

MInternational UON Collider Collaboration

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RCS parameters and optimization

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Reminder on design baselines

- Base for the work is the US <u>Muon Accelerator Program</u> (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: [presentation by D. Schulte]

Parameter	Unit	3 TeV	10 TeV	
L	10 ³⁴ cm ⁻² s ⁻¹	1.8	20	Repetition rate of 5 Hz \rightarrow RCS
Ν	1012	2.2	1.8	
f _r	Hz	5	5	
 (average)	т	7	10.5	
ε _L (norm, 1σ _z σ _E)	MeV m	7.5	7.5 🥆	
σ _E / E	%	0.1	0.1	
σ _z	mm	5	1.5	



The high-energy complex



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



- Hybrid RCSs have interleaved normal conducting (NC) and superconducting (SC) magnets.
- 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_{sc} = 10 T
- NC magnets require fast ramping within $B_{nc} = \pm 1.8$ T

Decided for realistic values: below saturation of both technologies

- Beam orbit not constant during acceleration
 - \rightarrow Orbit length and frev \neq const.
 - \rightarrow f_{RF} tuning must be provided





RCS Lattice

- Currently, we assume the RCS is made of FODO cells with phase advances of 90 degrees.
 - We assume we have nc cells of length Lc per arc and na arcs per RCS.
 - The muon beams run nt turns of length LRCS.
- The number of cells has been optimized to maximize the arc filling ratio.





Trajectory during ramp

- From injection to extraction the trajectory goes from the inner side to the outer side.
- The trajectory difference goes up to more than 13 mm.



RCS3





Path lenth variation





RCS2: variation with SC dipole field





U_____



RCS4: variation with SC dipole field





Parameters and tools: General parameter



brid RCS 2.37 750000

1703.0 10700 1.79 0.628 1070.2 3975.7 2.34

TESLA 1300 46367 28.04 335.7 16.07 0.45 300 9-cell 536 536 536 536 300 4.0 9.0 4.0 9.0 4.5 331.72 0.025 0.079 1.400

0.172

Detailed parameter table: [link]

	RCS1 → 314 GeV	RCS2 → 750GeV	RCS3 → 1.5TeV	1) 13 Basic data 15 Particles 16 Costs 17 Type	Symbol -	Unit - MC	Stage 1 Value Details μ RCS	Stage 2 Value Dotal U hybrid RCS	Stage 3 Js Value μ hybrid RCS
Circumference, $2\pi R$ [m]	5990	5590	10700	Dynamics Dynamics Acceleration time Injection energy Ejection energy		(ms) (MeV)/u (MeV)/u	0.34 63000 313830 defined by n	1.09704595 313830 750000	750
Energy factor, $E_{\rm ei}/E_{\rm ini}$	5.0	2.4	2.0	Energy ratio A Momentum at e Momentum at e Momentum at e Momentum at e Planned Survival rate	E _u /E _N pic pic n _{un} N_/N _u	MeV/c MeV/c	4.98 63106 313935 17 0.9	2.39 313935 750106 55 0.9	75 150
Repetition rate, f_{rep} [Hz]	5 (asym.)	5 (asym.)	5 (asym.)	Total survival rate Accel. Gradient, linear for survival Required energy gain per turn Transition gamma	N _a IN _o G ME	[MV/m] [MeV]	0.9 2.44 14755 20.41	0.81 1.33 7930 20.41	0
Number of bunches	1μ ⁺ , 1μ ⁻	1μ+, 1μ ⁻	1μ ⁺ , 1μ ⁻	Injection relativistic mass factor Ejection relativistic mass factor Injection v/c Ejection v/c	T _{ai} T _a B _{ai} B _a	- - %	597 2971 0.9999986 0.99999943	2971 7099 0.99999943 0.999999901	7 14 0.9999999 0.9999999
Bunch population	>2.5E12	>2.3E12	2.2E12	Parameter Classical RCS Radius Circumference Circumference Ratio Pack fraction	R 2πR R _{ps} /R, ?	(m) (m) -	953.3 5990 0.61	963.3 5990 1 0.61	17
Survival rate per ring	90%	9 <u>0%</u>	90%	Bend radius Tot. straight section length Injection bending field (average) RE Systems	Pg L _{at} B _{at}	m (m) (T)	581.8 2334.7 0.36 TESLA	581.8 2335.7 1.80 TESLA	10 39 TE:
Acceleration time, $t_{\rm acc}$ [ms]	0.34	1.04	2.37	77 Main RF frequency 70 Harmonic number 70 Revolution frequency sj 80 Revolution period 81 Max RF voltage	f _{ss} h f _{orr} Trev V _a	[MHz] - [kHz] [jus] [QV]	1300 25957 50.08 20.0 20.87	1300 25957 50.08 20.0 11.22	1 46 28 3
Number of turns	17	55	66	Rick Or porter Rick Or		· · · ·	0.4 Around 50 9-cell 696	0.4 Around 50 9-cell 374	Around 9-
Energy gain per turn, ΔE [GeV] (14.8	7.9	(11.4)	8 Gradient in cavity 9 Average energy gain per total straight Accelerating field per total straight Accelerating field gradient, with FF Stable phase Conversion forther mm mrad _ eVin	ΔΕ/L ΔΕ/L ΔΕ/L ΔΕ/L ψ,	[MV/m] [MeV/m] [MeV/m] [MV/m] [*]	30 6.3 8.9 22.3 45 69.40	30 3.4 4.8 12.0 45	221
Acc. gradient for survival [MV/m]	2.4	1.3	(1.1)	2 Constitutinal emittance (off: 4 doz) 2 Longitudinal emittance (off: 4 doz) 3 Longitudinal emittance (phase space area) 3 Injection bucket area 37 Ejection bucket area 48 Bucket area reduction factor		[eVs] [eVs] [eVs] [eVs]	0.0257.5 MeV m 0.079 0.62 1.37 0.172	0.025 0.079 1.01 1.56 0.172	0.
Acc. field in RF cavity [MV/m]	30 (45 optimistically)	30	30	Horizontal betatron tune Vertical betatron tune Average horizontal Twiss beta Average vertical Twiss beta Injection synchrotron frequency	Q _b Q _y Bh Bv	- [m] [m] [kHz]	10 10 76.33	10 10 25.07	14



Parameters and tools: General parameter



76.33

34.20 1.52

25.07

16.22

0.50 0.32

13

Average vertical Twiss beta

Injection synchrotron frequence

ction synchrotron freque

ection synchrotron tune

14.53

10.27

0.52

Detailed parameter table: [link]

	RCS1→314 GeV	RCS2-→750GeV	RCS3 → 1.5TeV	19 Basic data 19 Particles 19 Costs	Symbol -	Unit	Stage 1 Value Details µ	Stage 2 Value	Details Value
Circumference, $2\pi R$ [m]	5990	5590	10700	10 Type 10 Dynamics 21 Injection energy 22 Ejection energy		[ms] [MeV]/u [MeV]/u	0.34 63000 313830 defined by	1.09704595 313830 750000	2.37 750000 1500000
Energy factor, $E_{\rm ei}/E_{\rm inj}$	5.0	2.4	2.0	Energy ratio Momentum at e Momentum at e Momentum at e Momentum at e Planned Survival rate	E _u /E _w p/c P _{oun} N _u /N _w	MeV/c MeV/c	4.98 63106 313935 17 0.9	2.39 313935 750106 55 0.9	2.00 750106 1500106 66 0.9
Repetition rate, f _{rep} [Hz]	5 (asym.)	5 (asym.)	5 (asym.)	Accel. Gradient, linear for survival Required energy gain per turn Transition gamma Hendles energy for the second seco	К ₀ /И, G ЛЕ 7,	[MV/m] [MeV]	0.9 2.44 14755 20.41	0.81 1.33 7930 20.41	0.729 1.06 11364
Number of bunches	1μ+, 1μ ⁻	1μ+, 1μ ⁻	1μ+, 1μ ⁻	injection relativistic mass factor if Ejection relativistic mass factor if Injection v/c Ejection v/c Ej	T _a T _a B _a B _a	- - %	2971 0.9999986 0.99999943	2971 7099 0.999999943 0.999999901	14198 0.9999999901 0.9999999975
Bunch population	>2.5E12	>2.3E12	2.2E12	a Radius a Radius a Circumference Ratio a Pack fraction a Pack fraction a Bend radius a	R 2xR R _{p1} /R, ? P3	(m) (m) -	963.3 5990 0.61 581.8	953.3 5990 1 0.61 581.8	1703.0 10700 1.79 0.628 1070.2
Survival rate per ring	90%	90%	90%	Tot. straight section length finjection bending field (average) RF Systems Main RF frequency	L.,, B.,, I.,,	(m) (T) [MHz]	2334.7 0.36 TESLA 1300	2335.7 1.80 TESLA 1300	3975.7 2.34 TESLA 1300
Acceleration time, t_{acc} [ms]	0.34	1.04	2.37	Parmonic number Revolution frequency ej Revolution period Max RF voltage Max RF pover Rev Filling factor	h I _{orr} Trev V _{ii} E _{ii}	[kHz] [µs] [GV] [MW]	25957 50.08 20.0 20.87	25957 50.08 20.0 11.22	46367 28.04 35.7 16.07 0.45
Number of turns	17	55	66	Number RF stations Cavities Number of cavities Number of cavities Peak Impedance Gradient in cavity Aurace energy cain per total straight	· ? 		Around 50 9-cell 696 30	Around 50 9-cell 374 30	Around 50 9-cell 536 30
Energy gain per turn, ΔE [GeV]	14.8	7.9	11.4	Prevenge energy gam per total solargin Accelerating field per total straight Accelerating field gradient, with FF Stable phase Conversion factor mm mrad – eVs Accelerating field emittance (of 4 4 oz)	ΔΕ/L ΔΕ/L Φ, -	[MeV/m] [MV/m] [*] Vsimm mr#	6.3 8.9 22.3 45 69.40 0.0257.5 MeV m	4.8 4.8 12.0 45 165.86 0.025	4.0 9.0 45 331.72 0.025
Acc. gradient for survival [MV/m]	2.4	1.3	1.1	Kongitudinal emittance (phase space area) Injection bucket area Ejection bucket area Bucket area reduction factor Horizontal betatron tune	S ¹ A _{sol} A _{sol} A _b /A _{bot}	[eVs] [eVs] [eVs]	0.079 0.62 1.37 0.172	0.079 1.01 1.56 0.172	0.079 1.40 1.97 0.172
				10 Vertical betatron tune	Q _y	-	10	10	10

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



Synchrotron tune and number of RF stations

Courtesy: F. Batsch

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

$$Q_{\rm S} = \frac{\omega_{\rm S}}{\omega_0} = \sqrt{-\frac{h\eta e V_{\rm RF} \cos \phi_{\rm S}}{2\pi E \beta^2}} \propto \sqrt{V_{\rm RF} \cos \phi_{\rm S}} \qquad \text{LHC: } Q_{\rm s} = 0.005$$

- Stable synchrotron oscillations and phase focusing only for $Q_s \ll \frac{1}{\pi}$
- RCSs would exceed this limit: 0.3 < Qs < 1.5</p>

Several longitudinal kicks per turn for small Qs between stations, i.e., small Qs/n_{RF}

- Distribute RF system over nRF sections
- <u>n_{RF} is an important quantity to determine!</u>
- n_{RF}^{T} gives also the minimum number of arcs.

 RCS1, no intensity effects 30 0 RCS1, with intensity effects RCS2, no intensity effects . RCS3, no intensity effects 02 (%) Σε^Γ 10 0 20 40 Ó 60 80 100 ner

(T. Suzuki, KEK Report 96-10)



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	1μ+, 1μ ⁻	1μ+, 1μ ⁻	1μ+, 1μ ⁻
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	Ť	Ť	Ť
Energy gain per turn, ΔE [GeV]	÷	ŧ	ŧ
Acc. gradient for survival [MV/m]	Fast ramping	within $B_{\rm nc} = \frac{1}{2}$	±1.8 T
Acc. field in RF cavity [MV/m]	ţ	ţ	L.
Ramp rate, B _{nc} [T/s]	4199	3281	1518

1			Stage 1		Stage 2		Stage 3
< Basic data	Symbol	Unit	Value	Details	Value	Details	Value
s Particles	-		И		И		μ
Costs	•	MC	DCE		Induced Dicce		Induced FLORE
r Type			nc.o		nyonu no o		nyona RCS
Dynamics							
Acceleration time	T	[ms]	0.34		1.09704595		2.3
Injection energy	E	(MeV)/u	63000		313830		750000
Election energy	E	(Me)/lbr	2128204	efinari hu re	750000		1500000
Energy ratio	E.E.	(incept)	4.98	cirilou by it	2.39		2.0
Momentum at e	n/c	Mehlle	62106		212025		76010
Momentum at e	pic	Mallia	212025		750100		160010
Number of turns	0	Meerc	17		750200		100010
Number of turns	N IN		11		55		0
Planned Survival rate	1. (N		0.9		0.9		0.5
Total survival rate		Ch D Claud	0.9		0.81		0.72
Accel, Gradient, Intear for survival		[my/m]	2.44		1.33		1.0
Required energy gain per turn	ale -	[weex]	74/00		7930		1130
I ransición gamma	79		20.41		20.41		~30
Injection relativistic mass factor	7.0		597		2971		709
Ejection relativistic mass factor	Y _s		2971		7099		1419
Injection v/c	Peri	%	0.9999986		0.999999943		0.99999999901
Election v/c	B .	56	0.999999943		0.9999999901		0.9999999975
7							
Parameter Classical RCS							
Radius	R	[m]	953.3		953.3		1703.0
Circumference	2xR	[m]	5990		5990		10700
Circumference Ratio	B _{ini} /B _i				1		1.79
Pack fraction	?		0.61		0.61		0.628
Bend radius	8.	m	581.8		581.8		1070.2
Tot, straight section length	6	Iml	2334.7		2335.7		3975.7
Injection bending field (overage)	8.	m	0.36		1.80		234
DE							
Systems			TESLA		TESLA		TESLA
Main RE frequency	le.	[MHz]	1300		1300		1300
Harmonic number	h	[mine]	25957		25957		46367
Revolution frequency ei	1	Delty]	50.08		50.08		28.04
Revolution period	Trey	fusl	20.0		20.0		35.7
Max RF voltage	V.,.	[GV]	20.87		11.22		16.07
Max RF power	P	[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		[Q]					
Gradient in cavity	∆E/L	[MV/m]	30		30		30
Average energy gain per total straight	ΔE/L	[MeV/m]	6.3		3.4		2.9
Accelerating field per total straight	AE/L	[MeV/m]	8.9		4.8		4.0
Accelerating field gradient, with FF	ΔE/L	[MV/m]	22.3		12.0		9.0
Stable phase	۰,	["]	45		45		45
Conversion factor mm mrad – eVs		Vsimm mra	69.40		165.86		331.72
Longitudinal emittance (gE * 4gz)	ε,	[eVs]	0.0257.	5 MeV m	0.025		0.025
Longitudinal emittance (phase space area)	¢.,	[eVs]	0.079		0.079		0.079
Injection bucket area	A	[eVs]	0.62		1.01		1.40
Ejection bucket area	And	[eVs]	1.37		1.56		1.97
Bucket area reduction factor	A ₈ IA _{8.4}		0.172		0.172		0.172
Horizontal betatron tune	Q.,	-					
Vertical betatron tune	Q,						
Average horizontal Twiss beta	βh	[m]	10		10		10
Average vertical Twiss beta	βv	[m]	10		10		10
Injection synchrotron frequency	5.00	[kHz]	76.33		25.07		14.53
Ejection synchrotron frequency	6.0	[kHz]	34.20		16.22		10.27
Injection synchrotron tune Q	fraller		1.52		0.50		0.52

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Fast ramping considerations

Ramping times ≈ cavity filling time:

 $t_{\rm acc} = 0.3 \,\mathrm{ms} \, pprox \frac{Q_L}{\omega} = 0.27 \,\mathrm{ms}$

- Optimization problem between magnet powering and RF
- Linear ramping \rightarrow constant $V_{\text{RF}} \rightarrow$ simplest RF solution, best for μ
- Sinusoidal ramp function → performance decrease of 50%
- Study quasi-linear ramping by e.g. natural resonant discharge of e.g. two harmonics

Courtesy: F. Batsch





 Powering and ramping function optimization ongoing, combined with synchronous phase and RF voltage optimization (see <u>talk</u> by F. Batsch and <u>talk</u> by F. Boattini).



Energy against magnetic variation

- The magnetic field is varying quasi-linearly.
- The beam energy has a step-wise shape: energy bump at RF stations.



- If we consider RCS1: acceleration 60 \rightarrow 314 GeV in 17 turns and 32 RF stations.
- In the first arc: energy of 60 GeV but relative variation of the field of $\frac{314-60}{17\times32\times60} = 0.8\%!$
- µ+ and µ- are propagating in 2 opposite directions: impact of this variation to be discussed.



Summary and outlook

- The muon decay brings unique challenges: fast acceleration, large voltages, high intensities, high synchronous tune, small number of turns.
- The synchrotron tune mitigation implies a large number of RF stations and thus arcs (about 30).
- We still need to optimize several acceleration parameters: RF voltages, synchronous phase, acceleration time = decay.
- Still a lot of remaining questions: impact of power supply errors on the orbits, required reproducibility? Beam trajectory with quickly varying dipole fields? Field quality to be discussed this afternoon.
- That is crucial to discuss between RF, magnet, beam dynamics, shielding, and optics people!





- Detailed parameter table (by F. Batsch): <u>https://cernbox.cern.ch/index.php/s/I9VpITn</u> <u>cUeCBtiz</u>
- Parameters of the 4th RCS under study.

Collective effects and shielding not included

Example parameters for the muon RCSs

Tentative RCS parameters

	RCS1	RCS2	RCS3	RCS4
Hybrid RCS	No	Yes	Yes	Yes
Circumference [m]	5990	5990	10700	26659
Injection/extraction energy [TeV]	0.06/0.314	0.314/0.75	0.75/1.5	1.5/4.2
Survival rate [%]	90	90	90	90
Acceleration time [ms]	0.34	1.10	2.37	5.75
Number of turns	17	55	66	65
Energy gain/turn [GeV]	14.8	7.9	11.4	41.5
NC dipole field [T]	0.36/1.8	-1.8/1.8	-1.8/1.8	-1.8/1.8
SC dipole field [T]	-	10	10	16
NC/SC dipole length [m]	2.6/-	4.9/1.1	4.9/1.3	8.0/1.3
Number of arcs	34	26	26	26
Number of cells/arc	7	10	17	19
Cell length [m]	21.4	19.6	20.6	45.9
Path length diff. [mm]	0	9.1	2.7	9.4
Orbit difference [mm]	0	12.2	5.9	13.2
Min. dipole width [mm]	17.4	19.6	10.7	18.8
Min. dipole height [mm]	14.8	6.4	4.2	4.4

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Thank you to Fabian Batsch for providing most of the slides

Thank you for your attention