3/4
- the three energy stages between RCS 1-2, RCS 2-3 and RCS 3-4

5 objectives

- the four linear gradients required in each RCS for acceleration (attribute `linear_acceleration_gradient_for_survival` of `RCS` objects, multiplied by the RCS length), to be minimized
- the energy reach of RCS 4, to be maximized

Inequality constraint

- the `planned_global_survival_rate` of the RCSChain, must be above 0.9^4 = 0.656
- the three dipole `packing_fraction` of each RCS, must be below 0.66 or 0.7 for RCS4
- acceleration time in the RCS must be below 10 ms

Other assumptions

- All other parameters are the default ones
- RCS 1 injection energy is 63 GeV

Parameter optimization using David's python script

- **Use this as input for the optimization tool by David Amorim, Leonard Thiele, Marco Gast, ...**

```
# The default RCS chain parameters are recalled here
cern_rcs_chain_before_optimization_parameters = {'Information': {'Name': 'hybrid RCS chain default', 'version': '1',
                                                 'Date': '2024-01-08',
                                                 'Comment': ''},
                            'Parameters': {'Particle Name': 'PosMuon',
                                           'Number of stages': 3,
                                           'Stage type': ['Normal', 'Normal', 'Hybrid'],
                                           'Survival rate per stage': [0.9, 0.9, 0.9],
                                           'Energy stages [eV]': [63.0e9, 400e9, 1500.0e9, 4600.0e9],
                                           'Tunnel number': [0, 1, 1],
                                           'Tunnel lengths [m]': [6912, 26659],
                                           'Maximum B field Normal Conducting [T]': [1.8, 1.8,
                                                                                     1.8], # This was increased to 2 T
                                           'Maximum B field Super Conducting [T]': [10, 10, 10],
                                           'Initial number of particles': 2.7e12,
                                           'Maximum B field gradient compared to linear acceleration': [1.05, 1.05,
                                                                                                        1.05],
                                           'Total running hours [h]': 6000 * 20,
                                           'Cost per MWh [U]': 90,
                                           'Compute Bref and RF': [False, False, False], # We deactivate the Bref
                                                                                         #  and RF computations for the
                                                                                         # optimization routines to work
                                           'Repetition rate [Hz]':5,
                                           }
                            }
```

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