CERN-based options for the RCS chain

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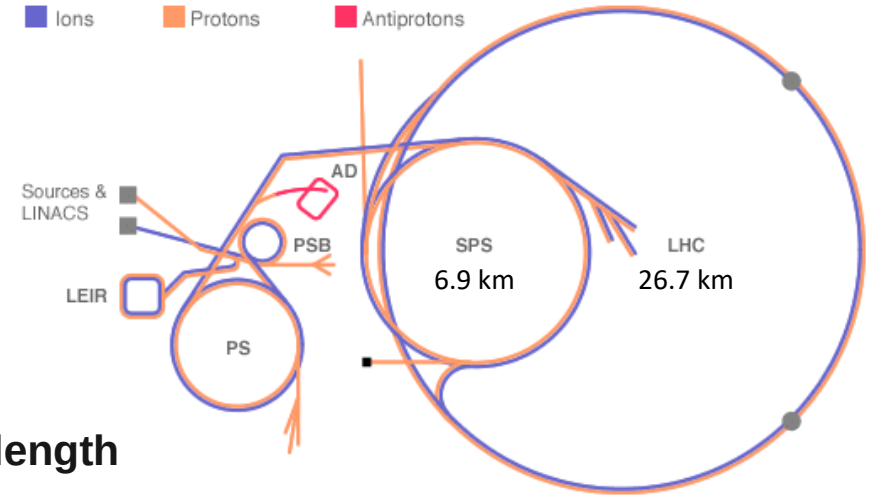
Outline

1. Possible scenarios for SPS and LHC
2. Parameters for these scenarios and their comparison
3. Usage of HTS in normal RCSs
4. Conclusion

RCS chain options for CERN-based scenarios



Start points:

- **SPS with 6912m circumference, LHC with 26659m**
- **Magnet strengths of 1.8T (NC) and 10T (SC)**
- **Magnet filling factors of the tunnel**
- **Optimization tool by D. Amorim 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

Not of interest!

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

Most interesting option:

- **4 TeV staged approach possible while using warm magnets**
- **Extend or upgrade to 9-10 TeV collider with new magnets (HTS) or hybrid RCS as 3rd RCS**

→ Accelerator chain with 3 RCS only

Note: Large number of cavities in 2nd RCS to be adjusted

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

Scenario 1xSPS, 1x LHC

Cost-wise Interesting if a 7 TeV collider is acceptable, but very large energy swing in 2nd RCS, feasibility unclear.

(Large energy swing might lead to large orbits excursions due to the hybrid magnet layout)

→ **Not pursued**

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	$E_{\text{ej}}/E_{\text{inj}}$	[-]	6.3	9.0
Injection Lorentz factor	γ_{inj}	[-]	597	3756
Ejection Lorentz factor	γ_{ej}	[-]	3756	33824
Survival rate	$N_{\text{ej}}/N_{\text{inj}}$	[-]	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	$\dot{B}_{\text{NC}}$	[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	$B_{\text{NC,inj}}$	[T]	0.29	-1.80
Ejection NC dipole field	$B_{\text{NC,ej}}$	[T]	1.80	1.80

=> 7 TeV collider

Much less cavities

HTS option: Reduction of losses in high field pulsing superferric magnets

Alternative scenario for 1x SPS, 2x LHC:

- **One Normal type RCS in SPS tunnel from 36GeV to 400GeV NC pulsed dipoles @1.8T aperture 30mmx50mm**
- **One Normal type RCS in LHC tunnel from 400GeV to about 3000GeV SC (HTS) pulsed dipoles @3T and 500T/s aperture 30mmx50mm**
- **One Hybrid type RCS in LHC tunnel from about 3000GeV to 5000GeV NC pulsed dipoles @1.8T and SC ff @ 10T aperture 30mmx80mm**

These numbers are the first result of a brainstorming meeting last Thursday with follow-up meeting in a larger round in September or October

Credits: A. Chancé and F. Boattini

Conclusion

- **In summary:**

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

- **As input for ESPP, a CERN-based scenario next to the greenfield approach will be included**
- **The marked option allows for a staged approach of 4 TeV and 9-10 TeV reusing the CERN infrastructure while using three RCS only**
- **The fine-tuned RF and real cost analysis as next steps**


CERN

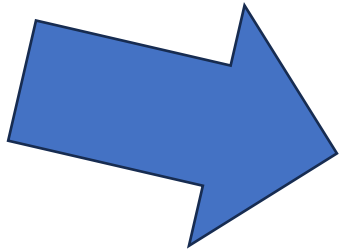
Energy swings in hybrid RCS

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

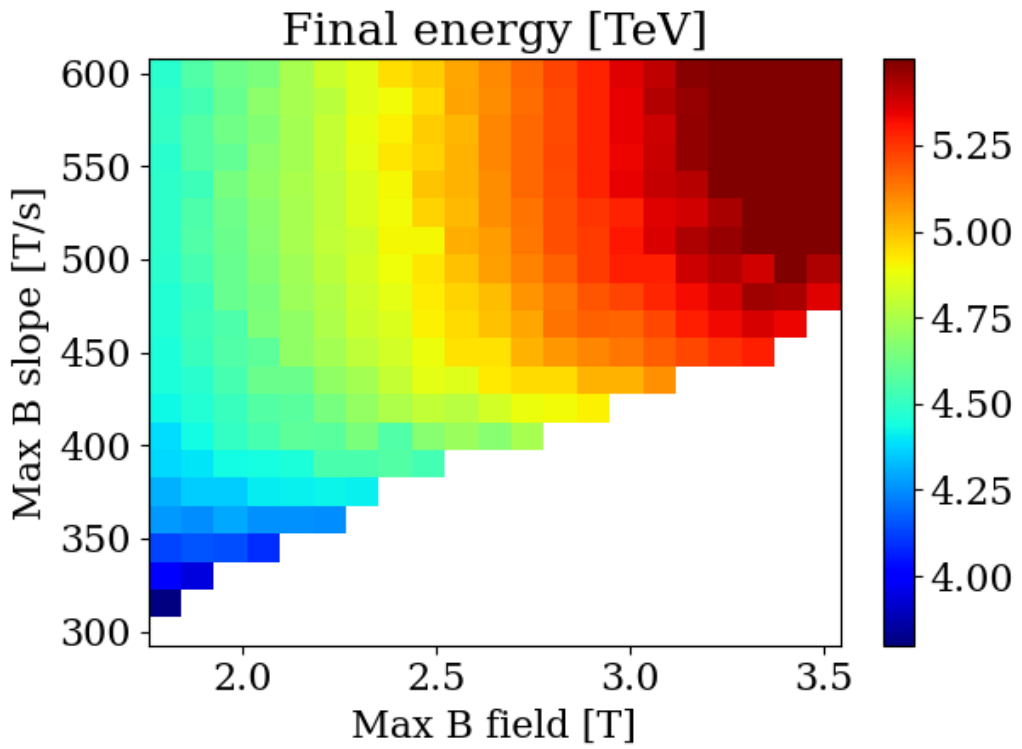
and by

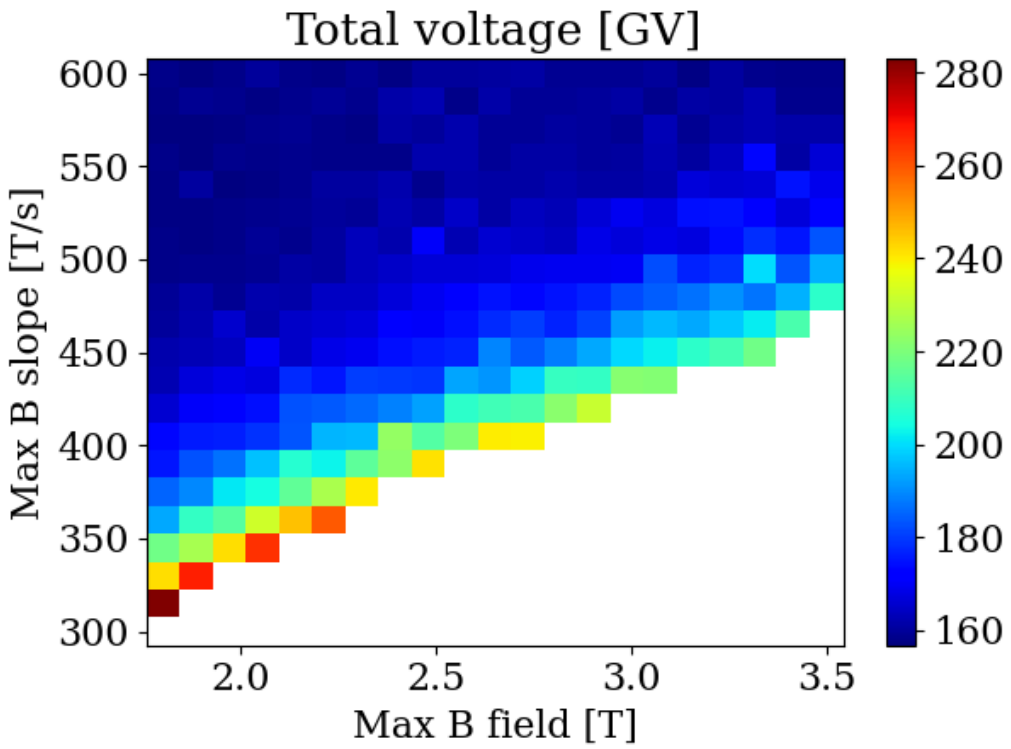
- $\frac{E_{ej}}{E_{inj}} = \frac{\frac{B_{sc}}{B_{nc}} * L_{sc,2} + L_{nc,2}}{\frac{B_{sc}}{B_{nc}} * L_{sc,1} + L_{nc,1}}$ **for a hybrid RCS as pre-injector**

Optimization: Total Voltage Energy and voltage

Courtesy: A. Chancé

A. Chancé analyzed the parameter space in which 5 TeV can be reached





Conclusion

Courtesy: A. Chancé

- To reach a final energy of 5 TeV, we need a field above 2.2 T.
- To reach a survival above 70%, we need a field slope above 400 T/s.
- To have at the same time a total voltage below 200 GV, a final energy of 5 TeV, and a survival above 70%, we should aim at a value in the HTS of 2.8T and a field slope of 450-500 T/s.