International
MUON Collider
Collaboration

Reports of the working group: Muon Acceleration

by Antoine Chance (CEA Paris-Saclay)

Acknowledgements:
F. Batsch, Christian Carli, H. Damerau , David Amorim , Kyriacos Skoufaris ,
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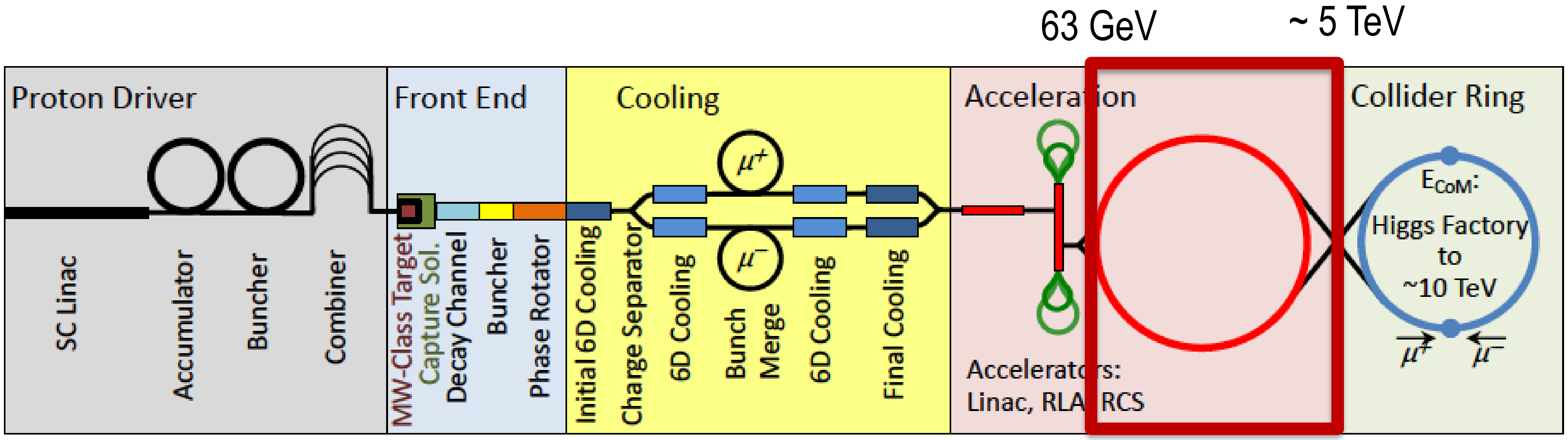
Goal: fast acceleration (after recirculating linacs) to collision energy

- Pulsed synchrotrons challenging
  - Very fast magnet ramping (power, eddy ..)
  - Orbit variations with fixed SC and cycled NC magnets
  - Circumference variations and longitudinal dynamics
  - Strong collective effects

- FFAs (vertical) as an alternative
- **A lot of iterations with other WGs** on magnet design, beam loss, collective effects, radiation protection ..



Tasks within MuCol

High Energy Complex

Task 1
Coordination and Communication

Task 2
Collider design

Task 3 (CEA, CERN, JAI, BNL)
Pulsed synchrotron and FFA design

Task 4
Beam dynamics

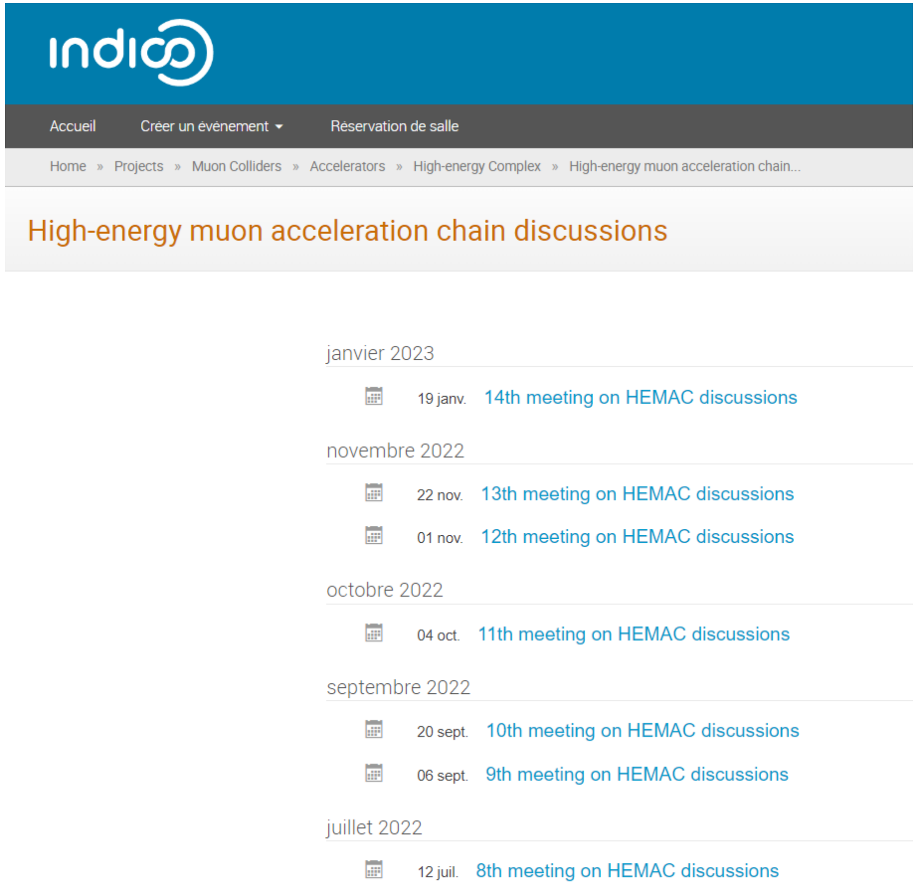
Task 5
MDI design and background to experiment

Task 6
Radiation studies for the accelerators

- The WG « Muon Acceleration » is covered by some tasks of MuCol.
- This WG is focused on parameter optimization, optics design, lattice integration.
- Some activities are in close interaction with other WGs:
  - Magnetic Systems (pulsed magnets)
  - RF systems
  - Beam-matter interaction
  - Collective effects
  - Matching conditions with WG Collider

Muon Acceleration WG

- 14 meetings to date, with participants from most collaborating institutes and universities
- Since February 2022 we meet:
  - to discuss in an informal setting initial ideas and options, and
  - in preparation of upcoming activities, in particular the EU MuCol



Home » Projects » Muon Colliders » Accelerators » High-energy Complex » High-energy muon acceleration chain...

High-energy muon acceleration chain discussions

janvier 2023

19 janv. 14th meeting on HEMAC discussions

novembre 2022

22 nov. 13th meeting on HEMAC discussions
01 nov. 12th meeting on HEMAC discussions

octobre 2022

04 oct. 11th meeting on HEMAC discussions

septembre 2022

20 sept. 10th meeting on HEMAC discussions
06 sept. 9th meeting on HEMAC discussions

juillet 2022

12 juil. 8th meeting on HEMAC discussions

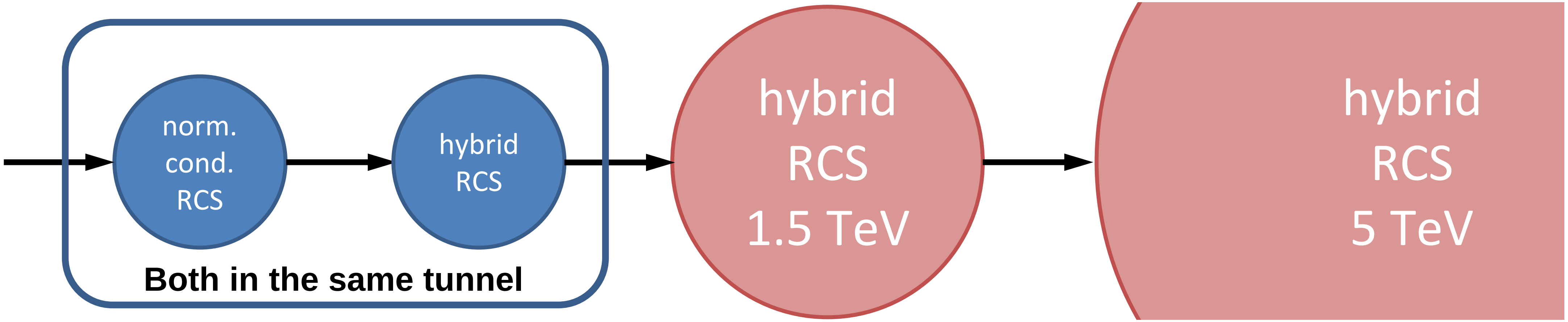
Site: https://indico.cern.ch/category/14979/

Rapid Cycling Synchrotron

Detailed parameter table: https://cernbox.cern.ch/index.php/s/l9VplTncUeCBtiz

- Chain of rapid cycling synchrotrons, counter-rotating μ^+/μ^- beams
  → 63 GeV → 0.31 TeV → 0.75 TeV → 1.5 TeV (→ 5 TeV)

Courtesy: Heiko Damerau

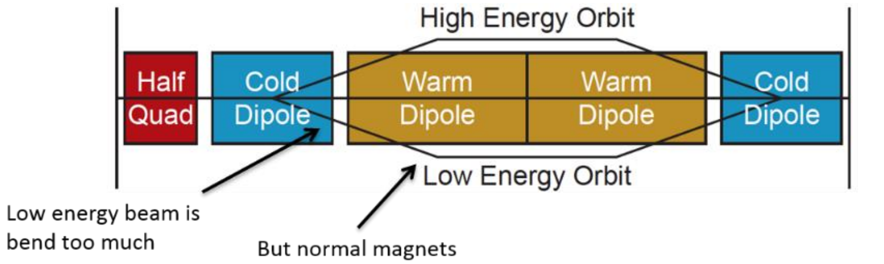


- Hybrid RCSs have intersecting normal conducting (NC) and superconducting (SC) magnets.
- The studies presented aim to determine the RF (cavity) and lattice parameter (number of RF stations, momentum compaction factor,…) → Parameteric study

A lot of constraints

- 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
- To decrease cost operation, we should:
  - Minimize the total voltage and thus energy gain per turn:

    Energy gain: $\Delta E = \frac{E_{ext}-E_{inj}}{\tau_{acc}}\frac{L_{RCS}}{c}$ ⇒ RCS as small as possible
  - Interest of a hybrid RCS: higher average field ⇒ smaller synchotron.
    - But different path lengths and orbits.
  - Optimize the dipole ramp to minimize the power consumption.
- Find the best ratio extraction/injection ratio between the different acceleration stages.



Low energy beam is bend too much

But normal magnets bend back

Significant aperture required to accommodate different beams

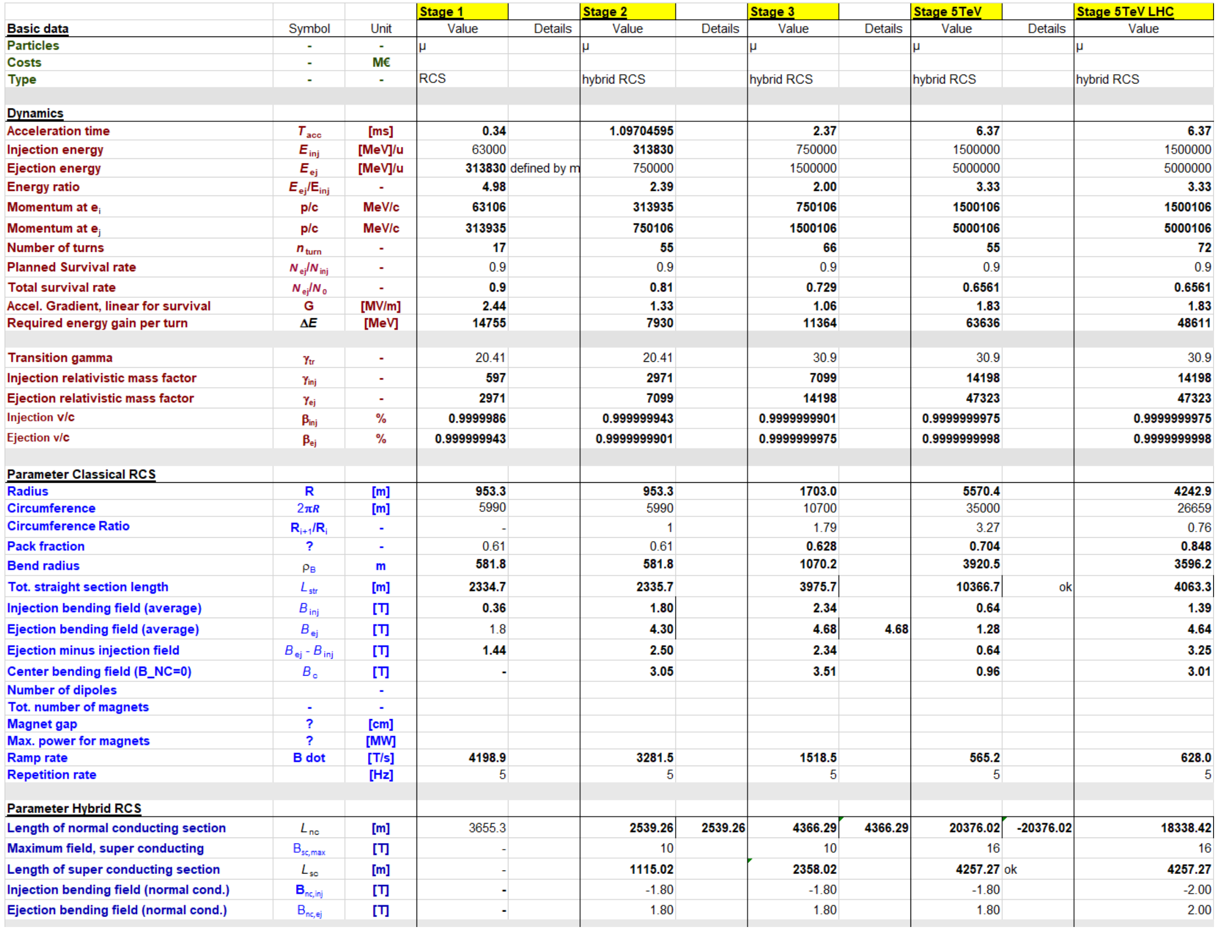
$$L_{NC} = 2\pi\frac{B\rho_{ext}-B\rho_{inj}}{B_{NC,ext}-B_{NC,inj}} = \pi\frac{B\rho_{ext}-B\rho_{inj}}{B_{NC}}$$

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

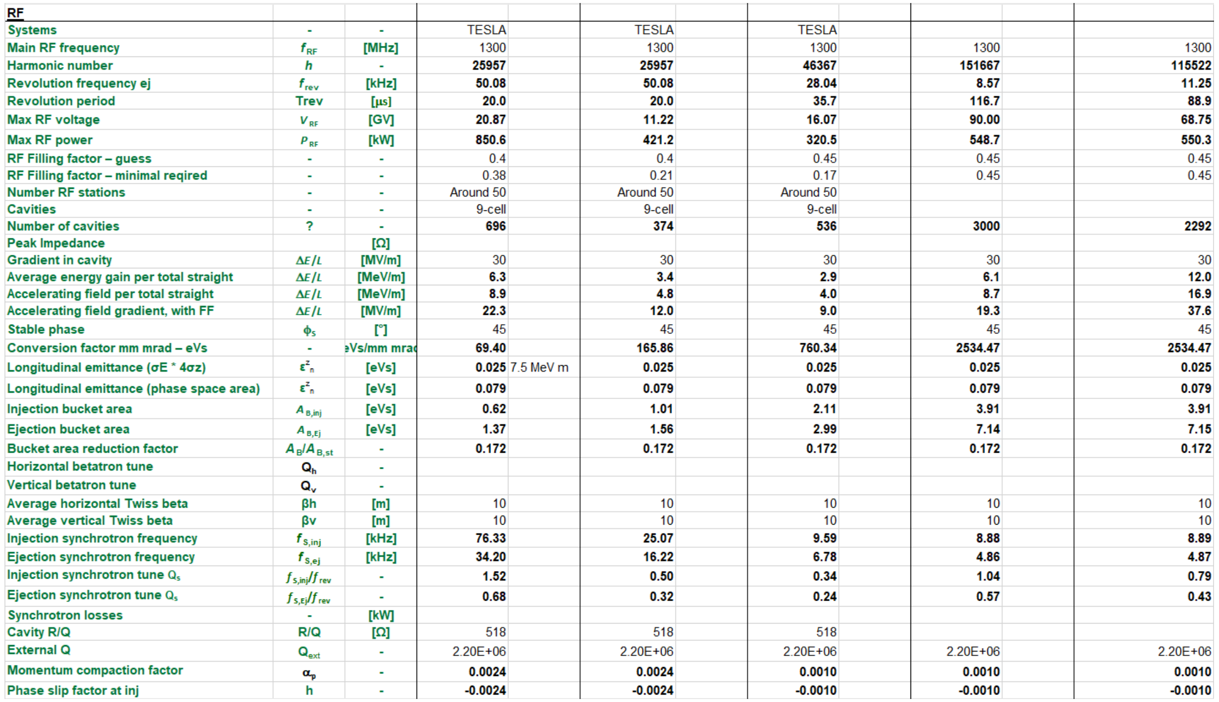
See presentation at Collaboration Meeting

Parameters and tools:
General parameter

Courtesy: Fabian Batsch



			Stage 1		Stage 2		Stage 3		Stage 5TeV		Stage 5TeV LHC
Basic data	Symbol	Unit	Value	Details	Value	Details	Value	Details	Value	Details	Value
Particles	-	-	μ		μ		μ		μ		μ
Costs	-	M€									
Type	-	-	RCS		hybrid RCS		hybrid RCS		hybrid RCS		hybrid RCS
Dynamics											
Acceleration time	T_{acc}	[ms]	0.34		1.09704595		2.37		6.37		6.37
Injection energy	E_{inj}	[MeV]/u	63000		313830		750000		1500000		1500000
Ejection energy	E_{ej}	[MeV]/u	313830	defined by m	750000		1500000		5000000		5000000
Energy ratio	E_{ej}/E_{inj}	-	4.98		2.39		2.00		3.33		3.33
Momentum at e_i	p/c	MeV/c	63106		313935		750106		1500106		1500106
Momentum at e_j	p/c	MeV/c	313935		750106		1500106		5000106		5000106
Number of turns	n_{turn}	-	17		55		66		55		72
Planned Survival rate	N_{ej}/N_{inj}	-	0.9		0.9		0.9		0.9		0.9
Total survival rate	N_{ej}/N_0	-	0.9		0.81		0.729		0.6561		0.6561
Accel. Gradient, linear for survival	G	[MV/m]	2.44		1.33		1.06		1.83		1.83
Required energy gain per turn	ΔE	[MeV]	14755		7930		11364		63636		48611
Transition gamma	γ_{tr}	-	20.41		20.41		30.9		30.9		30.9
Injection relativistic mass factor	γ_{inj}	-	597		2971		7099		14198		14198
Ejection relativistic mass factor	γ_{ej}	-	2971		7099		14198		47323		47323
Injection v/c	β_{inj}	%	0.9999986		0.999999943		0.9999999901		0.9999999975		0.9999999975
Ejection v/c	β_{ej}	%	0.999999943		0.9999999901		0.9999999975		0.9999999998		0.9999999998
Parameter Classical RCS											
Radius	R	[m]	953.3		953.3		1703.0		5570.4		4242.9
Circumference	$2\pi R$	[m]	5990		5990		10700		35000		26659
Circumference Ratio	R_{i+1}/R_i	-	-		1		1.79		3.27		0.76
Pack fraction	?	-	0.61		0.61		0.628		0.704		0.848
Bend radius	ρ_B	m	581.8		581.8		1070.2		3920.5		3596.2
Tot. straight section length	L_{str}	[m]	2334.7		2335.7		3975.7		10366.7	ok	4063.3
Injection bending field (average)	B_{inj}	[T]	0.36		1.80		2.34		0.64		1.39
Ejection bending field (average)	B_{ej}	[T]	1.8		4.30		4.68	4.68	1.28		4.64
Ejection minus injection field	$B_{ej} - B_{inj}$	[T]	1.44		2.50		2.34		0.64		3.25
Center bending field (B_NC=0)	B_c	[T]	-		3.05		3.51		0.96		3.01
Number of dipoles		-									
Tot. number of magnets	-	-									
Magnet gap	?	[cm]									
Max. power for magnets	?	[MW]									
Ramp rate	B dot	[T/s]	4198.9		3281.5		1518.5		565.2		628.0
Repetition rate		[Hz]	5		5		5		5		5
Parameter Hybrid RCS											
Length of normal conducting section	L_{nc}	[m]	3655.3		2539.26	2539.26	4366.29	4366.29	20376.02	-20376.02	18338.42
Maximum field, super conducting	$B_{sc,max}$	[T]	-		10		10		16		16
Length of super conducting section	L_{sc}	[m]	-		1115.02		2358.02		4257.27	ok	4257.27
Injection bending field (normal cond.)	$B_{nc,inj}$	[T]	-		-1.80		-1.80		-1.80		-2.00
Ejection bending field (normal cond.)	$B_{nc,ej}$	[T]	-		1.80		1.80		1.80		2.00

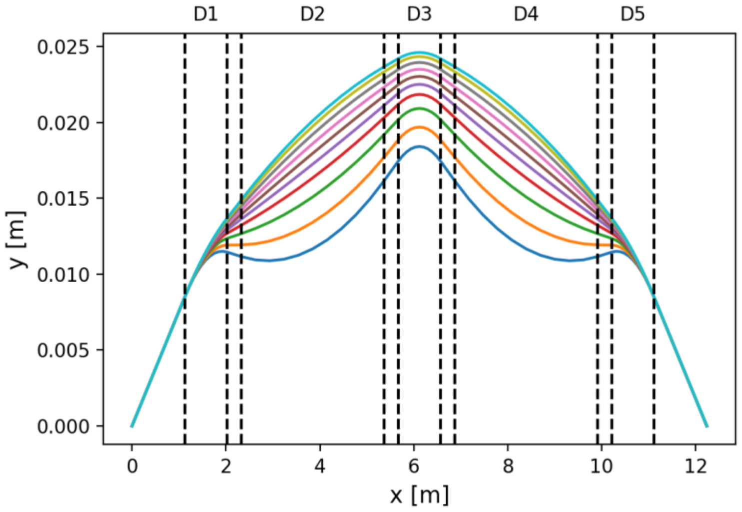


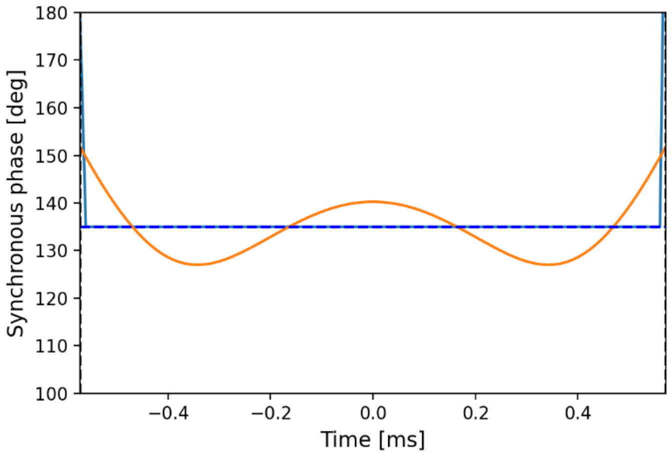
RF											
Systems	-	-	TESLA		TESLA		TESLA				
Main RF frequency	f_{RF}	[MHz]	1300		1300		1300		1300		1300
Harmonic number	h	-	25957		25957		46367		151667		115522
Revolution frequency ej	f_{rev}	[kHz]	50.08		50.08		28.04		8.57		11.25
Revolution period	Trev	[μs]	20.0		20.0		35.7		116.7		88.9
Max RF voltage	V_{RF}	[GV]	20.87		11.22		16.07		90.00		68.75
Max RF power	P_{RF}	[kW]	850.6		421.2		320.5		548.7		550.3
RF Filling factor – guess	-	-	0.4		0.4		0.45		0.45		0.45
RF Filling factor – minimal reqired	-	-	0.38		0.21		0.17		0.45		0.45
Number RF stations	-	-	Around 50		Around 50		Around 50				
Cavities	-	-	9-cell		9-cell		9-cell				
Number of cavities	?	-	696		374		536		3000		2292
Peak Impedance		[Ω]									
Gradient in cavity	$\Delta E/L$	[MV/m]	30		30		30		30		30
Average energy gain per total straight	$\Delta E/L$	[MeV/m]	6.3		3.4		2.9		6.1		12.0
Accelerating field per total straight	$\Delta E/L$	[MeV/m]	8.9		4.8		4.0		8.7		16.9
Accelerating field gradient, with FF	$\Delta E/L$	[MV/m]	22.3		12.0		9.0		19.3		37.6
Stable phase	ϕ_s	[°]	45		45		45		45		45
Conversion factor mm mrad – eVs	-	eVs/mm mrad	69.40		165.86		760.34		2534.47		2534.47
Longitudinal emittance (σE * 4σz)	ε^z_n	[eVs]	0.025	7.5 MeV m	0.025		0.025		0.025		0.025
Longitudinal emittance (phase space area)	ε^z_n	[eVs]	0.079		0.079		0.079		0.079		0.079
Injection bucket area	$A_{B,inj}$	[eVs]	0.62		1.01		2.11		3.91		3.91
Ejection bucket area	$A_{B,Ej}$	[eVs]	1.37		1.56		2.99		7.14		7.15
Bucket area reduction factor	$A_B/A_{B,st}$	-	0.172		0.172		0.172		0.172		0.172
Horizontal betatron tune	Q_h	-									
Vertical betatron tune	Q_v	-									
Average horizontal Twiss beta	βh	[m]	10		10		10		10		10
Average vertical Twiss beta	βv	[m]	10		10		10		10		10
Injection synchrotron frequency	$f_{S,inj}$	[kHz]	76.33		25.07		9.59		8.88		8.89
Ejection synchrotron frequency	$f_{S,ej}$	[kHz]	34.20		16.22		6.78		4.86		4.87
Injection synchrotron tune Q_s	$f_{s,inj}/f_{rev}$	-	1.52		0.50		0.34		1.04		0.79
Ejection synchrotron tune Q_s	$f_{s,Ej}/f_{rev}$	-	0.68		0.32		0.24		0.57		0.43
Synchrotron losses	-	[kW]									
Cavity R/Q	R/Q	[Ω]	518		518		518				
External Q	Q_{ext}	-	2.20E+06		2.20E+06		2.20E+06		2.20E+06		2.20E+06
Momentum compaction factor	α_p	-	0.0024		0.0024		0.0010		0.0010		0.0010
Phase slip factor at inj	h	-	-0.0024		-0.0024		-0.0010		-0.0010		-0.0010

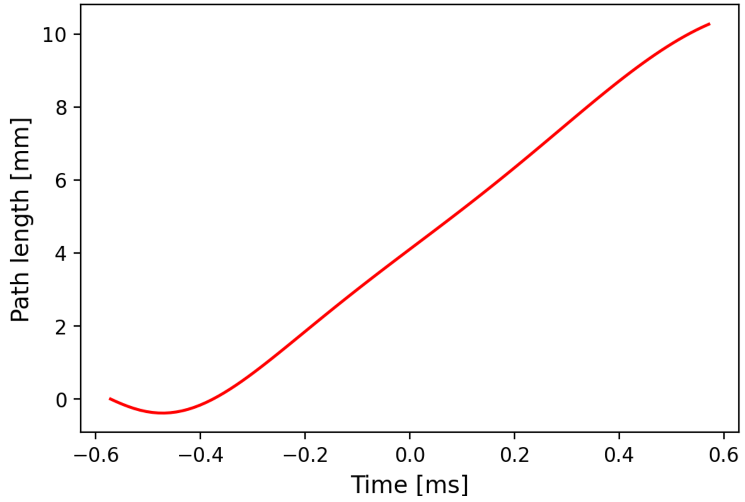
Detailed parameter table:

https://cernbox.cern.ch/index.php/s/I9VpITncUeCBtiz

RCS2:
Case SC first with 5 dipoles and 208 cells



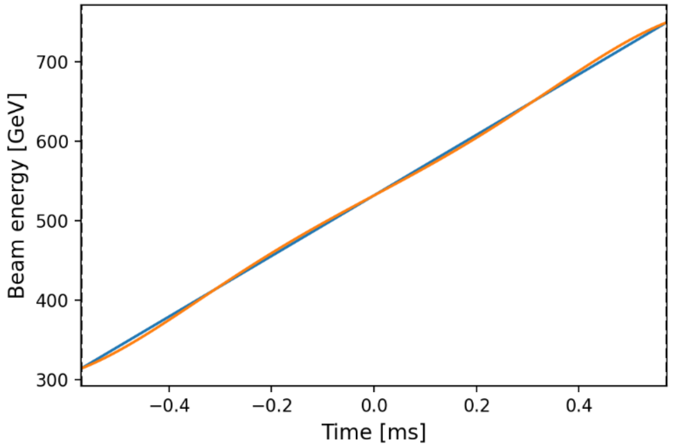




That is possible to get a path length variation of about 1 cm. However, the cell is very compact.

Although the energy ramp is quasi-linear, the synchronous phase varies by more than 10 degrees.

The voltage is assumed to be constant in the cavity.

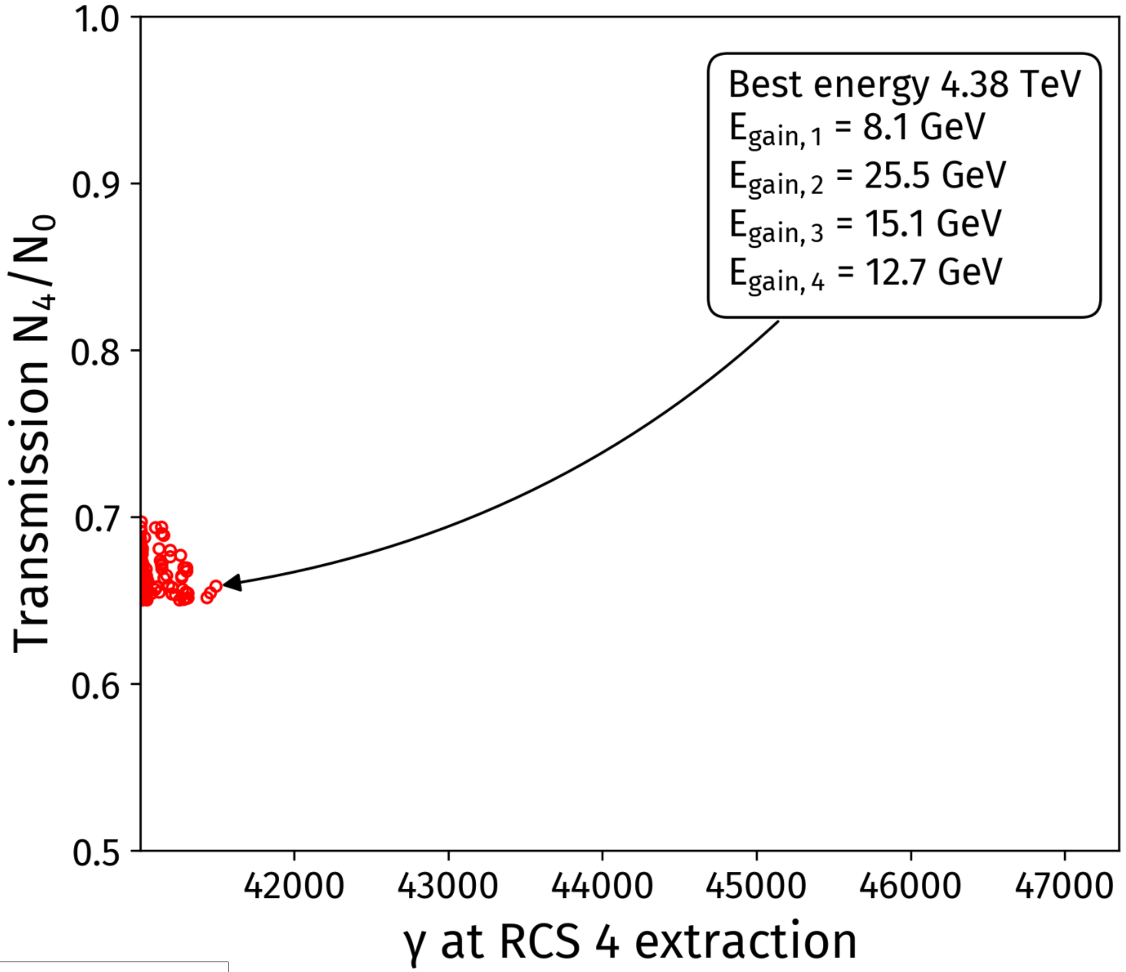


See presentation at Collaboration Meeting

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

SPS and LHC tunnels,
1.8T and 16T for RCS 4 magnets



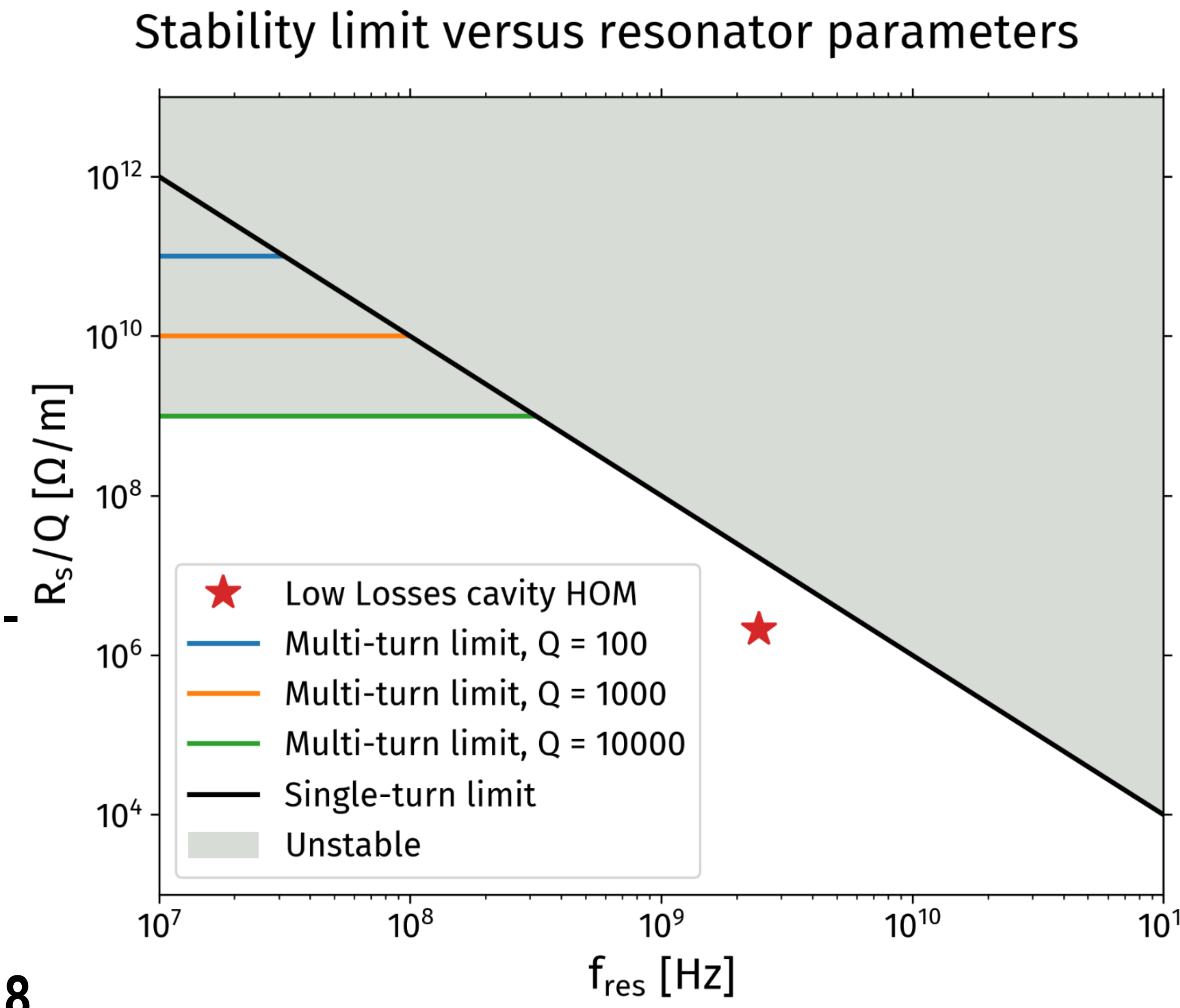
Courtesy: David Amorim

See HEMAC meeting 13

RCS 1: general stability criteria for RF cavity High Order Modes (HOMs)

- Cavity HOMs will create resonant wakefields
- Derived from simulations general stability criteria:
  - **R_s < 100 [MΩ/m] * Q / f^2 [GHz^2] (single turn)**
  - **R_s < 10^{13} Ω/m (multi-turn)**
- Example application for the most critical HOM of ILC-type cavity
  - **$[R_s/Q]_{threshold}$** = 100/2.45^2 = **16.7MΩ/m**
  - **$[R_s/Q]_{total}$ = 2.1 MΩ/m**
- **HOM below the predicted stability limit by factor 8**

See presentation at Collaboration Meeting



Courtesy: David Amorim

Longitudinal dynamics summary (1) – HOM power

Courtesy: Fabian Batsch

Question of HOM power for the TESLA cavity raised during collaboration meeting

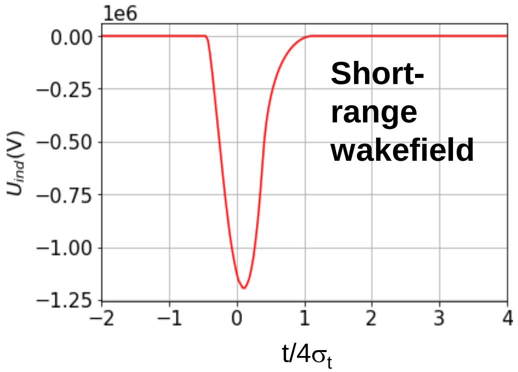
→ **Topic of Accelerators Design Meeting on February 27th**

→ **Calculation of HOM power in TESLA / ILC 1.3 GHz cavity calculated in two ways:**

1. **Calculate power loss through loss factor $k_{||}$ from simulations of the short-range wakefield containing the information about all HOM:**

$$k_{||} = \int \lambda(t) W_{||,SR}(t)dt, \text{ with } W_{||,SR} \text{ the short-range wake potential}$$

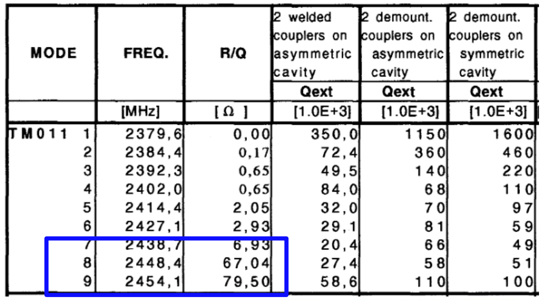
$$\rightarrow P_{HOM} = k_{||} * \frac{Q^2}{T_B} \text{ with bunch charge } Q \text{ and bunch spacing } T_B = T_{rev}$$



2. **Estimation from ABCI simulations and the approximated loss factor for short Gaussian bunches:**

$$k_{||} = \left|\frac{R}{Q}\right| \frac{\omega_r}{2} \; \left(\frac{\omega_r}{4} \text{ for Linac norm}\right)$$

→ **HOM loss factor is sum over all HOMs: $k_{||} = \sum k_{||,i}$**



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
	[MHz]	[Ω]	[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
8	2448,4	67,04	27,4	58	51
9	2454,1	79,50	58,6	110	100

From
“Higher order mode coupler for TESLA”, J. Sekutowisz

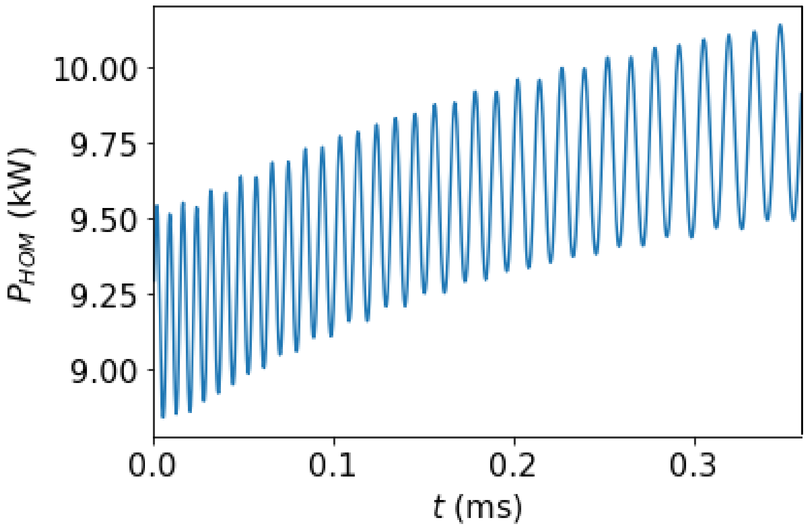
See here (TESLA) & paper (ILC LL)

Results for HOM power

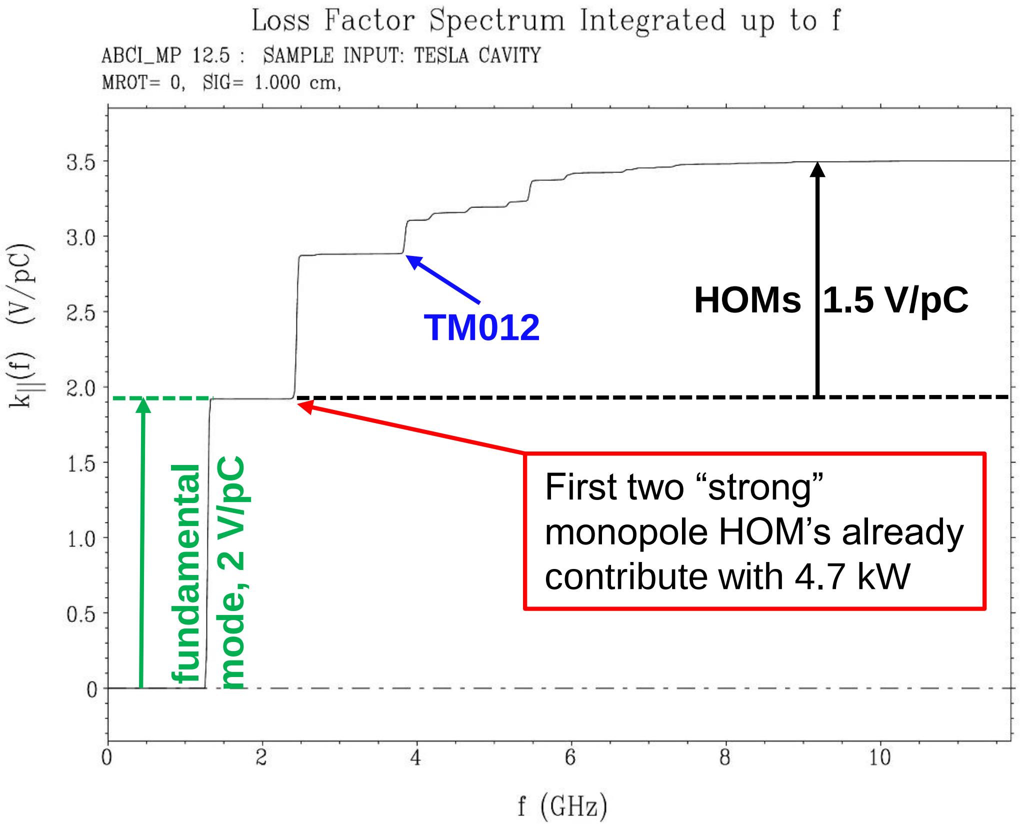
Courtesy: Fabian Batsch

1. From BLonD, for the induced voltage of 1.1 MV/m per cavity, we obtain around 10 kW per bunch and cavity for RCS1!

(Bunch population 2.54×10^{12}, Q=407 nC, T_{rev} = 20 µs → I = 20.4 mA)



2. From HOMs from ABCI: (ABCI file from S.-A. Udongwo):



First two “strong” monopole HOM’s already contribute with 4.7 kW

1.5 V/pC results in 7.9 kW!
→ Consistent with BLonD

- → Large 10 kW HOM power per bunch is a current concern, extremely challenging to handle
- → HOM power coupler for 3-4 kW under development → up to 20 kW per cavity estimate
- → The present parameter tables are based on the ILC cavity (1.3GHz), but a lower frequency, e.g. 800MHz, might be required if the power cannot be handled

RCS 1: Effect of chromaticity on transverse beam stability

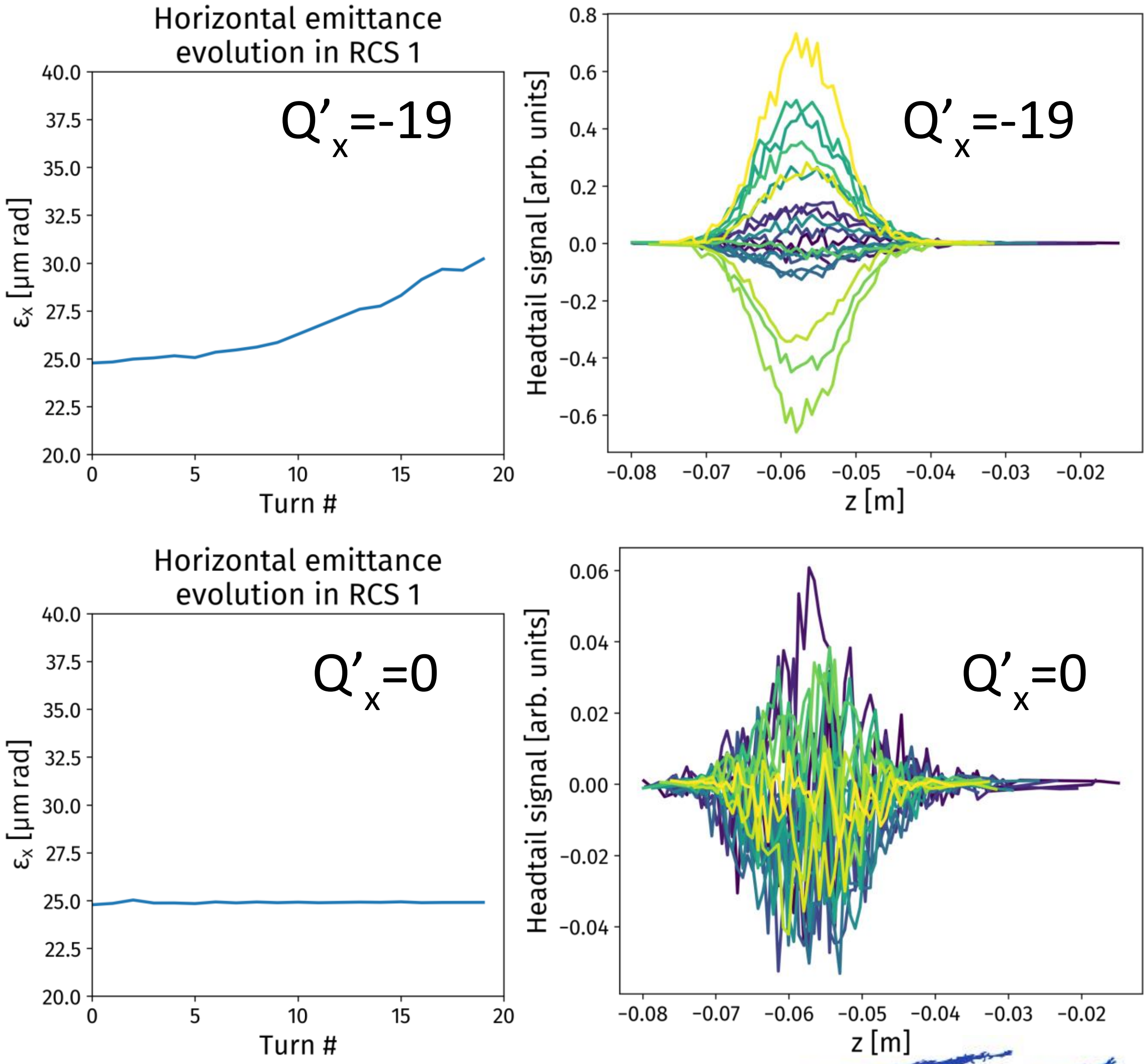
- Simulation with a **factor 2 on the impedance model**

- Check the effect of chromaticity
  - In particular for the **natural chromaticity** Q'=-Q
  - Could we operate without sextupoles?

- Visible **emittance growth** and **headtail motion** with **Q´=-19**

Courtesy: David Amorim

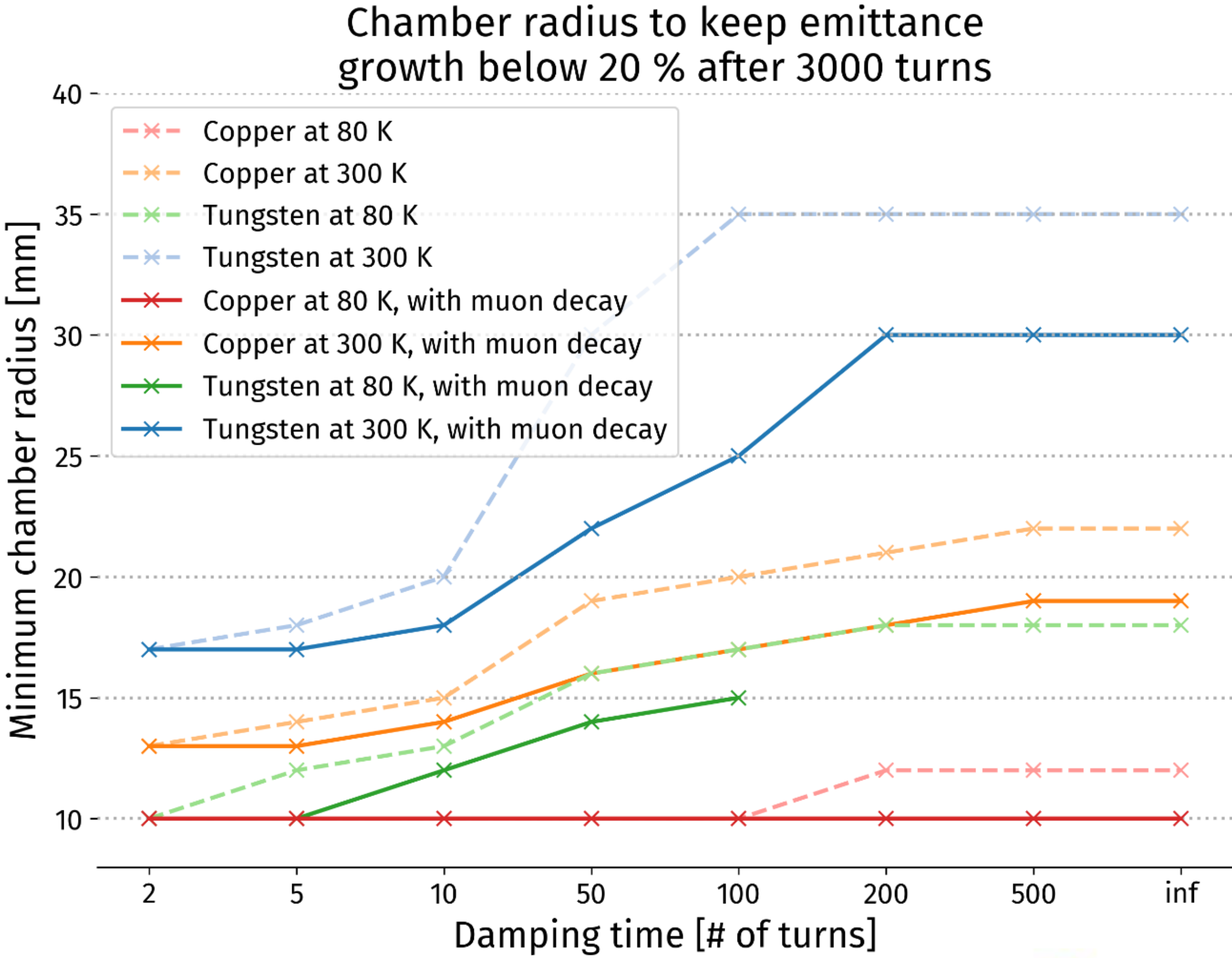
See Accelerator design meeting 21/11/2022



10 TeV collider: Minimum chamber radius achievable versus material

Courtesy: David Amorim

- Investigate different materials for the vacuum chamber
  - Tungsten 300 K and 80 K, Copper 300 K and 80 K
- Find the chamber radius such as the **emittance growth** stays **below 20 %** for different damper gains.
- With **100-turn damper**: **17 mm radius** required with **Copper at 300 K**, versus **25 mm** with **Tungsten at 300 K**

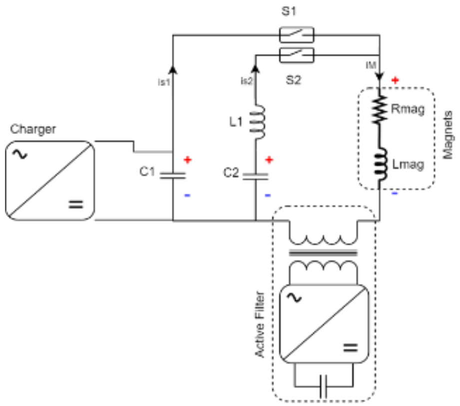


See presentation at Collaboration Meeting

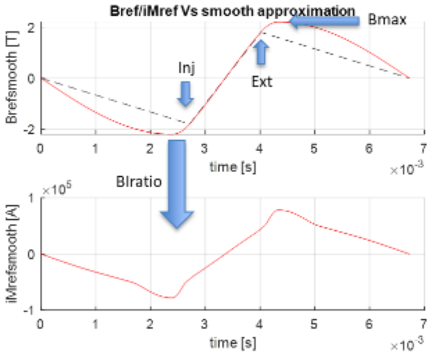
Accelerator magnets and powering system status

Preliminary results

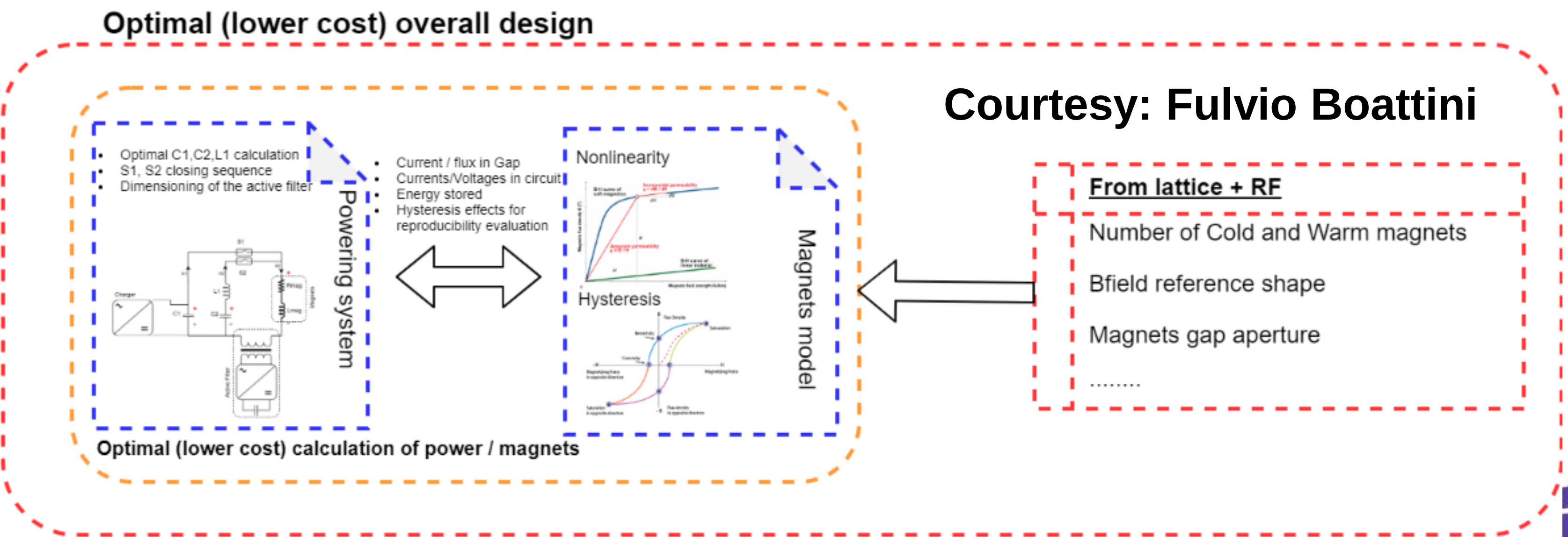
Due to the considerable level of peak power required by the acceleration stage, the best approach is to **use LC discharge circuits**. Dual harmonics discharge circuits have been analyzed. They can provide **close to linear Bref shapes during the acceleration**. A pure linear acceleration profile will probably be extremely expensive because of the huge correcting power that the power electronics would be called to provide via the active filter.



However, the total power must be divided into several sectors (~100). So many LC circuits will probably all resonate differently due to differences in the LC parameters (and temperature effects). **The active filter role would then be to correct the differences among all circuits** which boils down to defining the required control accuracy.



It is important to optimize the design of the accelerating magnets and the power system together, in order to find an optimal solution with an acceptable cost.



Optimal (lower cost) overall design

- Optimal C1,C2,L1 calculation
- S1, S2 closing sequence
- Dimensioning of the active filter

Powering system

- Current / flux in Gap
- Currents/Voltages in circuit
- Energy stored
- Hysteresis effects for reproducibility evaluation

Nonlinearity

Hysteresis

Magnets model

Optimal (lower cost) calculation of power / magnets

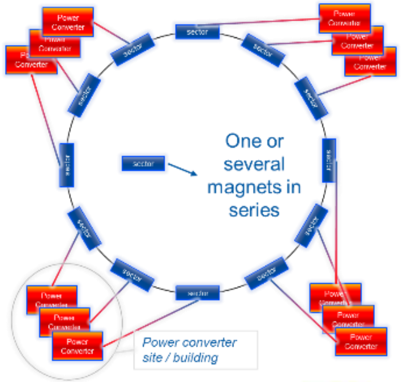
From lattice + RF

Number of Cold and Warm magnets

Bfield reference shape

Magnets gap aperture

……..



Courtesy: Fulvio Boattini

Accelerator magnets and powering system next steps

Courtesy: Fulvio Boattini

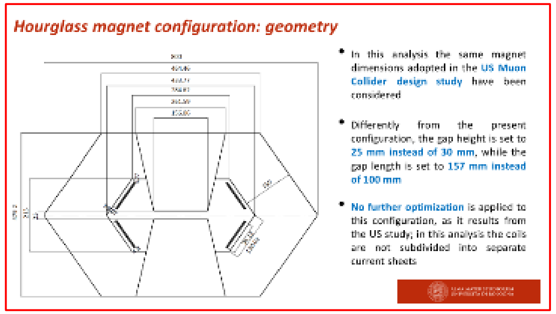
- *Resistive Magnets*

Comparison of different Dipoles designs with different steel materials (CERN/UNIBO):

Comparison will be made based on:

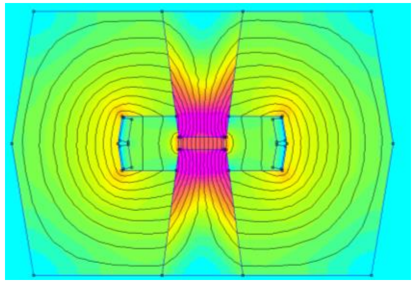
- Total NRG Vs Gap NRG ratio
- Losses in Iron and copper
- Material volume and cost

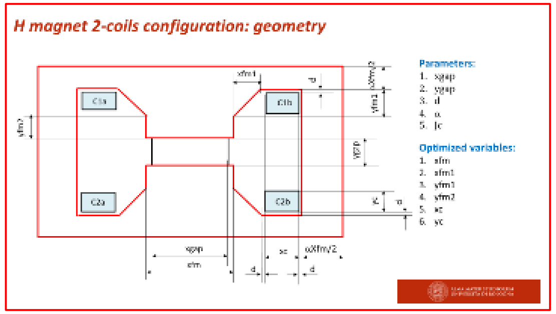
Integrated design of magnets and power systems requires magnetic models that consider saturation of magnetic materials and hysteresis (CERN/TUD)



Hourglass magnet configuration: geometry

- In this analysis the same magnet dimensions adopted in the US Muon Collider design study have been considered
- Differently from the present configuration, the gap height is set to 25 mm instead of 30 mm, while the gap length is set to 157 mm instead of 100 mm
- No further optimization is applied to this configuration, as it results from the US study; in this analysis the coils are not subdivided into separate current sheets





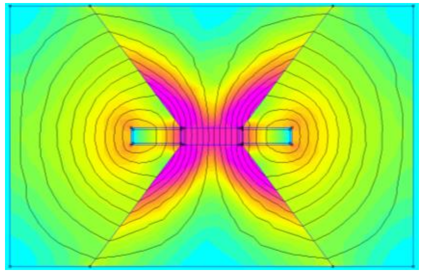
H magnet 2-coils configuration: geometry

Parameters:

1. xgap
2. ygap
3. d
4. α
5. Jc

Optimized variables:

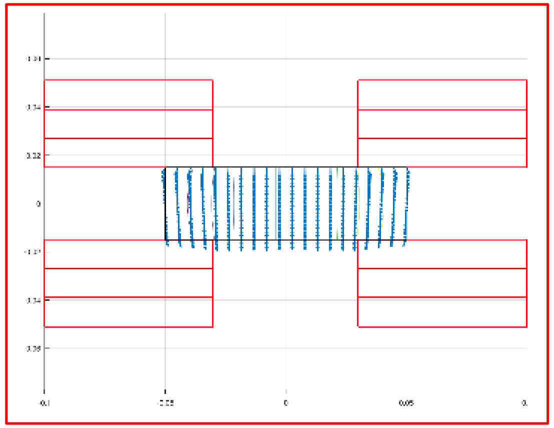
1. xfm
2. xfm1
3. yfm1
4. yfm2
5. xc
6. yc



- *Superconductive Magnets*

Exploring SC magnet concepts that may profit from a rectangular aperture

- Simplify magnet design, profiting from the small aperture (30 mm x 100 mm)
- Adapt coil geometry
- Attempt to use uniform technology through the collider complex
  - HTS windings (for robustness)
  - High current density (for cost reasons)
  - Operation at high temperature (for energy efficiency)
- We need to confirm beam decay losses (average 3W/m?)

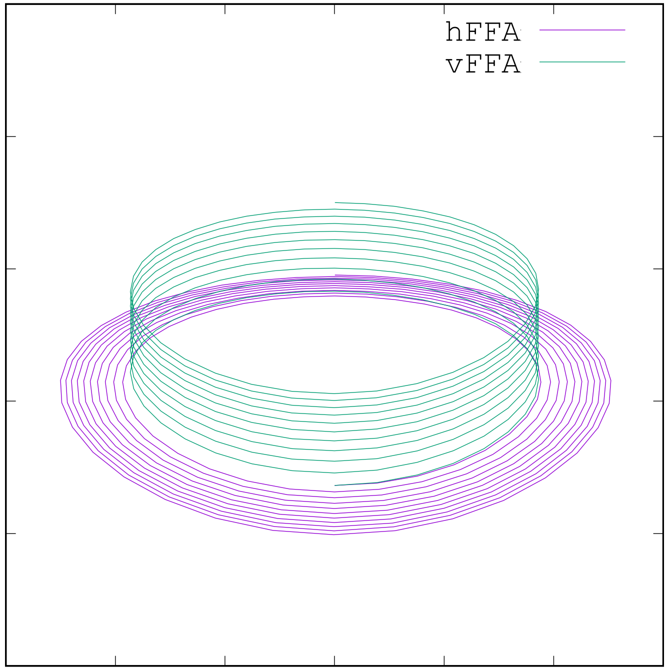


Flat racetracks
12 mm tape
J_E = 650 A/mm^2
B = 10 T

Calculations at Rref = 10 mm
B1 = 10.355
b3 = -7.2 units
b5 = -1.4 units
b7 = -0.03 units

FFAs for muon acceleration

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

hFFA	vFFA
- Higher energy orbits are radial enlargements of low energy orbits	- High energy orbits are exact vertically translated copies of low energy orbits
Zero chromaticity with $B = B_0 \left(\frac{r}{r_0}\right)^k$	- Zero chromaticity with $B = B_0 e^{mz}$
	- Zero momentum compaction factor
	- Quasi-isochronous (fixed RF frequency)

Drawback of the vFFA

Courtesy: Max Topp-Mugglestone

	FODO	FDF
Energy	50 GeV to 1.5 TeV	50 GeV to 1.5 TeV
Cell length	35 m	52.5 m
Magnet length	2 x 15 m	3 x 15 m
# of cell	810	540
Maximum field	8.7 T	10.6 T
Field index m	6.8	3.0
Orbit excursion	0.50 m	1.13 m
Cell tune	0.3957 / 0.0861	0.3510 / 0.1515

Table: early vFFA muon accelerator design parameter exercise (S. Machida, 2020)

- Limited understanding of optics
  - Unique coupling behaviour
    - Dominated by skew quadrupole focussing
    - Solenoid components in fringe fields
  - Nonplanar orbits
- Challenging optimisation

- Current research field: develop understanding of vFFA and optimise vFFA lattice for muon acceleration
  - Reduce ring size
  - Reduce excursion
  - Maximise dynamic aperture

Update of vFFA study

Courtesy: Max Topp-Mugglestone

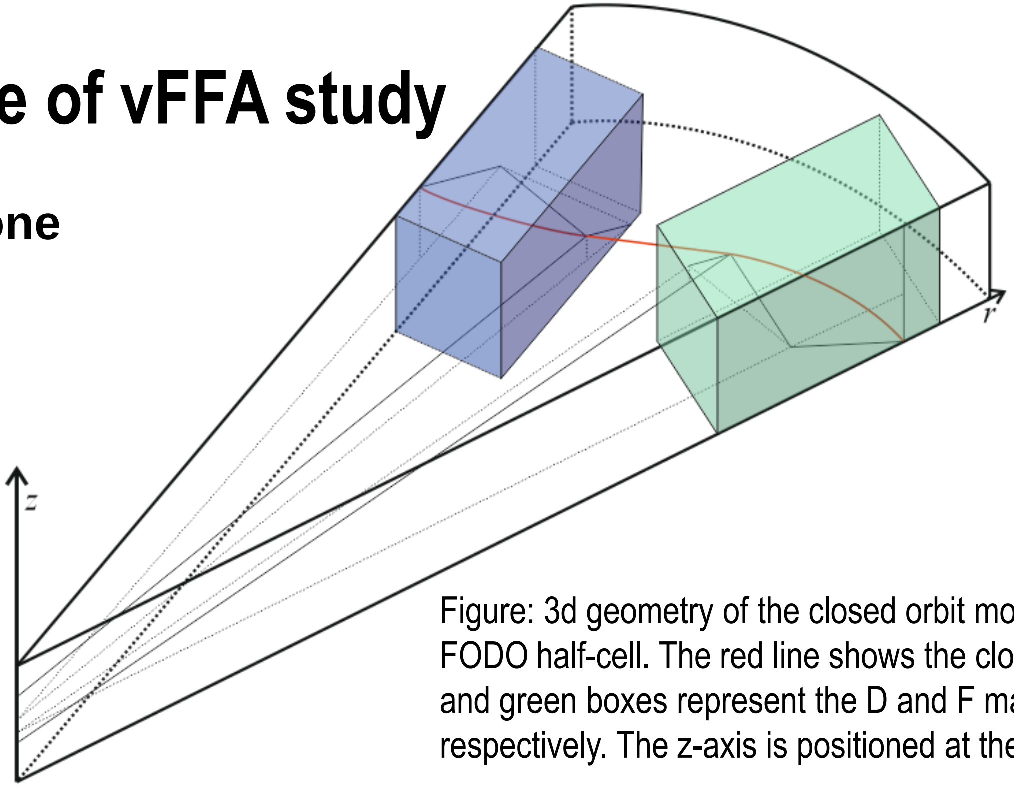


Figure: 3d geometry of the closed orbit model for a vFFA FODO half-cell. The red line shows the closed orbit; the blue and green boxes represent the D and F magnets respectively. The z-axis is positioned at the machine centre

- Analytic model of vFFA optics for large-ring FODO lattices has been developed
  - Non-planar orbit geometry
  - Parameters of closed orbit derived from geometric constraints
  - 4d decoupled tunes and stability of candidate lattices can be evaluated without numerical simulation*

Numerical crosscheck of new model is not complete!

- Next steps:
  - Numerical benchmarking of analytic model
  - Use analytic model to optimise vFFA lattices for muon acceleration
    - Optimising for lowest peak B-field, lowest excursion (difference in orbit position between injection and extraction) for given energy sweep.
- Physical prototype of vFFA magnet due for construction

Summary and next steps

- The main goal of this WG is to gather information (from other WGs) to get a **coherent parameter table** for a chain of pulsed synchrotrons or FFA. We get regular meetings in this aim.
- A parameter table is regularly updated here: **https://cernbox.cern.ch/index.php/s/l9VplTncUeCBtiz**
  - The current baseline has 4 RCS to go up to 5 TeV with possible reuse of LHC tunnel.
  - Genetic algorithms are considered also to optimize the different stages (already a **good agreement** with current table).
- We have a margin of 8 on stability due to (ILC-like) cavity impedance.
  - Nevertheless, the HOM power is huge: **10 kW**.
  - We will consider **another frequency like 800 MHz** to see the improvement.
- Stability studies show that we should correct the chromaticity in RCS1.
- For the collider, resistive wall impedances require a beam screen radius of 17 mm with Copper at 300 K against 25 mm with Tungsten at 300 K. The studies need to be updated for the acceleration chain.
- **Dual harmonics discharge circuits can provide close to linear Bref shapes** during the acceleration.
- We have first design of the resistive and SC magnets. The work is on-going.
- Analytic model of vFFA optics for large-ring has been developed. The next steps are numerical benchmarking, lattice optimization and magnet protype construction.

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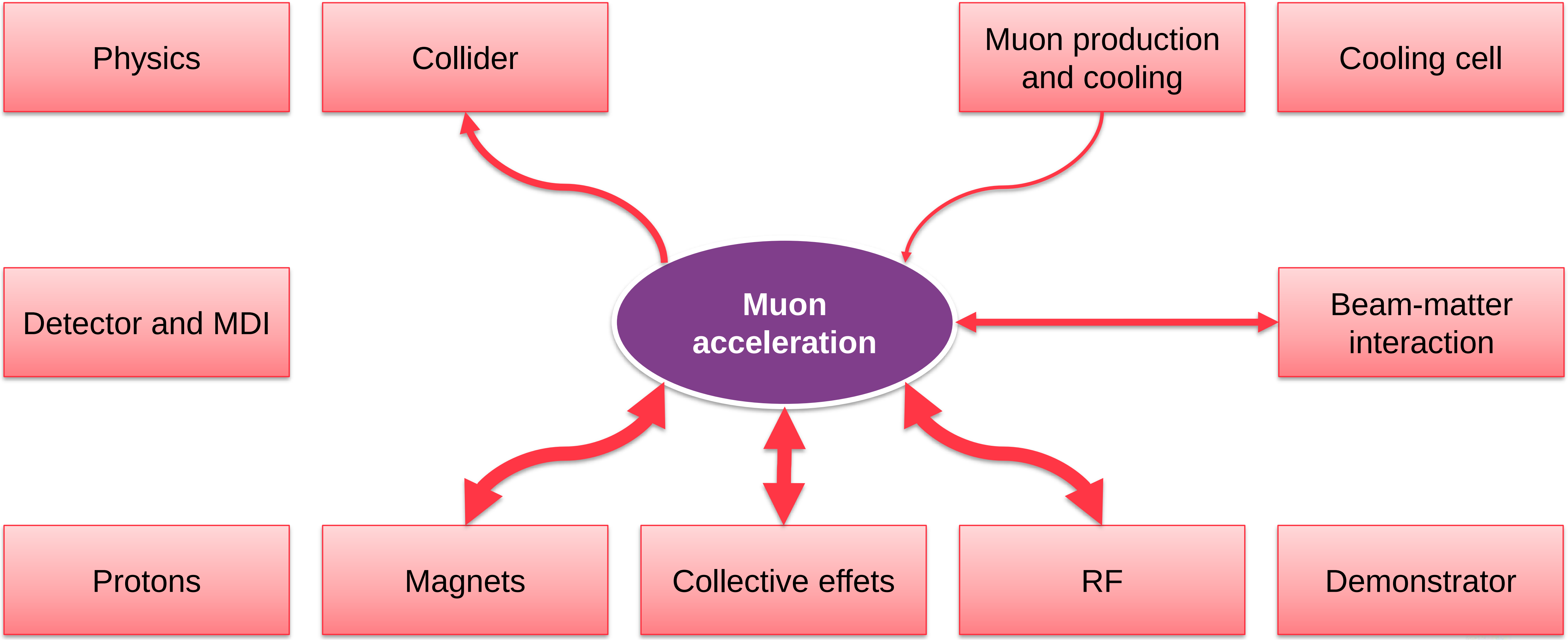
Backup

Strong interaction with other WPs



Physics

Collider

Muon production and cooling

Cooling cell

Detector and MDI

Muon acceleration

Beam-matter interaction

Protons

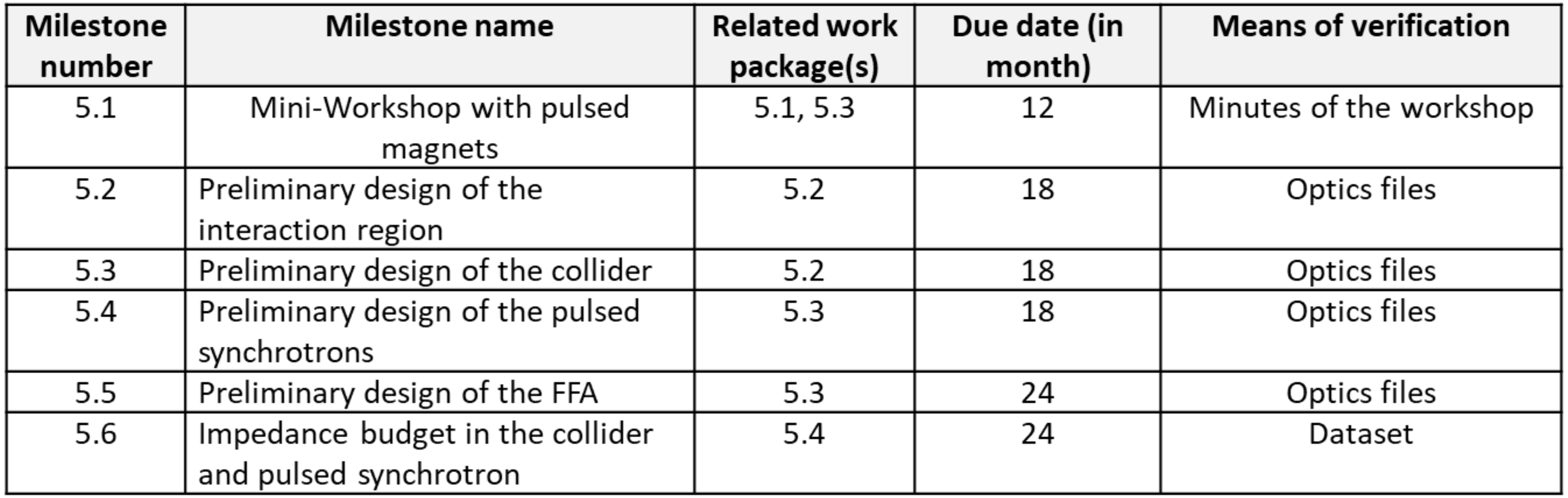
Magnets

Collective effets

RF

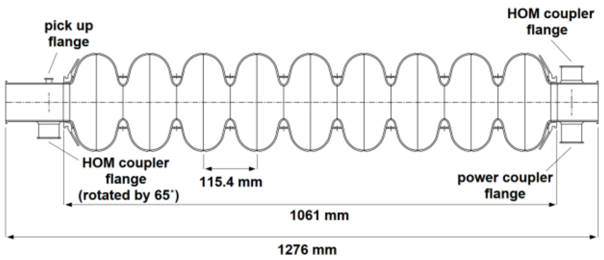
Demonstrator

MuCol
Milestones



Milestone number	Milestone name	Related work package(s)	Due date (in month)	Means of verification
5.1	Mini-Workshop with pulsed magnets	5.1, 5.3	12	Minutes of the workshop
5.2	Preliminary design of the interaction region	5.2	18	Optics files
5.3	Preliminary design of the collider	5.2	18	Optics files
5.4	Preliminary design of the pulsed synchrotrons	5.3	18	Optics files
5.5	Preliminary design of the FFA	5.3	24	Optics files
5.6	Impedance budget in the collider and pulsed synchrotron	5.4	24	Dataset

Parameters and tools:
RF – The TESLA cavity



From design report

- **Studies are based on the 1.3 GHz Tesla cavity (design report: Phys. Rev. ST Accel. Beams 3, 092001, 2000)**

  → see talk by A. Yamamoto

- **Relevant beam parameter**
  - **Bunch population 2.54x10^{12}, ε_L=0.01 eVs** → large intensity effects
  - **Bunch current 20.4 / 18.8 / 10.0 mA → 2x430 kW per cavity**
  - **700 / 374 / 532 cavities** in ring, distributed over n_{RF} RF stations (with 30 MV/m accelerating gradient)
  - **Synchronous phase 45°** (above transition: γ_{tr} = 20.41, 600 < γ < 14200)
- **TESLA Cavity parameter (9 cells, *L*=1.06 m):**
  - **f_{RF} = 1.3 GHz → harmonic number *h* = 25957 to 46367**
  - **R/Q = 518** Ω, total R_s = 306 GΩ
  - **Gradient 30 MV/m**
  - **Q_L = 2.2e6** (for beam loading compensation with Δf = 320 Hz)

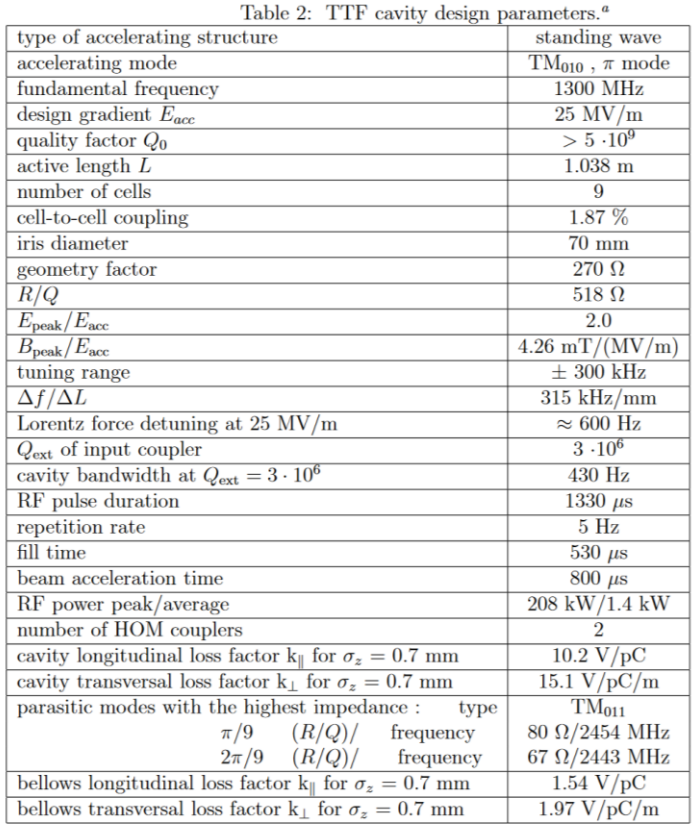


Table 2: TTF cavity design parameters.[a]

type of accelerating structure	standing wave
accelerating mode	TM_{010} , π mode
fundamental frequency	1300 MHz
design gradient E_{acc}	25 MV/m
quality factor Q_0	$> 5 \cdot 10^9$
active length L	1.038 m
number of cells	9
cell-to-cell coupling	1.87 %
iris diameter	70 mm
geometry factor	270 Ω
R/Q	518 Ω
E_{peak}/E_{acc}	2.0
B_{peak}/E_{acc}	4.26 mT/(MV/m)
tuning range	± 300 kHz
$\Delta f/\Delta L$	315 kHz/mm
Lorentz force detuning at 25 MV/m	≈ 600 Hz
Q_{ext} of input coupler	$3 \cdot 10^6$
cavity bandwidth at $Q_{ext} = 3 \cdot 10^6$	430 Hz
RF pulse duration	1330 μs
repetition rate	5 Hz
fill time	530 μs
beam acceleration time	800 μs
RF power peak/average	208 kW/1.4 kW
number of HOM couplers	2
cavity longitudinal loss factor $k_\parallel$ for $\sigma_z = 0.7$ mm	10.2 V/pC
cavity transversal loss factor $k_\perp$ for $\sigma_z = 0.7$ mm	15.1 V/pC/m
parasitic modes with the highest impedance : type $\pi/9$ $(R/Q)/$ frequency $2\pi/9$ $(R/Q)/$ frequency	TM_{011} 80 Ω/2454 MHz 67 Ω/2443 MHz
bellows longitudinal loss factor $k_\parallel$ for $\sigma_z = 0.7$ mm	1.54 V/pC
bellows transversal loss factor $k_\perp$ for $\sigma_z = 0.7$ mm	1.97 V/pC/m

From design report

Courtesy: Fabian Batsch