Top-level requirements for RCS, optics and aperture

Mini-Workshop on Rapid Cycled Synchrotrons, pulsed magnets and powering 15 May 2024

Special thanks to Fabian Batsch, Heiko Damerau, David Amorim, Lisa Soubirou, Fulvio Boattini for the slides and provided material

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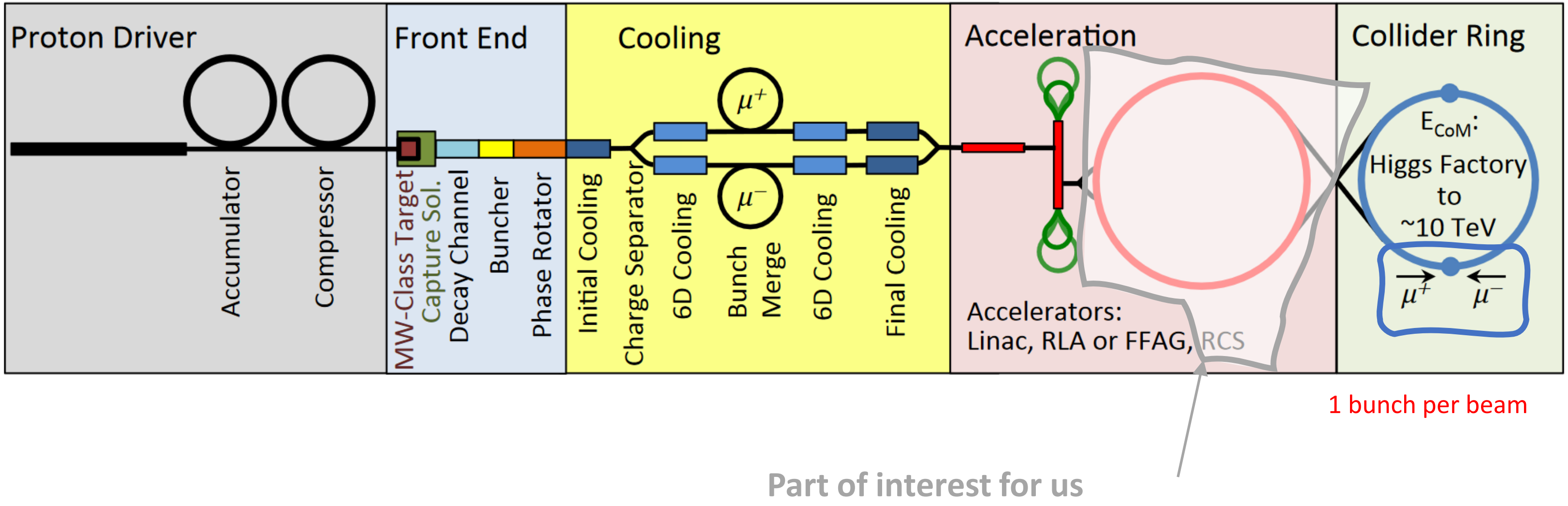
Reminder on design baselines

- Base for the work is the US Muon Accelerator Program (MAP)
- High energy complex consist of a chain of rapid cycling synchrotrons (RCS)



Reminder on design baselines

- Design oriented on reaching the performance parameter [webpage]
- The relevant target parameters are:

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

Top level requirements for the high energy complex (RCS)

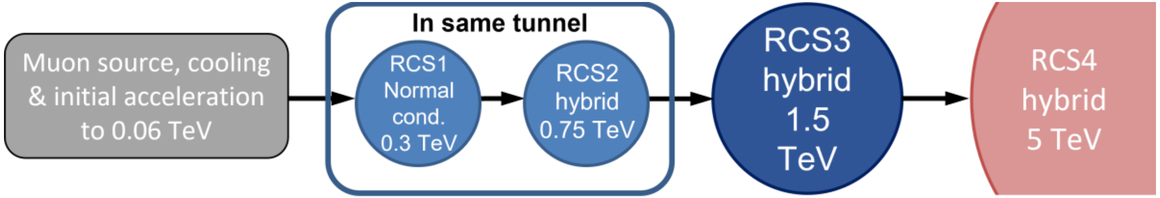
- **Goal:** Accelerate one single bunch beam of μ+/μ-
  - with a **charge of about 2e12** muons/bunch.
  - with a **repetition frequency of 5 Hz**.
  - from **about 63 GeV to 5 TeV**.
- **Figure of merit:**
  - Fast acceleration (the muons decay).
  - Feasible (if possible ;-)).
  - Cost efficient (should be more inexpensive than a 100-km-long linac).
  - Power efficient (do not use a nuclear plant to power the RCS!).

How fast?

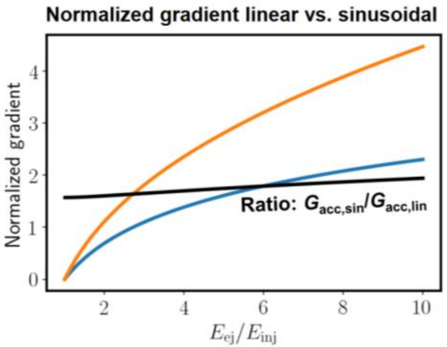
- Muons decay very fast (Rest lifetime: 2.2 μs).
- We should accelerate as fast: τ_{acc} as low as possible.
  - Muon survival: $\frac{N_{ext}}{N_{inj}} = \left(\frac{E_{ext}}{E_{inj}}\right)^{-\frac{\tau_{acc}}{\tau_{\mu}(\gamma_{ext}-\gamma_{inj})}}$ for a linear ramp
  - If we assume only one RCS, we should have $\tau_{acc} = 10$ ms for a transmission of 65%.
  - **The order of magnitude of the total acceleration time is 10 ms!**
- To decrease cost operation, we should:
  - Minimize the total voltage and thus energy gain per turn.
  - ⇒ RCS as small as possible ⇒ high average field.
  - ⇒ Ramp quasi-linear ⇒ Optimize the dipole ramp to minimize the power consumption.
  - Find the best ratio extraction/injection ratio between the different acceleration stages.
- **Tradeoff to find between RF and dipole powering costs.**

The RCSs ramping

- Unchanged RCS chain: 60 GeV → 310 GeV → 750 GeV → 1.5 TeV → 5 TeV



- Optimization problem for up-ramp between sinusoidal optimum for magnet powering and linear optimum for RF
- **Linear ramping**
  - → constant V_{RF}, simplest RF solution, best for μ
  - → unfeasible for magnet powering
- Non-linear ramping → reduced peak power ≙ magnet powering costs, but RF efficiency decreases



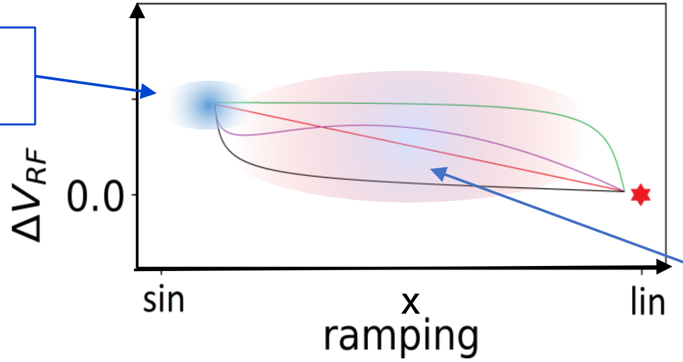
The optimization problem

- Goal: cost-optimized compromise with quasi-linear magnet and RF ramping

50% extra RF voltage
10+5+8+45 = 68 GV

Courtesy: F. Batsch

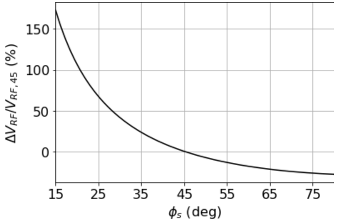
Extra voltage for the 4 RCS



Parameter space for optimization

- The required extra voltage is the sum of the gradient reduction due to nonlinear ramping and changes in the synchronous phase

$$\Delta V_{RF} = \frac{\pi}{2 \cdot arcsin(x)} V_{RF} \cdot \frac{\tau_{acc,lin}(x)}{\tau_{acc,sin}(x)} +$$

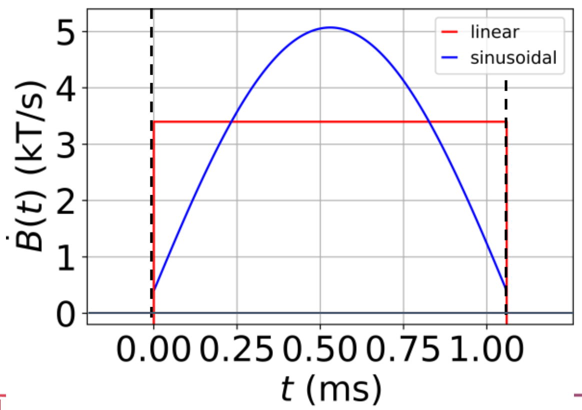


Reminder

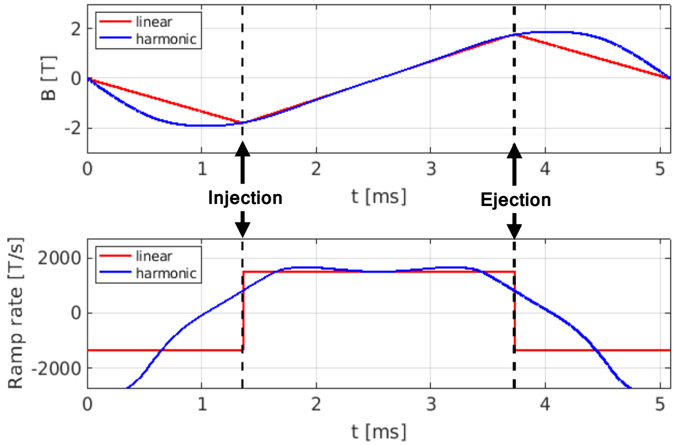
- **Magnet optimization focus on RCS2** as it has the highest ramp rate Ḃ of all hybrid RCS
- 'Quasi-nonlinear' RF necessary → lower RF voltage at beginning and end of the ramp, one maximum within for a chopped sinus, two maxima for a double harmonic approach
- **Maxima define costs!**

Courtesy: F. Batsch

Sinusoidal ramp in RCS2

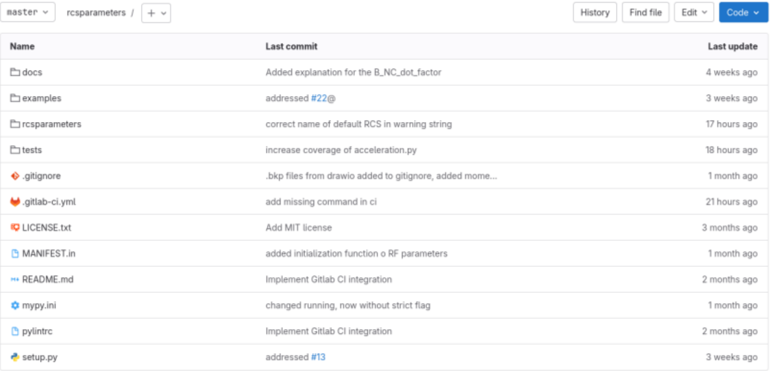


Example for double-harmonic, RCS3



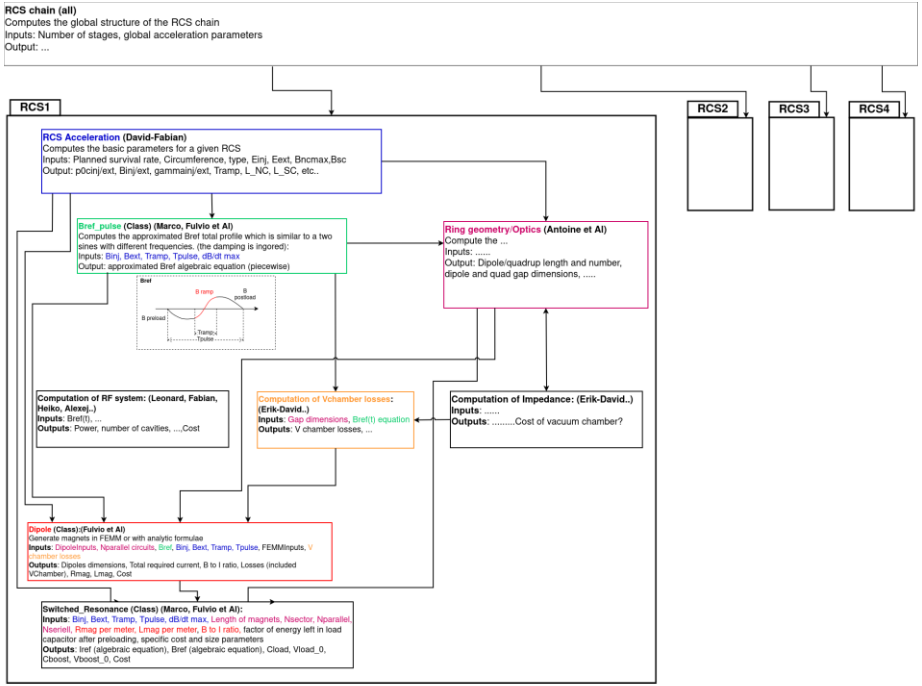
RCS parameter software

- The repository is located at https://gitlab.cern.ch/muon-collider-bd/rcsparameters
- It is currently "Internal", accessible to any person with a CERN account



master ⌄ rcsparameters / + ⌄ History Find file Edit ⌄ Code ⌄

Name	Last commit	Last update
docs	Added explanation for the B_NC_dot_factor	4 weeks ago
examples	addressed #22@	3 weeks ago
rcsparameters	correct name of default RCS in warning string	17 hours ago
tests	increase coverage of acceleration.py	18 hours ago
.gitignore	.bkp files from drawio added to gitignore, added mome...	1 month ago
.gitlab-ci.yml	add missing command in ci	21 hours ago
LICENSE.txt	Add MIT license	3 months ago
MANIFEST.in	added initialization function o RF parameters	1 month ago
README.md	Implement Gitlab CI integration	2 months ago
mypy.ini	changed running, now without strict flag	1 month ago
pylintrc	Implement Gitlab CI integration	2 months ago
setup.py	addressed #13	3 weeks ago



Courtesy: F. Boattini

RCS Parameters to be fixed

Parameters set as global parameters:

- Circumference
- Bunch population at injection
- Number of RF stations n_{RF}
- “Centre” synchronous phase
- Minimal required bucket area / RF filling factor
- Injection and ejection B fields
- Maximum ramp rate $\dot{B}$? E.g. 3 to 4 kT/s

	RCS1→314 GeV	RCS2→750GeV	RCS3→1.5TeV
Circumference, $2\pi R$ [m]	5990	5990	10700
Bunch population [10^{12}]	< 2.7	< 2.43	< 2.2
Survival rate [%]	~90	~90	~90
Acceleration time, t_{acc} [ms]	0.34	1.04	2.37
Number of turns	17	55	66
Energy gain per turn [GeV]	14.8	7.9	11.4
Avg. acc. gradient [MV/m]	2.4	1.3	1.1
Acc. field in RF cavity [MV/m]	30 (45 optimistically)	30	30
“Centre” synchronous phase	45	45	45
Minimal bucket area [eVs]	0.6?	0.6?	0.8?
Injection B field, NC [T]	0.36	-1.8	-1.8
Ejection B field, NC [T]	1.8	1.8	1.8

What RCS shape?

Courtesy: F. Batsch

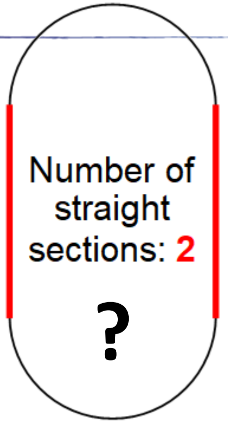
- Number of synchrotron oscillations per turn proportional to $\sqrt{V_{\mathrm{RF}}}$:

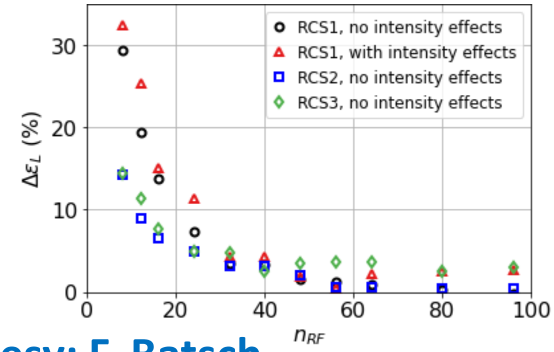
$$Q_S = \frac{\omega_S}{\omega_0} = \sqrt{-\frac{h\eta e V_{\mathrm{RF}} \cos\phi_S}{2\pi E \beta^2}} \propto \sqrt{V_{\mathrm{RF}} \cos\phi_S}$$

LHC: Q_s=0.005

(T. Suzuki, KEK Report 96-10)

- Stable synchrotron oscillations and phase focusing only for $Q_s \ll \frac{1}{\pi}$
- RCSs would exceed this limit: $0.3 < Q_s < 1.5$
  - Several longitudinal kicks per turn for small Qs between stations, i.e., small Q_s/n_{RF}
  - Distribute RF system over n_{RF} sections





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What RCS shape?

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$$Q_{\mathrm{S}} = \frac{\omega_{\mathrm{S}}}{\omega_0} = \sqrt{-\frac{h\eta e V_{\mathrm{RF}} \cos\phi_{\mathrm{S}}}{2\pi E \beta^2}} \propto \sqrt{V_{\mathrm{RF}} \cos\phi_{\mathrm{S}}}$$

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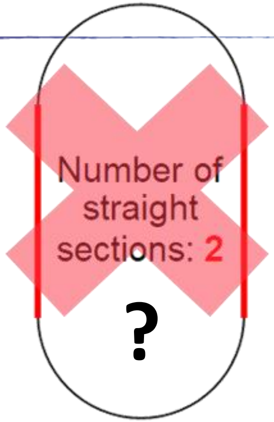
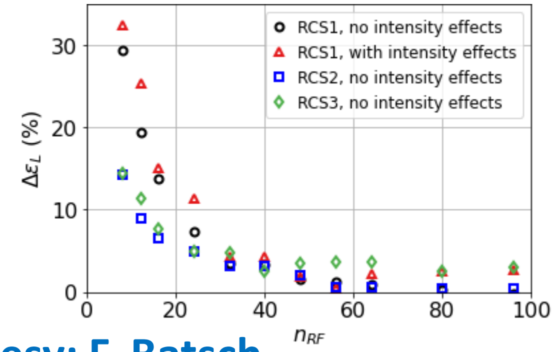


- Stable synchrotron oscillations and phase focusing only for $Q_s \ll \frac{1}{\pi}$
- RCSs would exceed this limit: 0.3 < Q_s < 1.5
  - Several longitudinal kicks per turn for small Qs between stations, i.e., small Q_s/n_{RF}
  - Distribute RF system over n_{RF} sections
- **n_{RF} is an important quantity to determine!**
  - → 32 for first RCS, 24 for higher energy.
- n_{RF} gives also the minimum number of arcs.



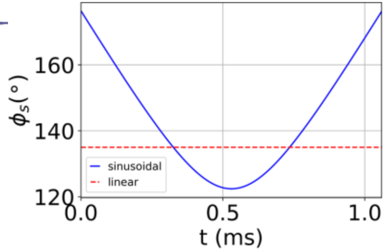
Courtesy: F. Batsch

RF parameters to be optimized

- Need for optimization of **voltage distribution** between the RCSs (i.e., different decays per RCS, but same total survival rate):

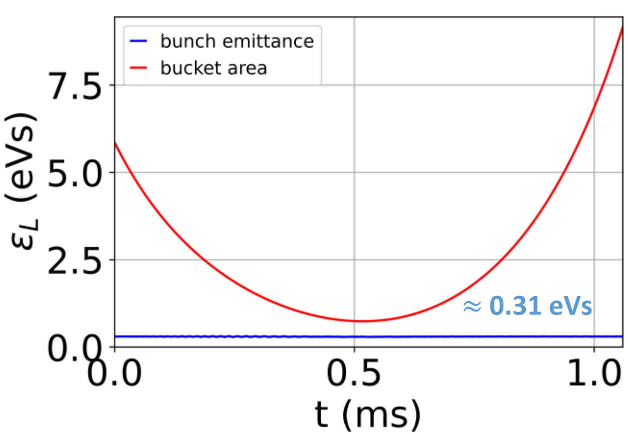
	RCS1→314 GeV	RCS2→750GeV	RCS3→1.5TeV
Circumference, $2\pi R$ [m]	5990	5990	10700
Bunch population [10^{12}]	< 2.7	< 2.43	< 2.2
Survival rate [%]	~90	~90	~90
Acceleration time, t_{acc} [ms]	0.34	1.04	2.37
Number of turns	17	55	66
Energy gain per turn [GeV]	14.8	7.9	11.4
Avg. acc. gradient [MV/m]	2.4	1.3	1.1

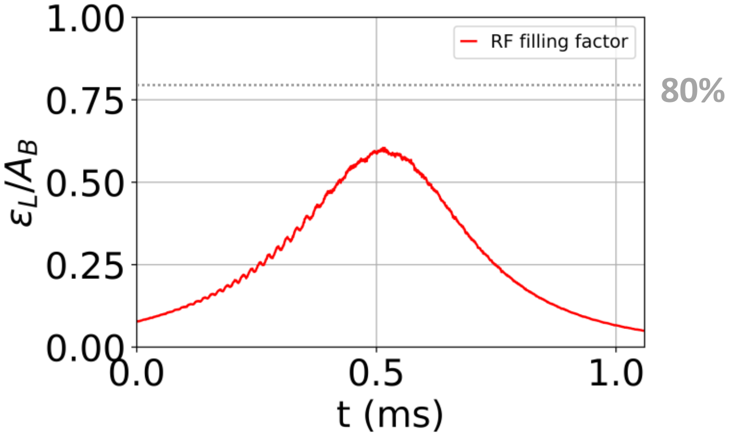
Synchronous phase choice



- Adjusting the RF voltage by allowing $\boldsymbol{\phi_s}$ to change
- Need for optimization of synchronous phase and bucket area

→ $\boldsymbol{V(t)}$ and $\boldsymbol{\phi_s(t)}$ define available bucket area $\boldsymbol{A_{\mathrm{B}}(t)}$ and bucket filling factor





Example of optimization with genetic algorithm

- Thanks to the class properties of the rcsparameters software, it is easy to change input parameters and see the impact on following properties.
- This opens the way to **optimization tools**: notebook example of an optimization using MOGA → allows to explore a wider range of parameters for our RCS chain
- **The values shown afterwards are just for example**

Case 1: LHC tunnel for RCS 4

- Objectives: Maximize final energy and minimize average gradient to keep the total number of RF cavities low.

Courtesy: D. Amorim

- **The maximum energy reached is 4.1 TeV**, keeping the dipole packing factor in the RCS below the 70 % asked in the simulation parameters The overall muon transmission rate is 0.83×0.92×0.94× 0.95 = 0.68.

Parameter	RCS 1	RCS 2	RCS 3	RCS 4
Circumference [m]	5990	5990	10700	27600
Normal-conducting magnet field [T]	1.8	1.8	1.8	1.8
Super-conducting magnet field [T]	10	10	10	16
Total transmission N_4/N_0			≥ 0.65	
Maximum packing factor	0.66	0.66	0.66	0.7
Ejection energy [GeV]	[250; 450]	[500; 1100]	[1150; 3000]	[3500; 5000]
Transmission rate [-]	[0.8; 0.95]	[0.8; 0.95]	[0.8; 0.95]	[0.8, 0.95]

Table 1: Parameters used for the "RCS 4 in LHC tunnel" optimization.

Parameter	Symbol	Unit	RCS 1	RCS 2	RCS 3	RCS 4
Injection energy	E_{inj}	[GeV/u]	63	305	742.4	1500
Ejection energy	E_{ej}	[GeV/u]	305	742.4	1500	4100
Energy ratio	$E_{\mathrm{ej}}/E_{\mathrm{inj}}$	[-]	4.8	2.4	2.1	2.7
Survival rate	$N_{\mathrm{ej}}/N_{\mathrm{inj}}$	[-]	0.83	0.92	0.94	0.95
Acceleration time	τ_{acc}	[ms]	0.603	0.867	1.4	3.0
Average accel. gradient	G_{avg}	[MV/m]	1.3	1.7	1.9	2.8
Ramp rate	$\dot{B}_{\mathrm{NC}}$	[kT/s]	2.4	4.2	2.5	1.2
Pack fraction	-	[-]	0.59	0.61	0.66	0.70

Table 2: Summarized results of the "RCS 4 in LHC tunnel" optimization.

Case 2: SPS tunnel for RCS 1 and RCS 2, and the LHC tunnel for RCS 4

- Objectives: Maximize final energy and minimize average gradient to keep the total number of RF cavities low.

Courtesy: D. Amorim

- **The maximum energy reached is 4.15 TeV**, keeping the dipole packing factor in the RCS below the 70 % asked in the simulation parameters The overall muon transmission rate is 0.92×0.93×0.88× 0.90 = 0.68.

Parameter	RCS 1	RCS 2	RCS 3	RCS 4
Circumference [m]	6900	6900	10700	27600
Normal-conducting magnet field [T]	1.8	1.8	1.8	1.8
Super-conducting magnet field [T]	10	10	10	16
Total transmission N_4/N_0		≥ 0.65		
Maximum packing factor	0.66	0.66	0.66	0.7
Ejection energy [GeV]	[250; 450]	[500; 1100]	[1150; 3000]	[3500; 5000]
Transmission rate [-]	[0.8; 0.95]	[0.8; 0.95]	[0.8; 0.95]	[0.8, 0.95]

Table 3: Parameters used for the "RCS in the SPS and LHC tunnels" optimization.

Parameter	Symbol	Unit	RCS 1	RCS 2	RCS 3	RCS 4
Injection energy	E_{inj}	[GeV/u]	63.0	373.5	853.0	1602
Ejection energy	E_{ej}	[GeV/u]	373.5	853.0	1602	4152
Energy ratio	E_{ej}/E_{inj}	[-]	5.9	2.3	1.9	2.6
Survival rate	N_{ej}/N_{inj}	[-]	0.92	0.93	0.88	0.90
Acceleration time	τ_{acc}	[ms]	0.284	0.939	3.2	5.6
Average accel. gradient	G_{avg}	[MV/m]	3.6	1.7	0.78	1.5
Ramp rate	$\dot{B}_{NC}$	[kT/s]	5.3	3.8	1.1	0.64
Pack fraction	-	[-]	0.63	0.59	0.65	0.70

Table 4: Summarized results of the "RCS 4 in LHC tunnel" optimization.

Case 2: SPS tunnel for RCS 1 and RCS 2, and the LHC tunnel for RCS 4

- Objectives: Maximize final energy and minimize average gradient to keep the total number of RF cavities low.

Courtesy: D. Amorim

- **The maximum energy can reach 5 TeV** if packing factor up to 80% and a peak NC dipole field of 2.0 T instead of 1.8 T.

Parameter	RCS 1	RCS 2	RCS 3	RCS 4
Circumference [m]	6900	6900	10700	27600
Normal-conducting magnet field [T]	1.8	1.8	1.8	1.8
Super-conducting magnet field [T]	10	10	10	16
Total transmission N_4/N_0		≥ 0.65		
Maximum packing factor	0.66	0.66	0.66	0.7
Ejection energy [GeV]	[250; 450]	[500; 1100]	[1150; 3000]	[3500; 5000]
Transmission rate [-]	[0.8; 0.95]	[0.8; 0.95]	[0.8; 0.95]	[0.8, 0.95]

Table 3: Parameters used for the "RCS in the SPS and LHC tunnels" optimization.

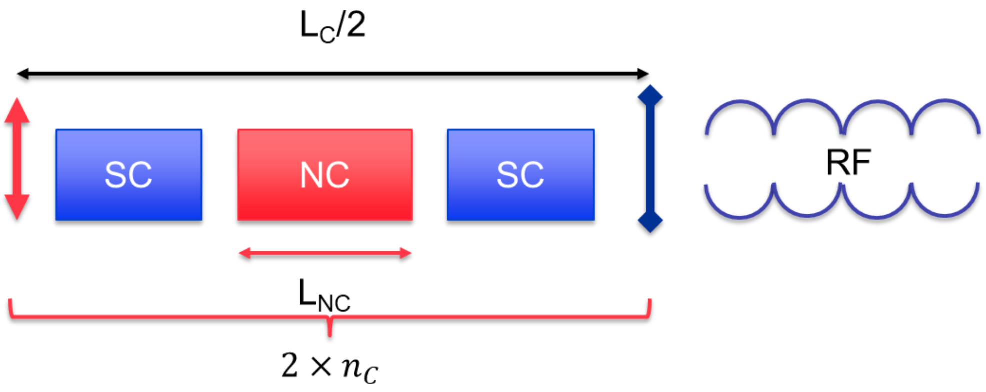
NC magnet field [T]	Pack fraction RCS 4	Energy reach [TeV]
1.8	0.7	4.1
	0.75	4.3
	0.8	4.5
2.0	0.7	4.5
	0.75	4.8
	0.8	5.0

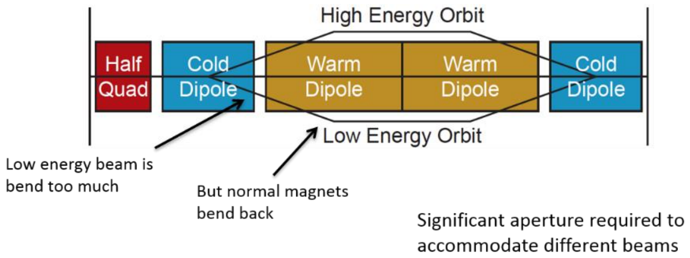
Genetic optimization

- A lot of parameters of the RCS chain can be quickly computed given a few input parameters:
  - Top level parameters of the RCS Chain and of each RCS
  - Normal conducting magnets ramp profile and powering requirements
  - RF cavities properties and associated hardware requirements
  - The cost models are also included in the tool
- This can be used for general optimization of the RCS chain, or specific optimization for each RCS
- The genetic optimizer coupled with the rcsparameter software enables a great flexibility for the optimization of the parameters.
  - We can also include constraints on the maximum field slope, maximum peak field, maximum RF gradient (linked to the pack factor)…
  - We can also explore other scenarios: 2 RCS in LHC tunnel, different circumference for RCS3,…

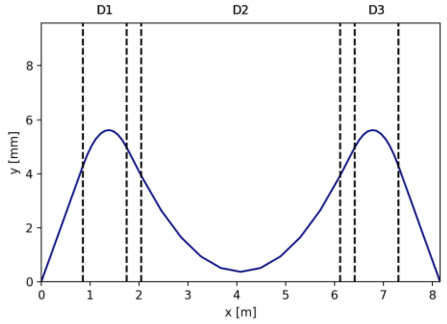
What RCS pattern?

- We assume an RCS made of FODO cells with phase advances of 90°.
- The number of cells has been optimized to maximize the arc filling ratio.

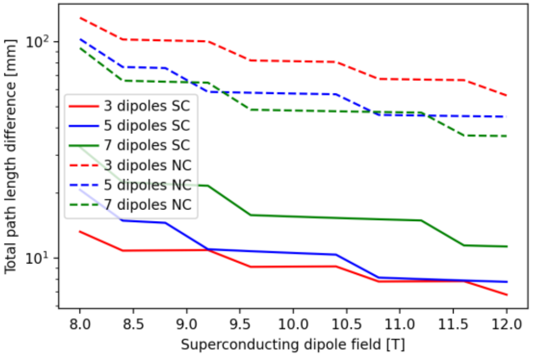


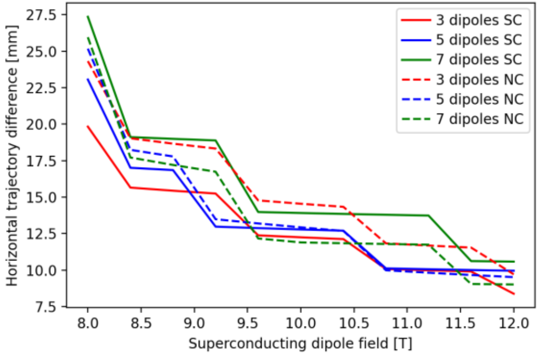


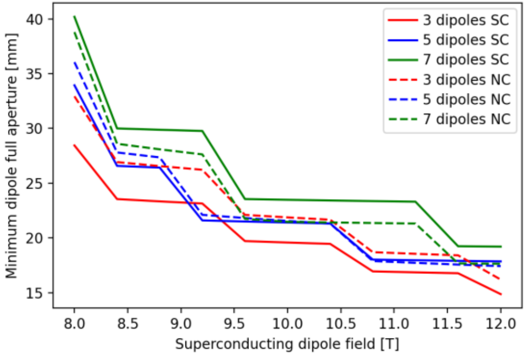
- How many cells per arc? How many dipoles per cell?
- Which field?



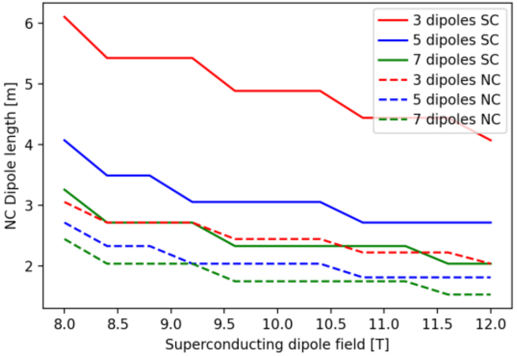
Reminder RCS2: variation with SC dipole field (to be updated)

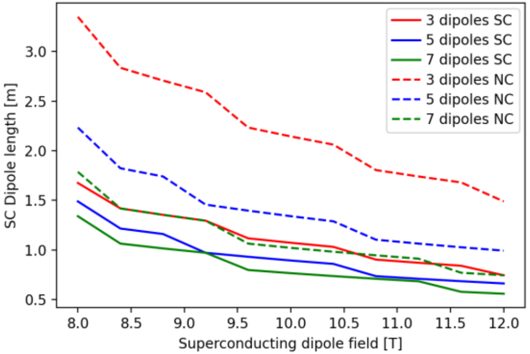


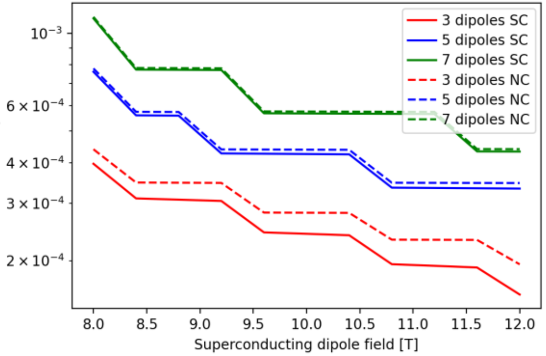




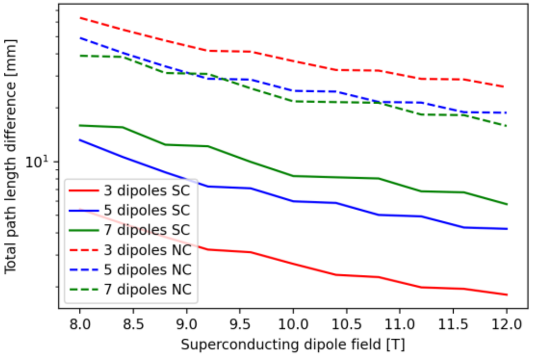
See Soubirou's presentation about the good field region

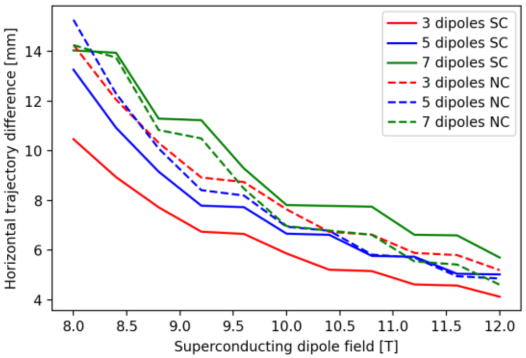


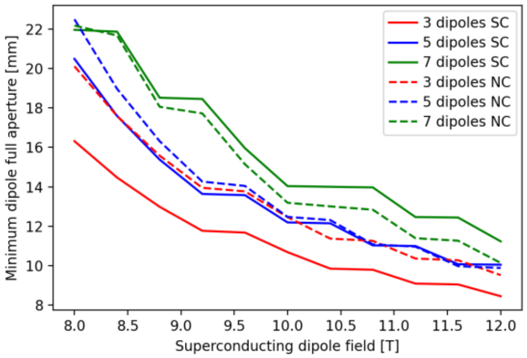


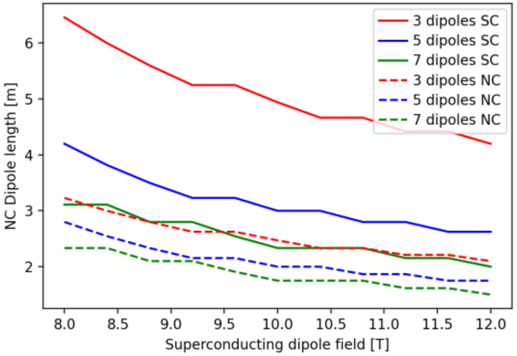


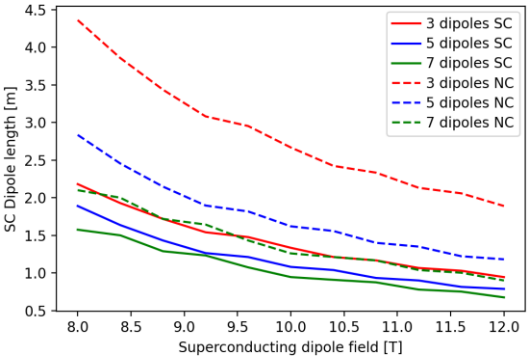
Reminder RCS3: variation with SC dipole field (to be updated)

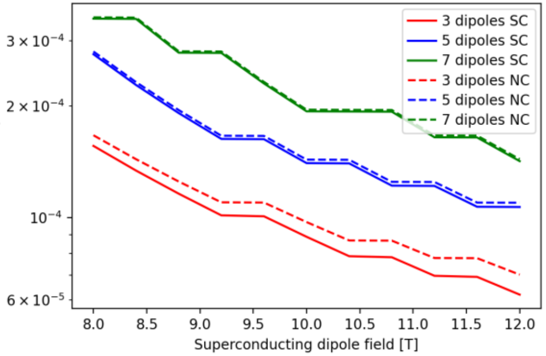












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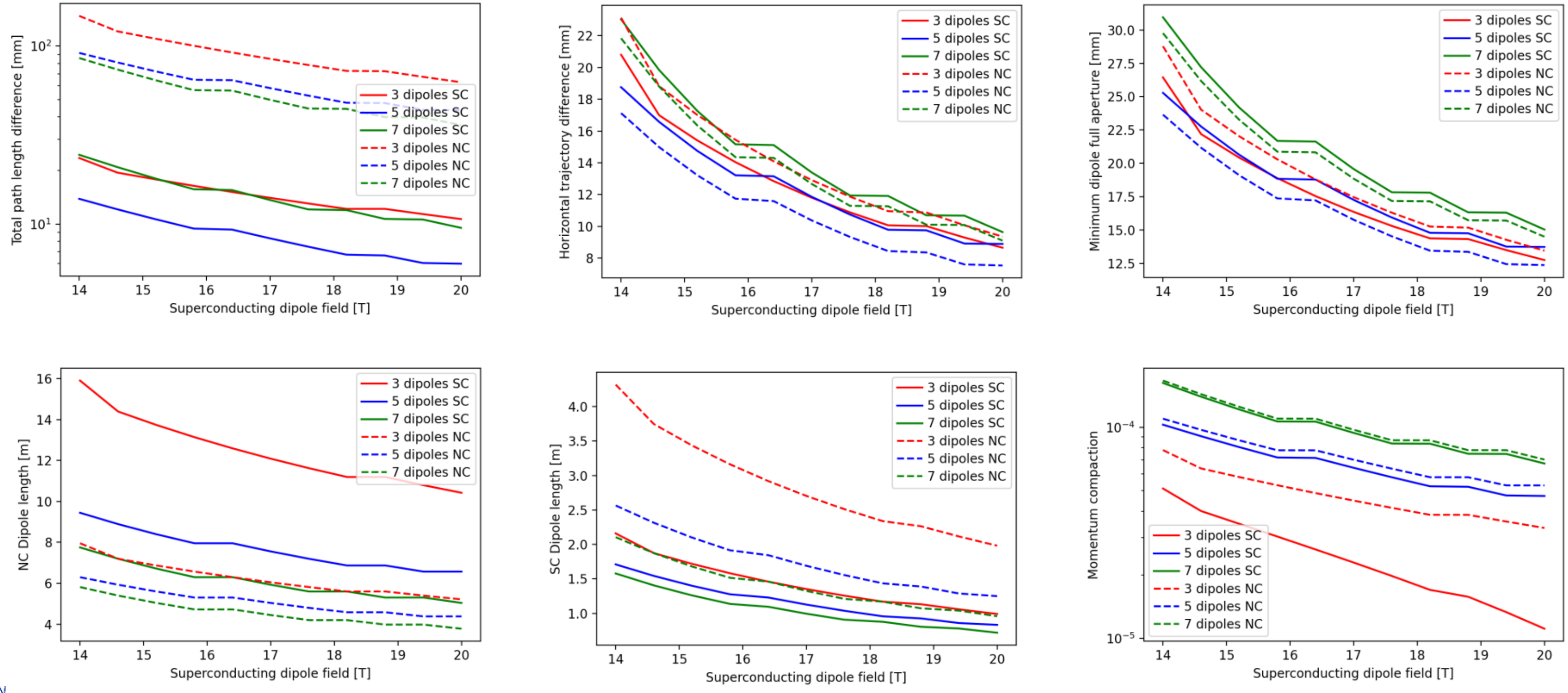
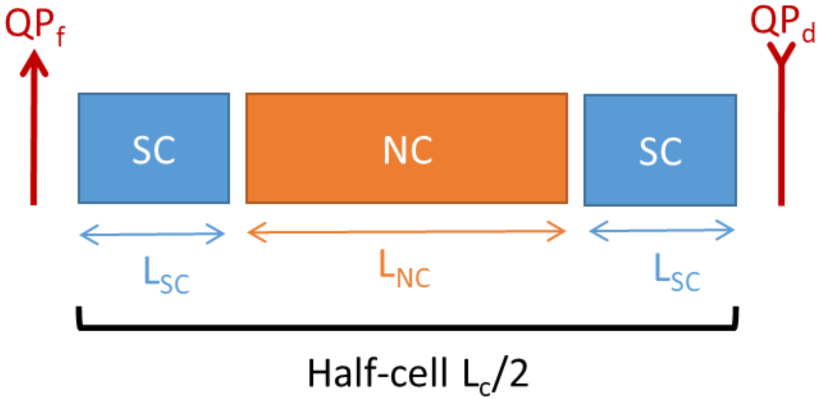


Geometry in Xsuite

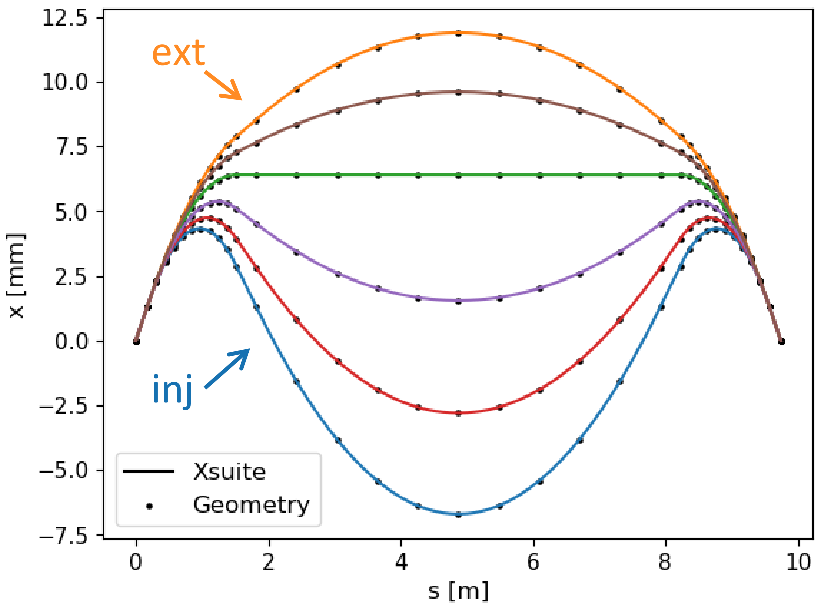
- First tests in Xsuite using the geometry class
- Study: RCS2, hybrid synchrotron
- FODO cells: μ=90°
- Study of a half-cell.

RCS 2
C = 5990 m
n_a = 26 arcs
n_c = 8 cells per arc
pattern: [SC,NC,SC]

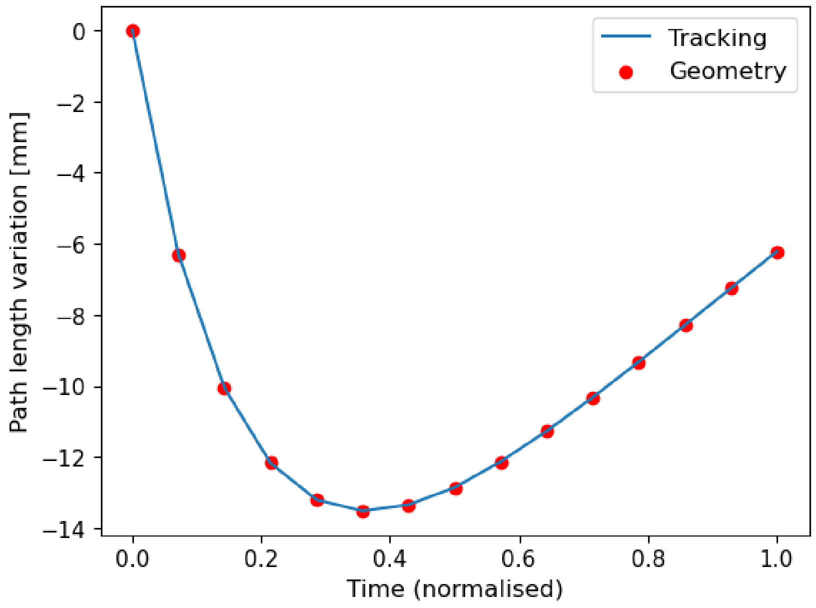


RCS 2, hybrid
Pattern of half-cell: BSC, BNC, BSC

Trajectories from injection to extraction



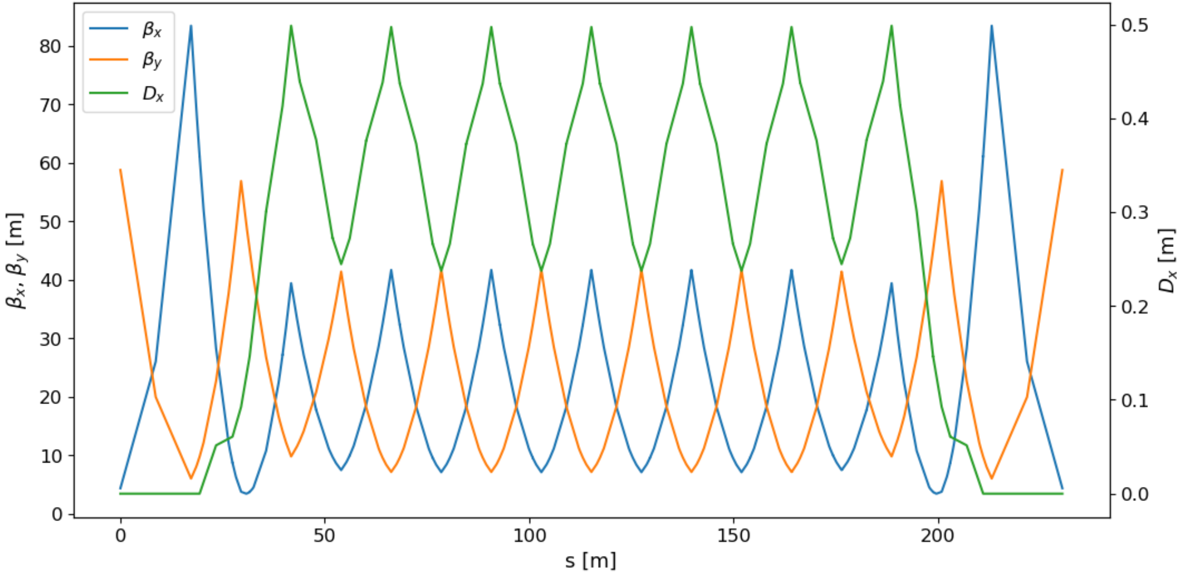
Path length variation from injection



Consistent with results from geometry class !

Preliminary optics of RCS2

At injection



Courtesy: L. Soubirou

RCS 2
C = 5990 m
n_a = 26 arcs
n_c = 8 cells per arc

- FODO structure
- Thin multipole approximation
- Dispersion suppressor for RF insertion
- Cavity in RF insertion + Kick in energy integrated

Optic and machine parameters

RCS 2	
Momentum compaction factor α_c	0.00032
Horizontal tune Q_x	67.775
Vertical tune Q_y	58. 552
Natural horizontal chromaticity	-101.7
Natural vertical chromaticity	-80.8
Synchrotron tune Q_s	0.181

RF	
Total Voltage	11.22 GV
Synchronous phase ϕ_s	45° (ϕ=180-45°)
Frequency	1.3 GHz

Normalized integrated strength of quads	1/m
Quad FODO	+/- 0.116
Quad DS foc	0.114, 0,138, 0,121
Quad DS defoc	-0.108, -0.116, -0.051

Summary

- A tool has been developed to help in determining the RCS parameters. There is still a room for optimization but the main lessons/needs are:
  - The ramp should be as linear as possible to minimize the total RF voltage.
  - To reach a total survival rate above 65%, we need pulsed magnets with a peak slope of 3-5 kT/s.
  - Higher peak field, especially for the RCS4, helps in reaching higher extraction energy.
  - We need to distribute the RF along the RCS to avoid losing the beam or a dramatic longitudinal emittance growth. The RF cavities should be integrated in the lattice.
  - The hybrid cell begins with a SC dipole instead of a NC dipole: the trajectory variation will be much larger in the NC dipole.

Dipole aperture

- The current lattice is very preliminary and needs some optimization (chromatic terms) + we need to compare with other cell structures (multi-bend,…) but only the beam size has been considered.
- The aperture for the beam is rectangular because of the horizontal trajectory variation but we need:
  - To evaluate the minimum required beam vacuum radius for collective effects.
  - Due to the trajectory variation, the aperture needs in the SC and NC dipoles are different. What are the allowed transitions between the vacuum chamber in the pulsed magnets (Eddy currents) and the one in the SC dipoles?
  - Can we move transversally the center of the vacuum chamber from a dipole to another?
  - To integrate the needs for machine protection and radiation issues.
  - To ad some margins due to the jitter on the pulsed magnet field.

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Case 1: LHC tunnel for RCS 4

Parameter	Symbol	Unit	RCS 1	RCS 2	RCS 3	RCS 4
Injection energy	E_{inj}	[eV/u]	63.0G	305.0G	742.4G	1.5T
Ejection energy	E_{ej}	[eV/u]	305.0G	742.4G	1.5T	4.1T
Energy ratio	$E_{\text{ej}}/E_{\text{inj}}$	[-]	4.8	2.4	2.1	2.7
Injection Lorentz factor	γ_{inj}	[-]	597.3	2.9k	7.0k	14.6k
Ejection Lorentz factor	γ_{ej}	[-]	2.9k	7.0k	14.6k	38.8k
Survival rate	$N_{\text{ej}}/N_{\text{inj}}$	[-]	0.83	0.92	0.94	0.95
Acceleration time	τ_{acc}	[s]	603.4u	866.9u	1.4m	3.0m
Average accel. gradient	G_{avg}	[V/m]	1.3M	1.7M	1.9M	2.8M
Ramp rate	$\dot{B}_{\text{NC}}$	[T/s]	2.4k	4.2k	2.5k	1.2k
Machine radius	R	[m]	953.3	953.3	1.7k	4.2k
Circumference	$2\pi R$	[m]	6.0k	6.0k	10.7k	26.6k
Pack fraction	-	[-]	0.59	0.61	0.66	0.70
Bend radius	ρ_B	[m]	565.3	580.0	1.1k	3.0k
Total NC dipole length	L_{NC}	[m]	3.6k	2.5k	4.7k	14.9k
Total SC dipole length	L_{SC}	[m]	0.0	1.1k	2.4k	3.7k
SC dipole field	B_{SC}	[T]	10.0	10.0	10.0	16.0
Average Injection dipole field	B_{inj}	[T]	372.4m	1.8	2.2	1.7
Average ejection dipole field	B_{ej}	[T]	1.8	4.3	4.6	4.6
Injection NC dipole field	$B_{\text{NC,inj}}$	[T]	372.4m	-1.8	-1.8	-1.8
Ejection NC dipole field	$B_{\text{NC,ej}}$	[T]	1.8	1.8	1.8	1.8

Table 6: Detailed results of the "RCS 4 in LHC tunnel" optimization.

Courtesy: D. Amorim

Case 2: SPS tunnel for RCS 1 and RCS 2, and the LHC tunnel for RCS 4

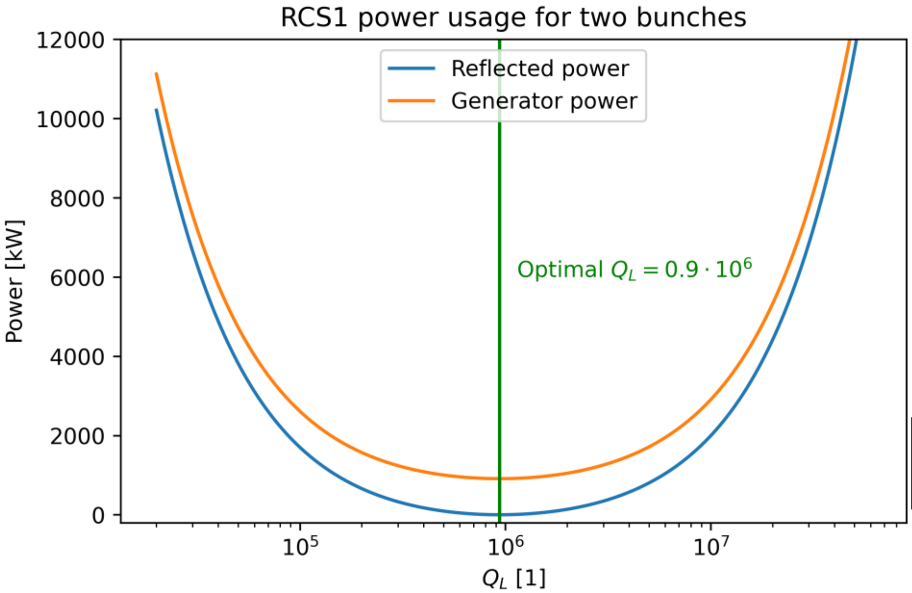
Parameter	Symbol	Unit	RCS 1	RCS 2	RCS 3	RCS 4
Injection energy	E_{inj}	[eV/u]	63.0G	373.5G	853.0G	1.6T
Ejection energy	E_{ej}	[eV/u]	373.5G	853.0G	1.6T	4.2T
Energy ratio	$E_{\mathrm{ej}}/E_{\mathrm{inj}}$	[-]	5.9	2.3	1.9	2.6
Injection Lorentz factor	γ_{inj}	[-]	597.3	3.5k	8.1k	15.2k
Ejection Lorentz factor	γ_{ej}	[-]	3.5k	8.1k	15.2k	39.3k
Survival rate	$N_{\mathrm{ej}}/N_{\mathrm{inj}}$	[-]	0.92	0.93	0.88	0.90
Acceleration time	τ_{acc}	[s]	284.4u	938.8u	3.2m	5.6m
Average accel. gradient	G_{avg}	[V/m]	3.6M	1.7M	778.0k	1.5M
Ramp rate	$\dot{B}_{\mathrm{NC}}$	[T/s]	5.3k	3.8k	1.1k	638.0
Machine radius	R	[m]	1.1k	1.1k	1.7k	4.2k
Circumference	$2\pi R$	[m]	6.9k	6.9k	10.7k	26.6k
Pack fraction	-	[-]	0.63	0.59	0.65	0.70
Bend radius	ρ_B	[m]	692.4	648.9	1.1k	3.0k
Total NC dipole length	L_{NC}	[m]	4.4k	2.8k	4.4k	14.8k
Total SC dipole length	L_{SC}	[m]	0.0	1.3k	2.6k	3.8k
SC dipole field	B_{SC}	[T]	10.0	10.0	10.0	16.0
Average Injection dipole field	B_{inj}	[T]	304.0m	1.9	2.6	1.8
Average ejection dipole field	B_{ej}	[T]	1.8	4.4	4.8	4.7
Injection NC dipole field	$B_{\mathrm{NC,inj}}$	[T]	304.0m	-1.8	-1.8	-1.8
Ejection NC dipole field	$B_{\mathrm{NC,ej}}$	[T]	1.8	1.8	1.8	1.8

Table 7: Detailed results of the "RCS 4 in LHC tunnel" optimization.

Courtesy: D. Amorim

Quality factor optimization

- Decrease Q_L away from optimal value to (partially) mitigate multi-turn beam loading, even though the reflected power is increased:



Alternatively:
Increase RF voltage to compensate beam loading

From L. Thiele, see his presentation afterwards

Overview over RF calculations

Overall flow in the python package:

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

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

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

$B(t)$, $\dot{B}(t)$ (and parameters from higher instances)

↓

$\gamma(t)$, $E(t)$, $G_{acc}(t)$ → Max. gradient & number of cavities for costs

↓

$\phi_s(t)$, $V_{acc}(t)$

↓

Bucket area $A_B(t)$, bucket filling factor and other criteria