IMCC Annual meeting
21 June 2023

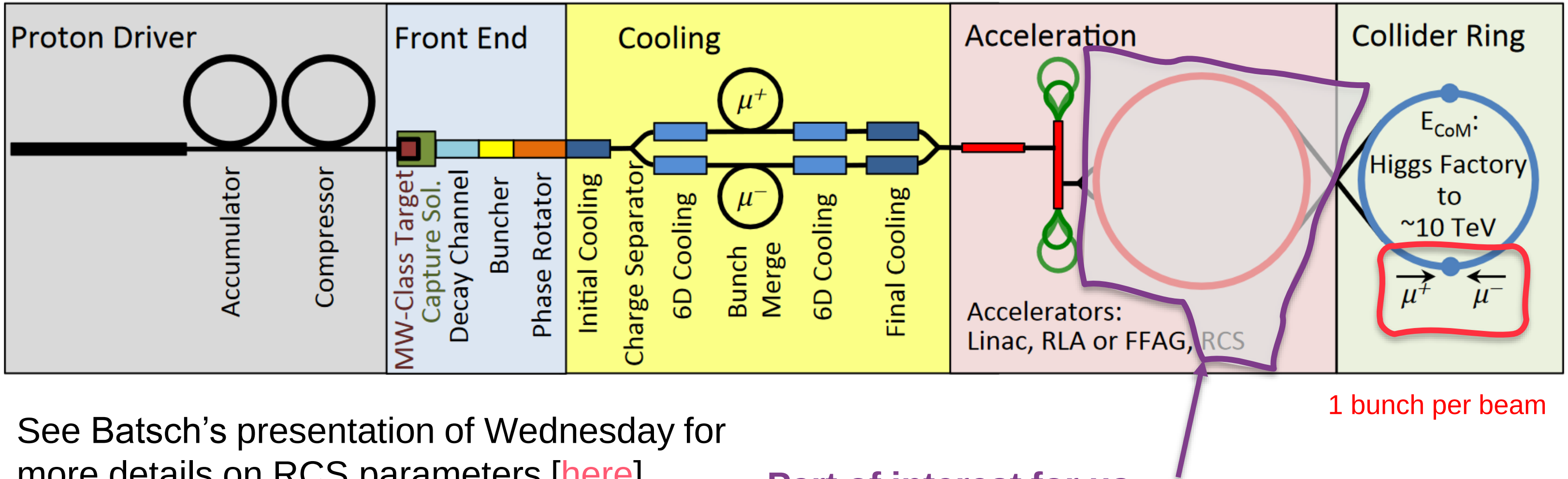
From top level to RCS parameters

Antoine CHANCE (CEA) on behalf of the whole High-energy complex team with great help of magnet and RF colleagues

Funded by the European Union under
Grant Agreement n. 101094300

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)



1 bunch per beam

Part of interest for us

See Batsch's presentation of Wednesday for more details on RCS parameters [here]

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**
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 **60 GeV to 5 TeV**.
- **Figure of merit**:
  - Fast acceleration (the muons decay).
  - Feasible (if possible ;-)).
  - Cost efficient (should be cheaper than a 100-km-long linac).
  - Power efficient (do not use a nuclear plant to power the RCS!).

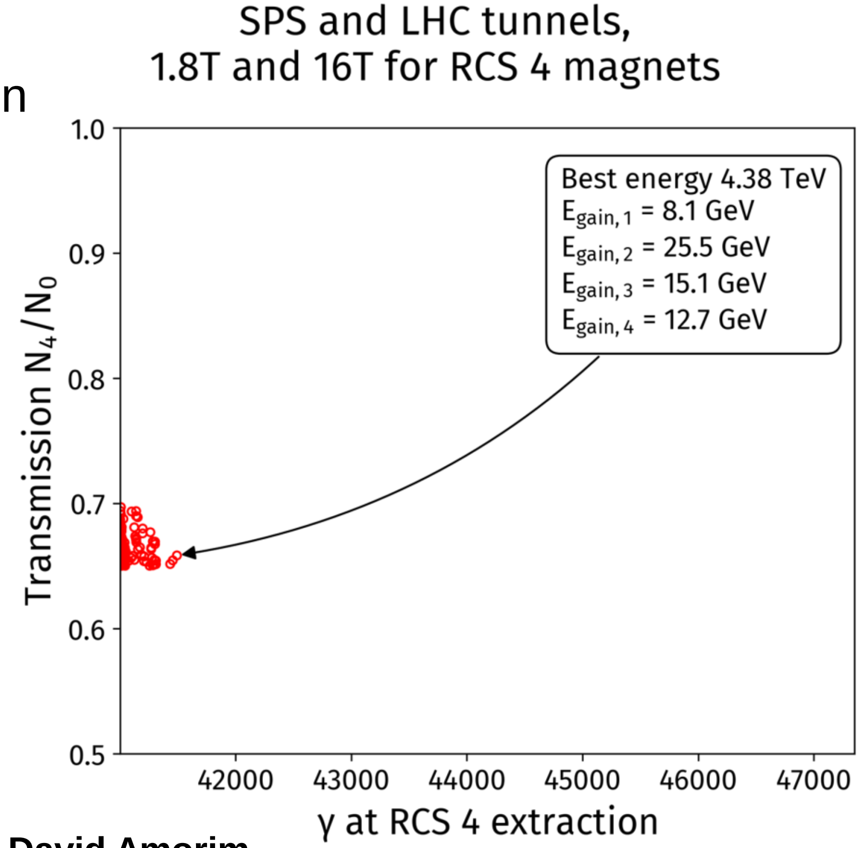
How fast?

- Muons decay very fast (Rest lifetime: 2.2 µs).
- We should accelerate as fast: τ_{acc} as low as possible.
  - Muon survival: $\frac{N_{ext}}{N_{inj}} = \left(\frac{E_{ext}}{E_{inj}}\right)^{-\frac{\tau_{acc}}{\tau_{\mu}\left(\gamma_{ext}-\gamma_{inj}\right)}}$ for a linear ramp
  - If we assume only one RCS, we should have $\tau_{acc} = 10\ \mathrm{ms}$ 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**.

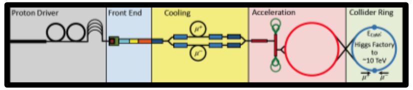
What energy swing?

First test of Genetic Algorithms for accelerator parameters optimization

- Example: try to **fit the RCS 4 in the LHC tunnel** (27 km), the RCS 1 and RCS 2 in the SPS tunnel (7 km)
  - With stronger field magnets (16 T for the SC and 2.0 T for NC magnets)
  - Preserving the beam transmission through the chain
- Reach **4.4 TeV per beam** after **rough optimization**
- Similar values reached by F. Batsch with parametric study

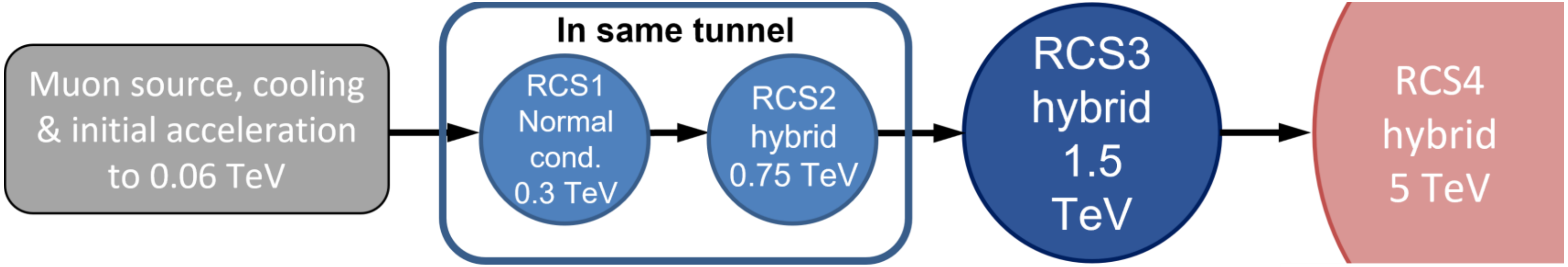


Courtesy: David Amorim



What energy swing?

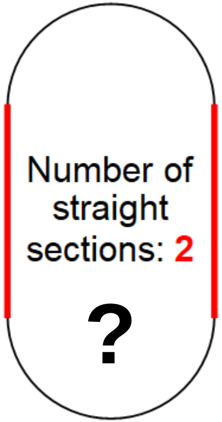
- Chain of rapid cycling synchrotrons, counter-rotating m+/m- beams
  → 60 GeV → 314 GeV → 750 GeV → 1.5 TeV → 5 TeV



- Hybrid RCSs have interleaved normal conducting (NC) and superconducting (SC) magnets.

- This would be the first hybrid RCSs in the world!

What RCS shape?


Number of straight sections: **2**

?

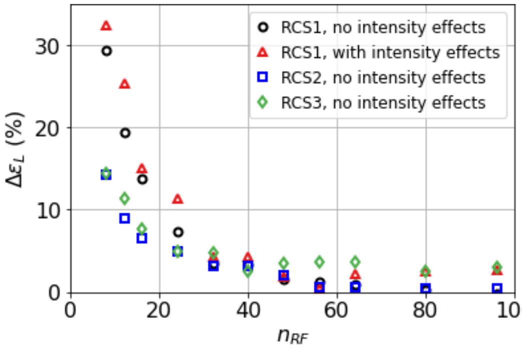
Courtesy: F. Batsch

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

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

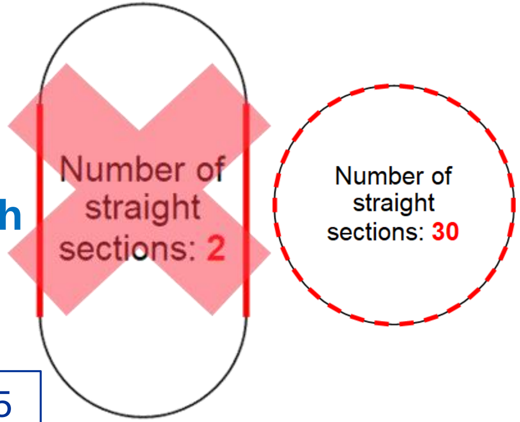
LHC: Q_s=0.005

- Stable synchrotron oscillations and phase focusing only for $Q_s \ll \frac{1}{\pi}$
- RCSs would exceed this limit: 0.3 < Qs < 1.5 **(T. Suzuki, KEK Report 96-10)**
  - Several longitudinal kicks per turn for small Qs between stations, i.e., small Qs/n_{RF}
  - Distribute RF system over nRF 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.



What RCS shape?

Courtesy: F. Batsch



Number of straight sections: 2

Number of straight sections: **30**

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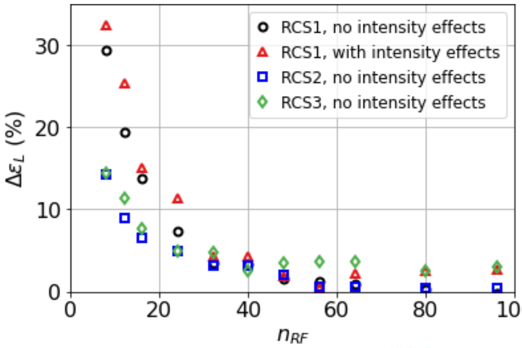
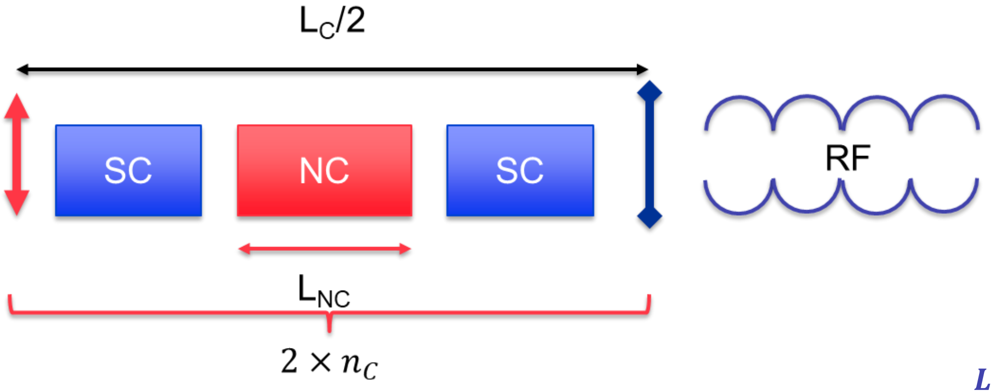
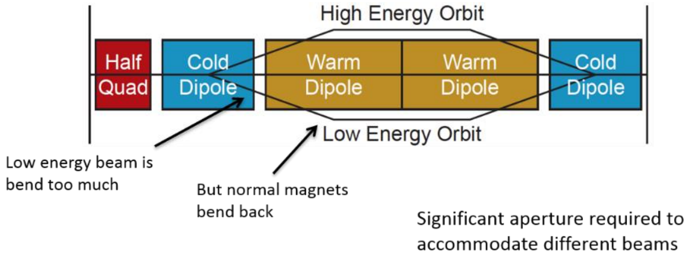


What RCS pattern?

- 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.





Low energy beam is bend too much

But normal magnets bend back

Significant aperture required to accommodate different beams

$$L_{NC} = 2\pi \frac{B\rho_{ext} - B\rho_{inj}}{B_{NC,ext} - B_{NC,inj}} = \pi \frac{B\rho_{ext} - B\rho_{inj}}{B_{NC}}$$

$$L_{SC} = 2\pi \frac{B\rho_{inj} B_{NC,ext} - B\rho_{ext} B_{NC,inj}}{B_{SC}(B_{NC,ext} - B_{NC,inj})} = \pi \frac{B\rho_{inj} + B\rho_{ext}}{B_{SC}}$$

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

Trajectory variation in a hybrid RCS?

- In a hybrid RCS, the path length is not constant.

→ **f_{RF} tuning to be provided**

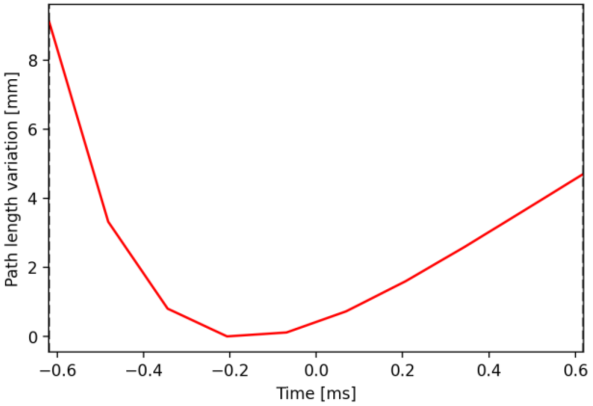
→ **What frequency range and tuning speed?**

- $\Delta f/f = \Delta l/(2\pi R) \approx 1.52 \cdot 10^{-6}$
- $\rightarrow \Delta f \approx 2$ kHz $\rightarrow d\Delta f/dt \approx 10$ MHz/s

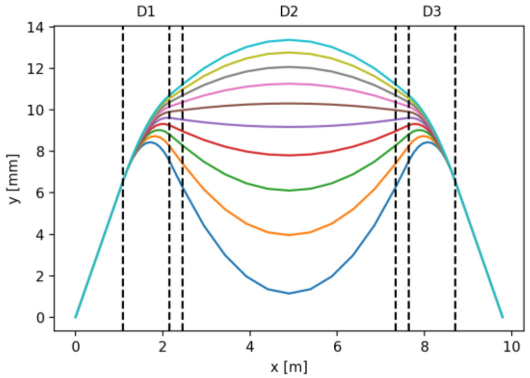
→ **Driver for the tuner technology change.**

- 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.
- **Should be taken into account for field quality definition.**

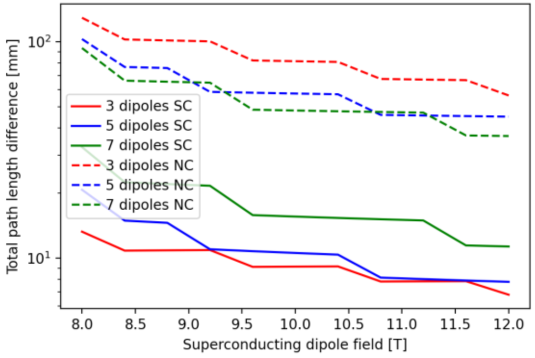
RCS2

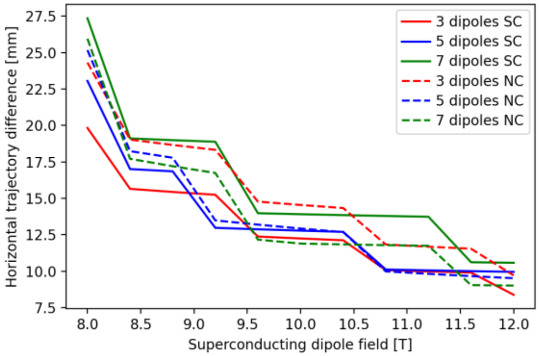


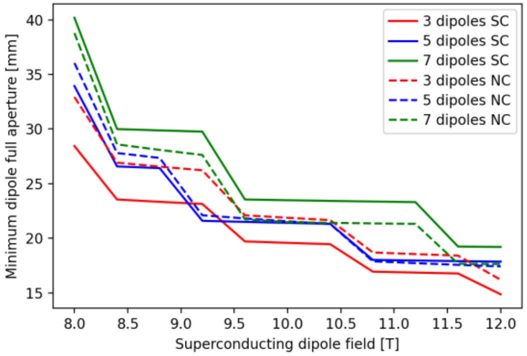
RCS2

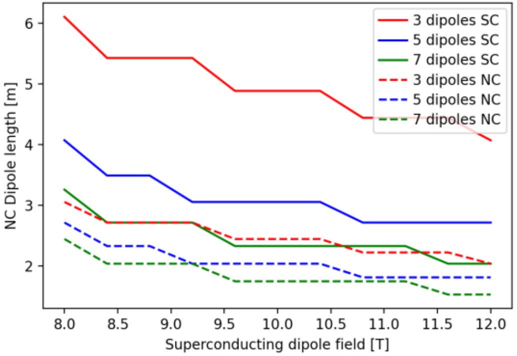


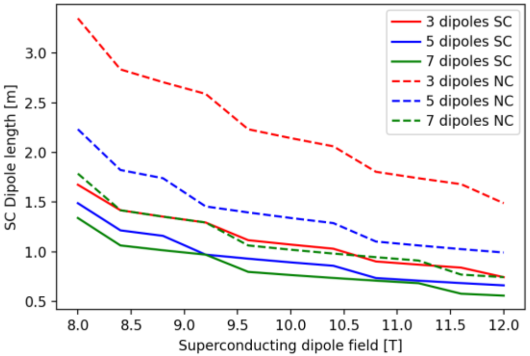
What SC dipole field?

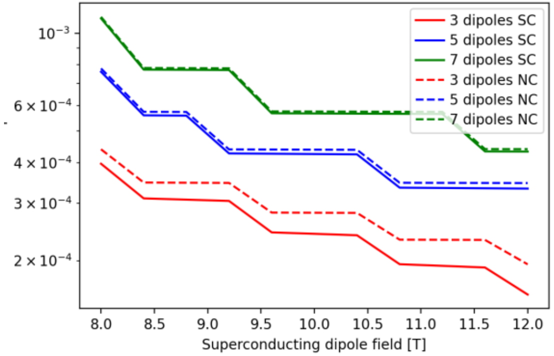












Fast ramping considerations

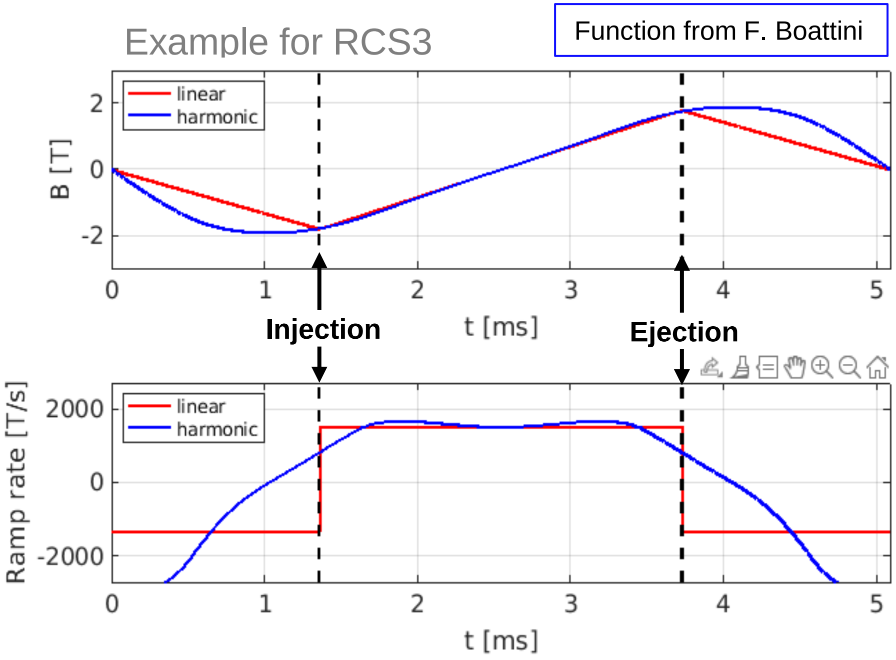
Courtesy: F. Batsch

- Ramping times ≈ cavity filling time:

$$t_{\mathrm{acc}} = 0.3\ \mathrm{ms} \approx \frac{Q_L}{\omega} = 0.27\ \mathrm{ms}$$

- **Optimization problem** between magnet powering and RF
- **Linear ramping** → constant V_{RF} → simplest RF solution, best for μ
- **Non-linear ramping** → decrease peak power ≙ magnet powering costs significantly (see talk by F. Boattini)
- **Sinusoidal ramp function** → performance decrease of 50%

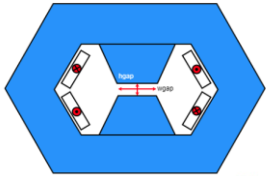
→ **Study quasi-linear ramping** by e.g. natural resonant discharge of e.g. two harmonics



Which Fast-ramping Magnets?

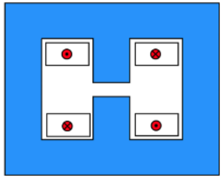
F. Boattini et al.

Hourglass frame magnet



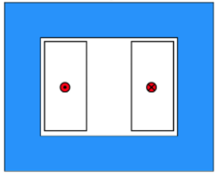
5.07 kJ/m

H magnet



5.65…7.14 kJ/m

Window frame magnet

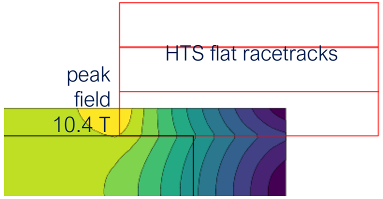


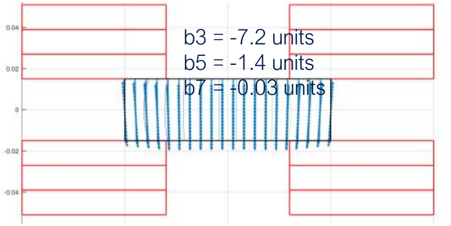
5.89 kJ/m

Main challenge is management of the power in the resistive dipoles (several tens of GW):

- Minimum stored magnetic energy
- Highly efficient energy storage and recovery

Simple HTS racetrack dipole could match the beam requirements and aperture



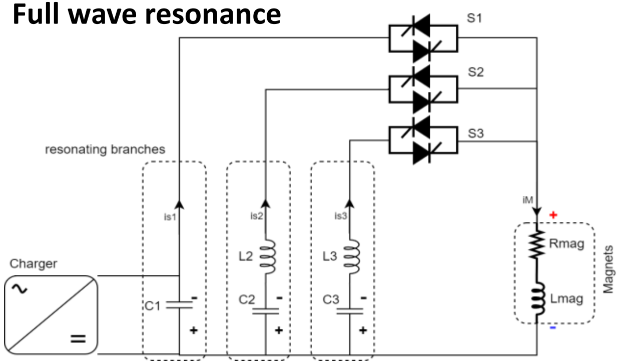


b3 = -7.2 units
b5 = -1.4 units
b7 = -0.03 units

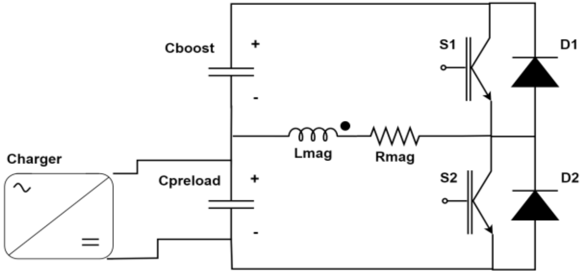
Rectangular magnet bore 100 mm x 30 mm

Differerent power converter options investigated

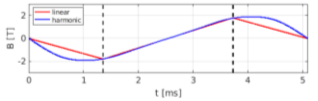
Full wave resonance



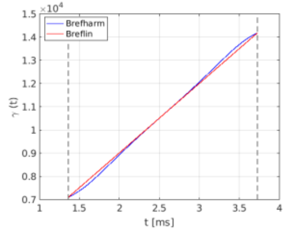
Commutated resonance (new)



RF requirements ?

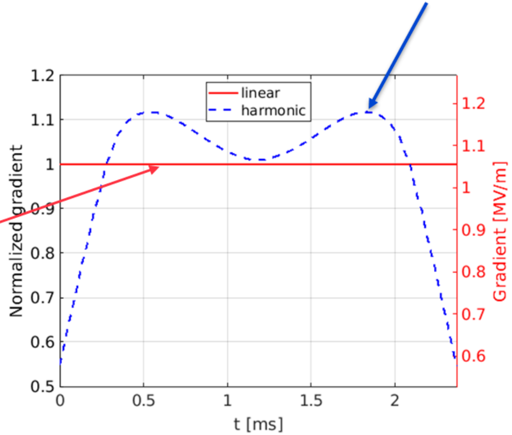


Courtesy: F. Batsch



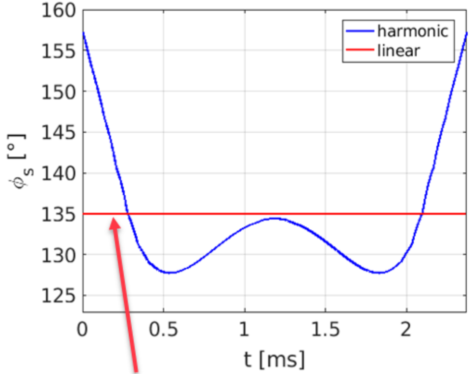
- **V_{acc} and G_{acc} must be increased by 12% to achieve the same τ_{acc} ⇔ ≠ 200% as for a sine-like ramp!**

Example for RCS3



Constant gradient for linear ramp

Average gradient over ring for 90% survival



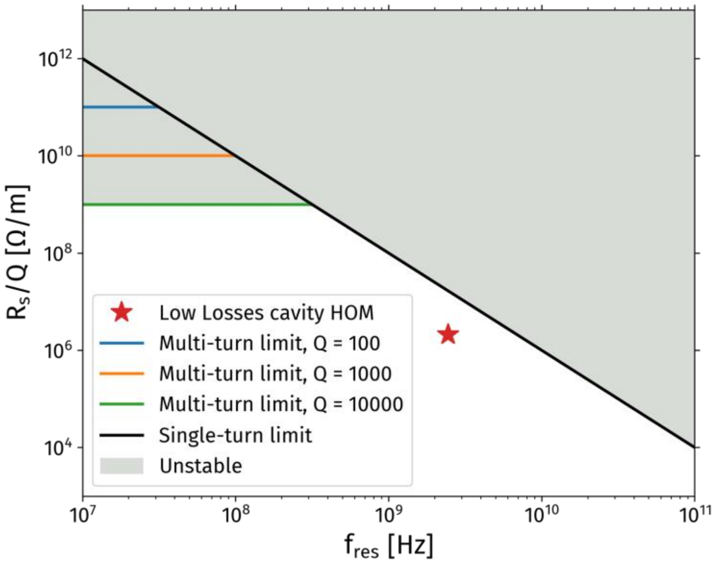
$\phi_{s,0}$ = π - 45° for linear, above transition

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

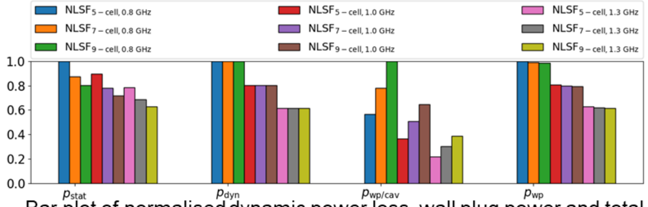
Which RF impedance?
Which RF structure and frequency?

- Calculations performed **WITH NO transverse offset.**

Stability limit versus resonator parameters

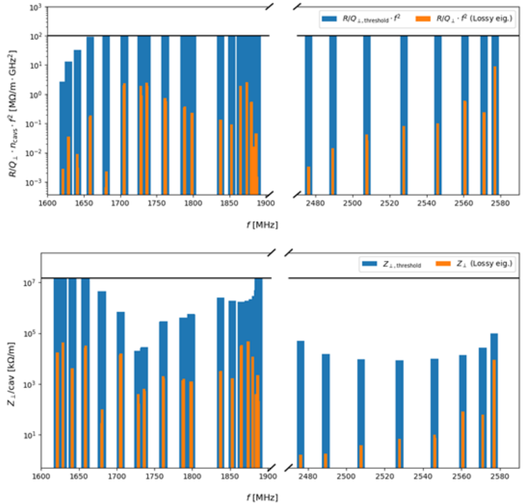


Courtesy: David Amorim



Bar plot of normalised dynamic power loss, wall plug power and total HOM power

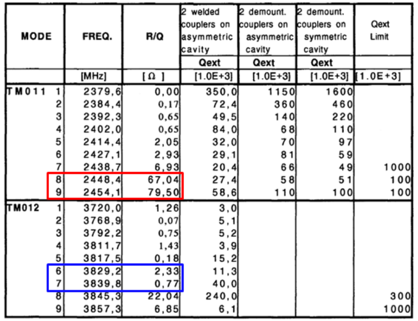
Courtesy: Sosoho-Abasi Udongwo



Transverse impedance of dipole modes in first and second HOM dipole passband and transverse impedance threshold bar plot for the TESLA cavity geometry

HOM power?

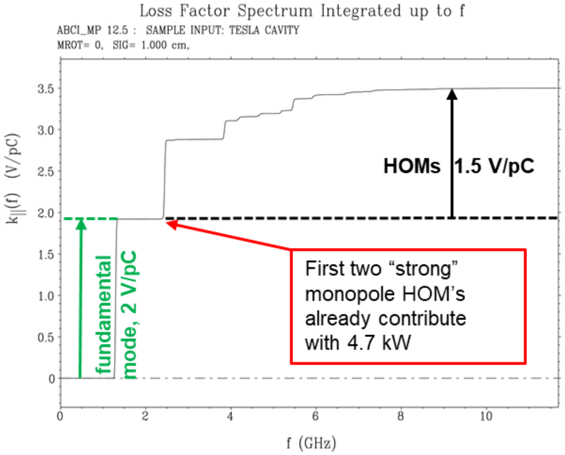
Table 2 Values of Qext for the monopole modes



MODE		FREQ.	R/Q	2 welded couplers on asymmetric cavity Qext	2 demount. couplers on asymmetric cavity Qext	2 demount. couplers on symmetric cavity Qext	Qext Limit
		[MHz]	[Ω]	[1.0E+3]	[1.0E+3]	[1.0E+3]	[1.0E+3]
TM011	1	2379,6	0,00	350,0	1150	1600	
	2	2384,4	0,17	72,4	360	460	
	3	2392,3	0,65	49,5	140	220	
	4	2402,0	0,65	84,0	68	110	
	5	2414,4	2,05	32,0	70	97	
	6	2427,1	2,93	29,1	81	59	
	7	2438,7	6,93	20,4	66	49	1000
	8	2448,4	67,04	27,4	58	51	100
	9	2454,1	79,50	58,6	110	100	100
TM012	1	3720,0	1,26	3,0			
	2	3768,9	0,07	5,1			
	3	3792,2	0,75	5,2			
	4	3811,7	1,43	3,9			
	5	3817,5	0,18	15,2			
	6	3829,2	2,33	11,3			
	7	3839,8	0,77	40,0			
	8	3845,3	22,04	240,0			300
	9	3857,3	6,85	6,1			1000

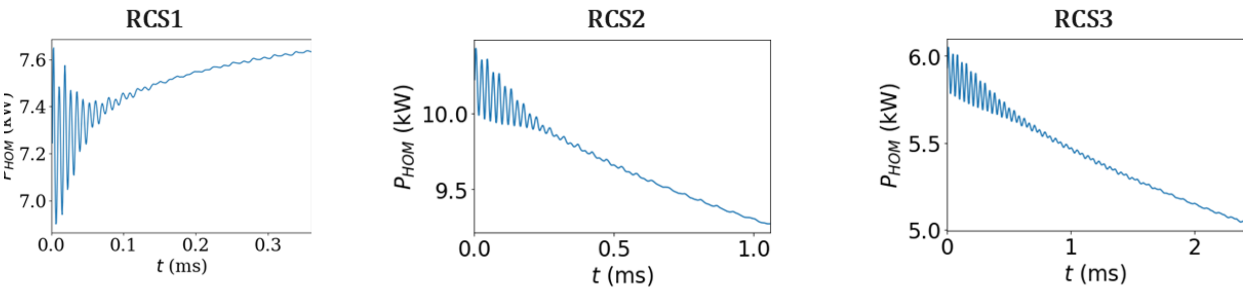
From
"Higher order mode coupler for TESLA", J. Sekutowisz

- Example: Calculations performed for TESLA Low-loss
- (ABCI file from S.-A. Udongwo)



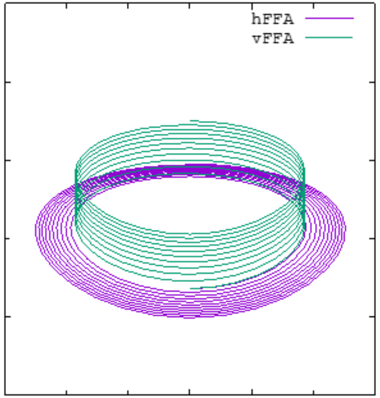
First two "strong" monopole HOM's already contribute with 4.7 kW

Beam-induced power losses



Courtesy: Fabian Batsch

FFA as Alternatives?



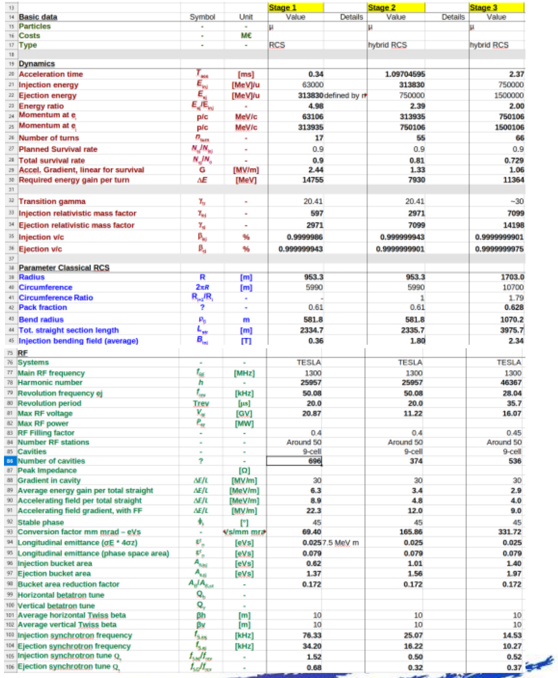
Courtesy: Max Topp-Mugglestone

- Why FFAs?
  - Time-independent magnetic fields
  - No ramp times
  - Rate of acceleration limited only by RF
  - Mitigates engineering challenges of designing and powering fast-ramping dipoles
  - All magnets can be superconducting DC magnets
  - At high energy, pulsed synchrotrons limited by the maximum field in pulsed magnets.
- Limited understanding of optics
  - Unique coupling behaviour
    - Dominated by skew quadrupole focussing
    - Solenoid components in fringe fields
  - Nonplanar orbits
- Challenging optimization: update foreseen end 2023.
- See Scott Berg's presentation [here]

Parameters and tools.
Table under constant evolution.

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	$1\mu^+$, $1\mu^-$	$1\mu^+$, $1\mu^-$	$1\mu^+$, $1\mu^-$
Bunch population	>2.5E12	>2.3E12	2.2E12
Survival rate per ring	90%	90%	90%
Acceleration time, t_{acc} [ms]	0.34	1.04	2.37
Number of turns	17	55	66
Energy gain per turn, ΔE [GeV]	14.8	7.9	11.4
Acc. gradient for survival [MV/m]	2.4	1.3	1.1
Acc. field in RF cavity [MV/m]	30 (45 optimistically)	30	30



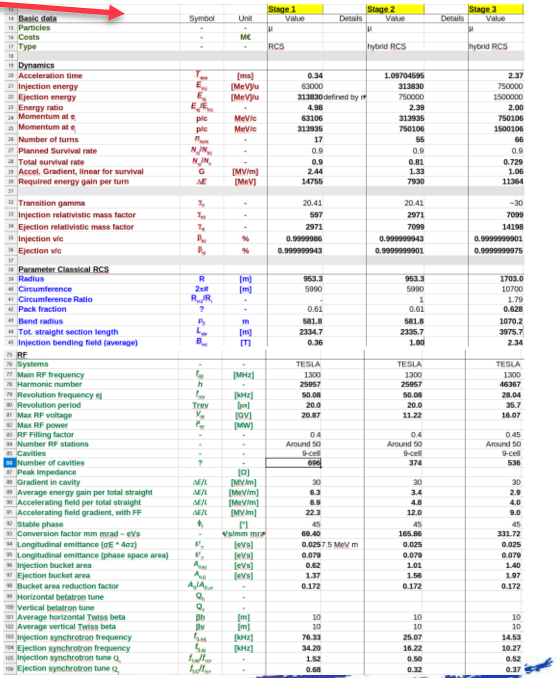
				Stage 1		Stage 2		Stage 3
13								
14	Basic data	Symbol	Unit	Value	Details	Value	Details	Value
15	Particles	-	-	μ		μ		μ
16	Costs	-	M€					
17	Type	-	-	RCS		hybrid RCS		hybrid RCS
18								
19	Dynamics							
20	Acceleration time	T_{acc}	[ms]	0.34		1.09704595		2.37
21	Injection energy	E_{inj}	[MeV]/u	63000		313830		750000
22	Ejection energy	E_{ej}	[MeV]/u	313830	defined by r	750000		1500000
23	Energy ratio	E_{ej}/E_{inj}	-	4.98		2.39		2.00
24	Momentum at e_i	p/c	MeV/c	63106		313935		750106
25	Momentum at e_j	p/c	MeV/c	313935		750106		1500106
26	Number of turns	n_{turn}	-	17		55		66
27	Planned Survival rate	N_{ej}/N_{inj}	-	0.9		0.9		0.9
28	Total survival rate	N_{ej}/N_0	-	0.9		0.81		0.729
29	Accel. Gradient, linear for survival	G	[MV/m]	2.44		1.33		1.06
30	Required energy gain per turn	ΔE	[MeV]	14755		7930		11364
31								
32	Transition gamma	γ_{tr}	-	20.41		20.41		~30
33	Injection relativistic mass factor	γ_{inj}	-	597		2971		7099
34	Ejection relativistic mass factor	γ_{ej}	-	2971		7099		14198
35	Injection v/c	β_{inj}	%	0.9999986		0.999999943		0.9999999901
36	Ejection v/c	β_{ej}	%	0.999999943		0.9999999901		0.9999999975
37								
38	Parameter Classical RCS							
39	Radius	R	[m]	953.3		953.3		1703.0
40	Circumference	$2\pi R$	[m]	5990		5990		10700
41	Circumference Ratio	R_{i+1}/R_i	-	-		1		1.79
42	Pack fraction	?	-	0.61		0.61		0.628
43	Bend radius	ρ_0	m	581.8		581.8		1070.2
44	Tot. straight section length	L_{str}	[m]	2334.7		2335.7		3975.7
45	Injection bending field (average)	B_{inj}	[T]	0.36		1.80		2.34
75	RF							
76	Systems	-	-	TESLA		TESLA		TESLA
77	Main RF frequency	f_{RF}	[MHz]	1300		1300		1300
78	Harmonic number	h	-	25957		25957		46367
79	Revolution frequency ej	f_{rev}	[kHz]	50.08		50.08		28.04
80	Revolution period	Trev	[μs]	20.0		20.0		35.7
81	Max RF voltage	V_{RF}	[GV]	20.87		11.22		16.07
82	Max RF power	P_{RF}	[MW]					
83	RF Filling factor	-	-	0.4		0.4		0.45
84	Number RF stations	-	-	Around 50		Around 50		Around 50
85	Cavities	-	-	9-cell		9-cell		9-cell
86	Number of cavities	?	-	696		374		536
87	Peak Impedance		[Ω]					
88	Gradient in cavity	$\Delta E/L$	[MV/m]	30		30		30
89	Average energy gain per total straight	$\Delta E/L$	[MeV/m]	6.3		3.4		2.9
90	Accelerating field per total straight	$\Delta E/L$	[MeV/m]	8.9		4.8		4.0
91	Accelerating field gradient, with FF	$\Delta E/L$	[MV/m]	22.3		12.0		9.0
92	Stable phase	ϕ_s	[°]	45		45		45
93	Conversion factor mm mrad – eVs	-	Vs/mm mra	69.40		165.86		331.72
94	Longitudinal emittance (σE * 4σz)	ε^{r}_{n}	[eVs]	0.025	7.5 MeV m	0.025		0.025
95	Longitudinal emittance (phase space area)	ε^{r}_{n}	[eVs]	0.079		0.079		0.079
96	Injection bucket area	$A_{b,inj}$	[eVs]	0.62		1.01		1.40
97	Ejection bucket area	$A_{b,ej}$	[eVs]	1.37		1.56		1.97
98	Bucket area reduction factor	$A_B/A_{B,st}$	-	0.172		0.172		0.172
99	Horizontal betatron tune	Q_h	-					
100	Vertical betatron tune	Q_v	-					
101	Average horizontal Twiss beta	βh	[m]	10		10		10
102	Average vertical Twiss beta	βv	[m]	10		10		10
103	Injection synchrotron frequency	$f_{S,inj}$	[kHz]	76.33		25.07		14.53
104	Ejection synchrotron frequency	$f_{S,ej}$	[kHz]	34.20		16.22		10.27
105	Injection synchrotron tune Q_s	$f_{S,inj}/f_{rev}$	-	1.52		0.50		0.52
106	Ejection synchrotron tune Q_s	$f_{S,ej}/f_{rev}$	-	0.68		0.32		0.37

Parameters and tools:
Table under constant evolution.

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	$1\mu^+$, $1\mu^-$	$1\mu^+$, $1\mu^-$	$1\mu^+$, $1\mu^-$
Bunch population	>2.5E12	>2.3E12	2.2E12
Survival rate per ring	90%	90%	90%
Acceleration time, t_{acc} [ms]	0.34	1.04	2.37
Number of turns	17	55	66
Energy gain per turn, ΔE [GeV]	14.8	7.9	11.4
Acc. gradient for survival [MV/m]	2.4	1.3	1.1

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



		Symbol	Unit	Stage 1 Value	Details	Stage 2 Value	Details	Stage 3 Value
14	Basic data							
15	Particles	-	-	μ		μ		μ
16	Costs	-	M€					
17	Type	-	-	RCS		hybrid RCS		hybrid RCS
18								
19	Dynamics							
20	Acceleration time	T_{acc}	[ms]	0.34		1.09704595		2.37
21	Injection energy	E_{inj}	[MeV]/u	63000		313830		750000
22	Ejection energy	E_{ej}	[MeV]/u	313830	defined by n	750000		1500000
23	Energy ratio	E_{ej}/E_{inj}	-	4.98		2.39		2.00
24	Momentum at e_i	p/c	MeV/c	63106		313935		750106
25	Momentum at e_j	p/c	MeV/c	313935		750106		1500106
26	Number of turns	n_{turn}	-	17		55		66
27	Planned Survival rate	N_{ej}/N_{inj}	-	0.9		0.9		0.9
28	Total survival rate	N_{ej}/N_0	-	0.9		0.81		0.729
29	Accel. Gradient, linear for survival	G	[MV/m]	2.44		1.33		1.06
30	Required energy gain per turn	ΔE	[MeV]	14755		7930		11364
31								
32	Transition gamma	γ_{tr}	-	20.41		20.41		~30
33	Injection relativistic mass factor	γ_{inj}	-	597		2971		7099
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40	Circumference	$2\pi R$	[m]	5990		5990		10700
41	Circumference Ratio	R_{i+1}/R_i	-	-		1		1.79
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76	Systems	-	-	TESLA		TESLA		TESLA
77	Main RF frequency	f_{RF}	[MHz]	1300		1300		1300
78	Harmonic number	h	-	25957		25957		46367
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82	Max RF power	P_{RF}	[MW]					
83	RF Filling factor	-	-	0.4		0.4		0.45
84	Number RF stations	-	-	Around 50		Around 50		Around 50
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106	Ejection synchrotron tune Q_s	$f_{S,ej}/f_{rev}$	-	0.68		0.32		0.37

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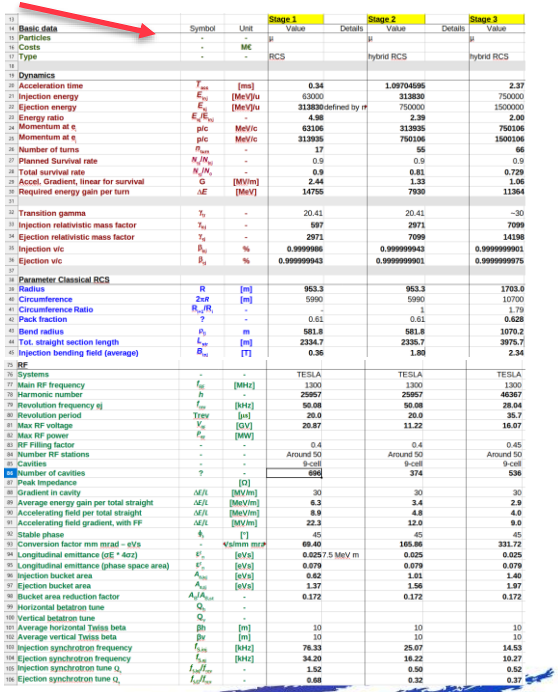
Survival rate per ring	90%	90%	90%
Acceleration time [ms]	0.34	1.04	2.37
Number of turns			
Energy gain per turn, ΔE [GeV]			
Acc. gradient for survival [MV/m]			
Acc. field in RF cavity [MV/m]			
Ramp rate, $\dot{B}_{nc}$ [T/s]	4199	3281	1518

Fast ramping within $B_{\rm nc} = \pm 1.8$ T



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106	Ejection synchrotron tune Q_s	$f_{S,ej}/f_{rev}$	-	0.68		0.32		0.37

A lot of fruitful discussions

- What ramping is optimum?
  - **Magnet people**: Linear ramp needs a lot of power. Quasi-linear ramp for consumption minimization.
  - **RF people**: going away from a linear ramp will ask for extra gradient and thus extra voltage.
  - **Optics people:**
    - Muon survival is mainly linked to the acceleration time rather than the ramp shape.
    - Optimization of the synchronous^phase
  - **What is the most cost effective** between more RF cavities/voltage and more powering power?
- How many power stations?
  - **Longitudinal dynamics:** we need at least 32 RF stations.
  - **Optics people:**
    - With only 32 stations, the curvature radius vary by near 1% due to the magnetic field variation while running one arc → Needs more RF stations to have a smoother energy variation!
    - But if we increase the number of RF stations, we need to fully integrate the cavity in arc cells.
    - Can we live with dispersion in cavities? If not, need to use multi-bend achromats → very small momentum compaction.
  - **Beam dynamics people:**
    - Keep a large momentum compaction for stability!

A lot of fruitful discussions

- What field quality?
  - **Magnet people**:
    - Should we use harmonics or good field region?
    - What tolerance on dynamic errors (powering supplies) and static errors (misaligments)?
  - **Optics people:**
    - Massive tracking studies are necessary: to use field maps. Very likely to have strong detuning of the machine because of misalignements/orbit errors in the sextupoles.
    - Order of magnitude on the error spectrum?
    - What are the magnitude of Eddy currents? Maybe a driver.
    - Limitation on fast dipole correctors?
  - **Beam dynamics people**:
    - Collective effects will give the minimum beam pipe radius.
- Interfaces with collider/muon cooling?
  - What matching conditions to the colliders and between RCS? **Emittance may grow by 90%!**
  - Needs bunch compression during the acceleration to get the collider bunch length.
  - What longitudinal profile after muon cooling?

A lot of fruitful discussions

- Which transverse HOM and cavity geometry?
  - **Beam dynamics:**
    - The October specifications were with no transverse cavity offset.
    - With current HOM, we need a 2-turn damper. Otherwise, the beam is lost after a few RF cavities (less than one turn!) if a transverse error of a few tens of μm. Work in progress.
  - **RF people:**
    - HOM tolerances will be probably updated.
    - Comparison of different geometries and frequencies to handle HOM power and required impedances.
- Other topics: Beam instrumentation? Shielding? Vacuum?...

- My final conclusion:
  - **That is crucial to discuss between RF, magnet, beam dynamics, shielding, and optics people!**
  - **A hybrid synchrotron with so fast acceleration is really a unique (and exciting) machine!**

International
MUON Collider
Collaboration

Thank you to all the team for the great work

DE LA RECHERCHE À L'INDUSTRIE
cea

Thank you for your attention

2) What driving devices?

$$L_{NC} = 2\pi \frac{B\rho_{ext} - B\rho_{inj}}{B_{NC,ext} - B_{NC,inj}} = \pi \frac{B\rho_{ext} - B\rho_{inj}}{B_{NC}}$$

$$L_{SC} = 2\pi \frac{B\rho_{inj} B_{NC,ext} - B\rho_{ext} B_{NC,inj}}{B_{SC}(B_{NC,ext} - B_{NC,inj})} = \pi \frac{B\rho_{inj} + B\rho_{ext}}{B_{SC}}$$

- We need **fast-ramping dipoles**.
  - Repetition rate of 5 Hz but ramp in a few ms.
  - Should be in the linear response in the beam ramp.
  - Power efficient.
- We need **SC dipoles** (with quite large aperture to manage beam losses).
  - To increase the average bending magnets.
- We need **a lot of RF cavities** to accelerate.
  - Large gradient to reduce the number and the footprint.
  - Good quality factor for cost operation.
  - Small impedance for collective effects (discussed later)