International MUON Collider Collaboration

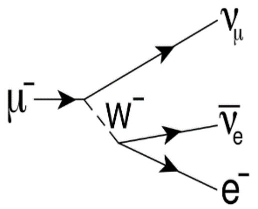
Reports of the working groups: Acceleration and collider

by Antoine Chance (CEA Paris-Saclay)
and Christian Carli (CERN)

Acknowledgements:
F. Batsch, H. Damerau , David Amorim , Kyriacos Skoufaris , Fulvio Boattini,
Max Topp-Mugglestone, I. Karpov, Elias Metral, Scott Berg,
Luca Bottura, Alexej Grudiev, Daniel Schulte

High Energy Complex working group

- Acceleration to high energy (after rec. linacs)
  - Pulsed synchrotrons challenging
    - Very fast magnet ramping (power, eddy ..)
    - Orbit variations with fixed SC and cycled NC magnets
    - Circumference variations and longitudinal dynamics
  - FFAs (vertical) an alternative
- Collider ring
  - Very challenging conditions for lattice
    - Small β^*, short bunches, large energy spread..
    - High energy, neutrino radiation
    - Chromatic effects and compensation …..
  - Iterations with WGs on magnet design, beam loss, MDI, radiation protection ..



Parametric study for a rapid cycling ...
Dr Antoine Chance

RF parameter choices and longitudin...
Mr Fabian Batsch

Transverse impedance and stability ...
Dr David Amorim

Update on studies on vertical FFAs
Max Topp-Muggle...

3 TeV collider transverse impedance ...
Dr David Amorim

Wednesday 14:00
6/R-012

Magnet cycling considerations	*Fulvio Boattini*	
40/S2-D01 - Salle Dirac, CERN	14:00 - 14:20	
RF cycling considerations	*Mr Fabian Batsch*	
40/S2-D01 - Salle Dirac, CERN	14:20 - 14:40	
Collider ring lattice proposal	*Kyriacos Skoufaris*	
40/S2-D01 - Salle Dirac, CERN	14:40 - 15:00	
Neutrino radiation for a realistic collider	*Christian Carli*	
40/S2-D01 - Salle Dirac, CERN	15:00 - 15:20	

Thursday 14:00
40/S2-D01

Dedicated sessions on Wednesday and Thursday afternoon

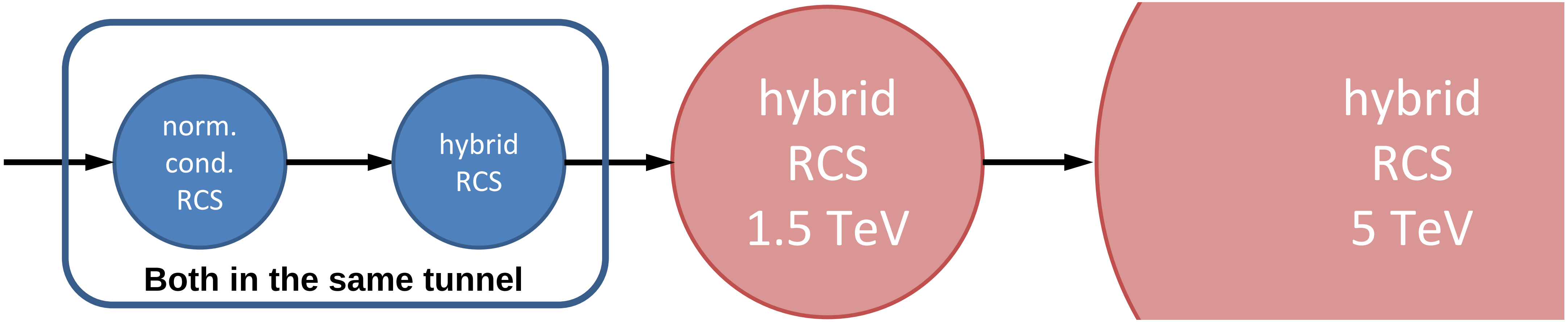
Contributions to and interaction with many WGs (MDI, magnets, beam loss, RP, RF ..)

Rapid Cycling Synchrotron

Detailed parameter table: https://cernbox.cern.ch/index.php/s/I9VpITncUeCBtiz

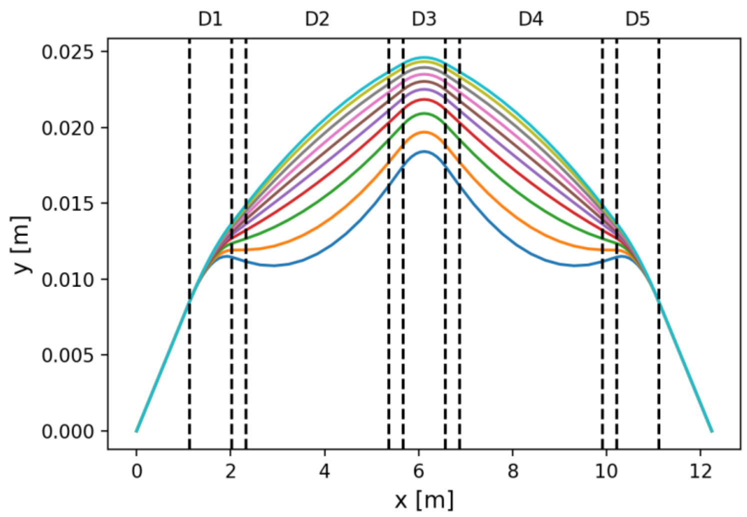
- **Chain of rapid cycling synchrotrons, counter-rotating μ^+/μ^- beams**
  $\rightarrow$ 63 GeV $\rightarrow$ 0.31 TeV $\rightarrow$ 0.75 TeV $\rightarrow$ 1.5 TeV ($\rightarrow$ 5 TeV)

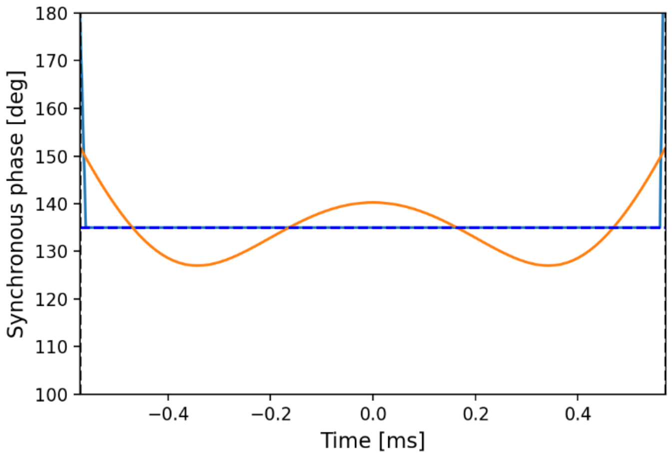
Courtesy: Heiko Damerau

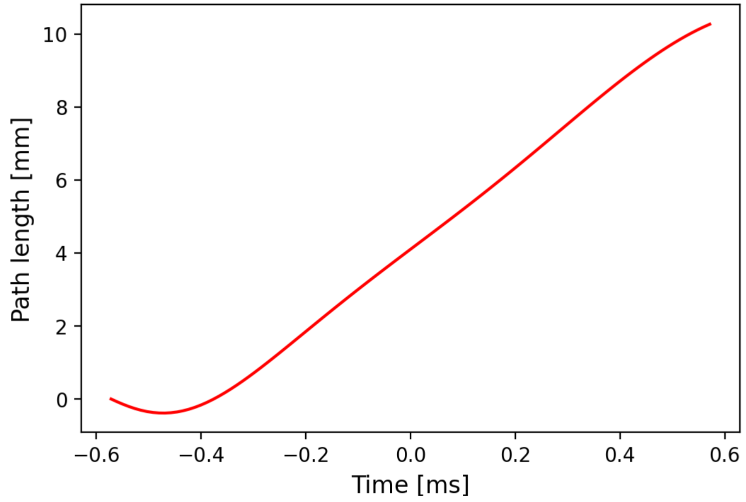


- **Hybrid RCSs have intersecting normal conducting (NC) and superconducting (SC) magnets**
- **The studies presented aim to determine the RF (cavity) and lattice parameter (number of RF stations, momentum compaction factor,…)**

RCS2:
Case SC first with 5 dipoles and 208 cells



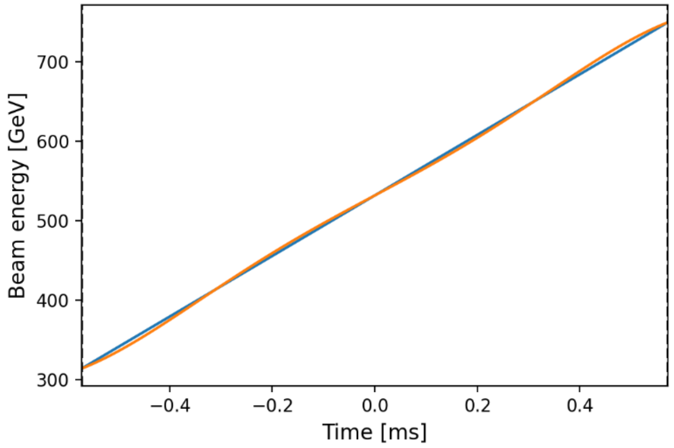




That is possible to get a path length variation of about 1 cm.
However, the cell is very compact.

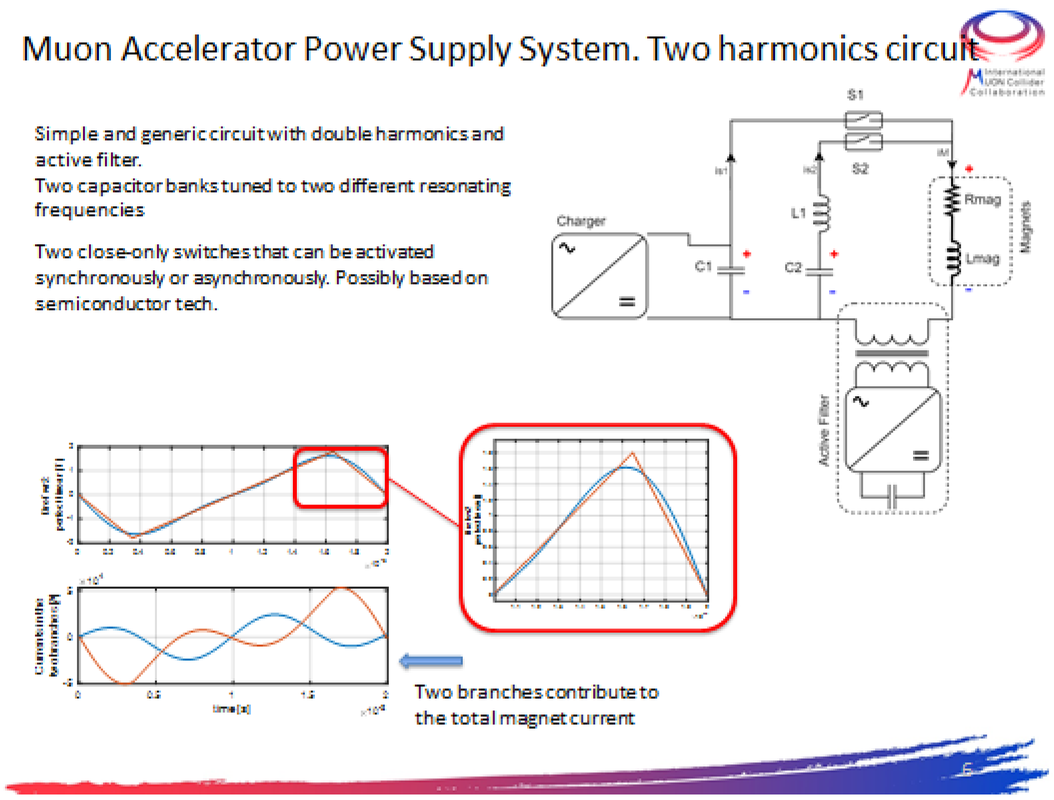
Although the energy ramp is quasi-linear, the synchronous phase varies by more than 10 degrees.

The voltage is assumed to be constant in the cavity.

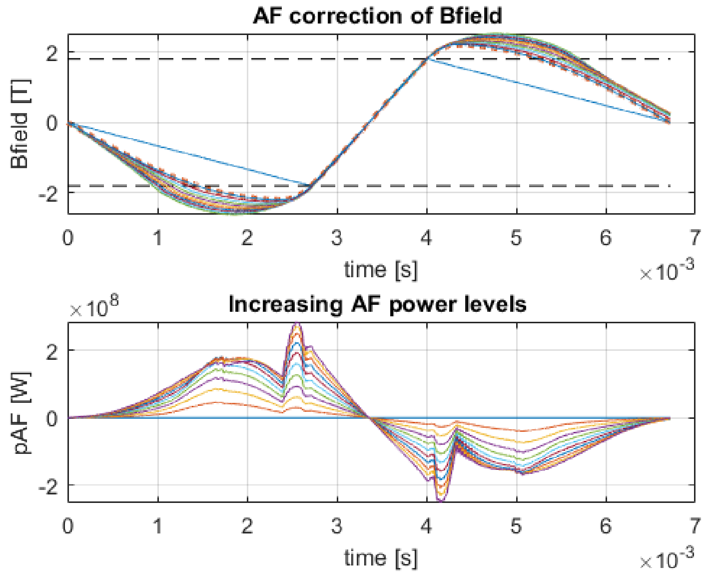


Magnet cycling

Courtesy: Fulvio Boattini



- Multi-step optimization: Bref calculation, Circuit parameters, optimization of free oscillation, Active Filter contribution



Synchrotron tune and number of RF stations (TESLA-like cavities)

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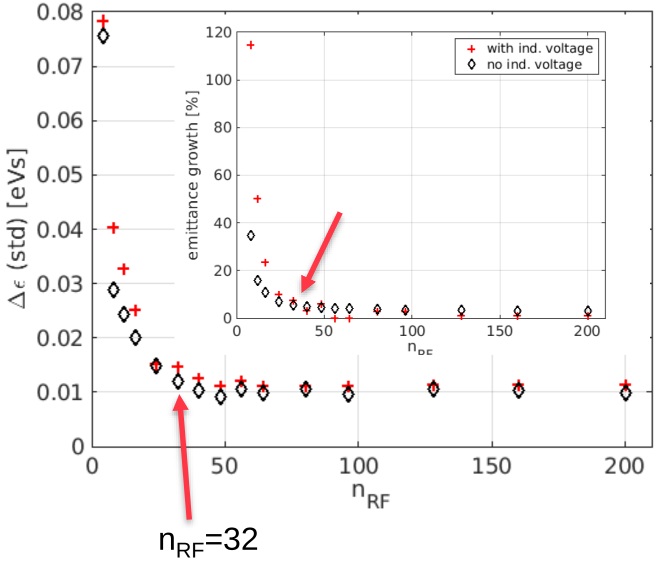
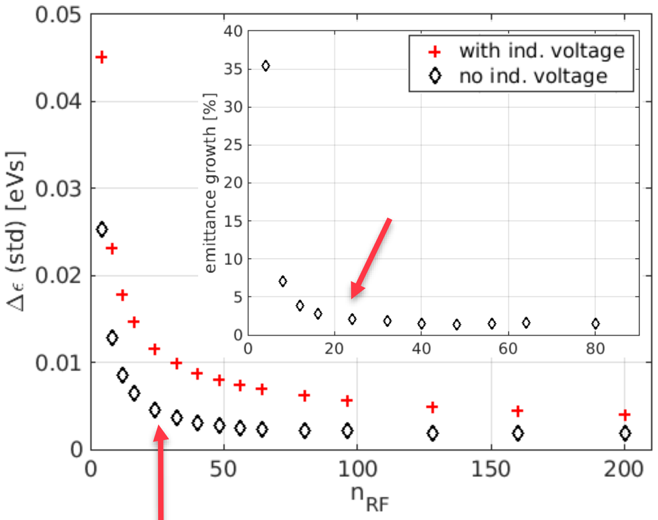
Courtesy: Fabian Batsch

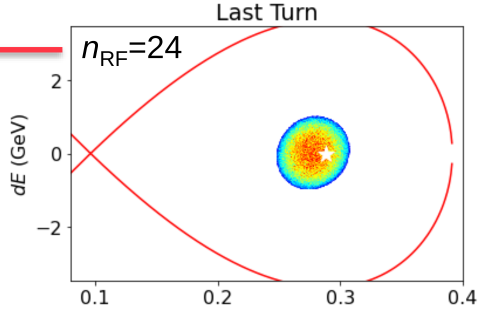
Results for each RCS and with and without induced voltage / intensity effects:

RCS1, $\Delta\varepsilon$ (std)

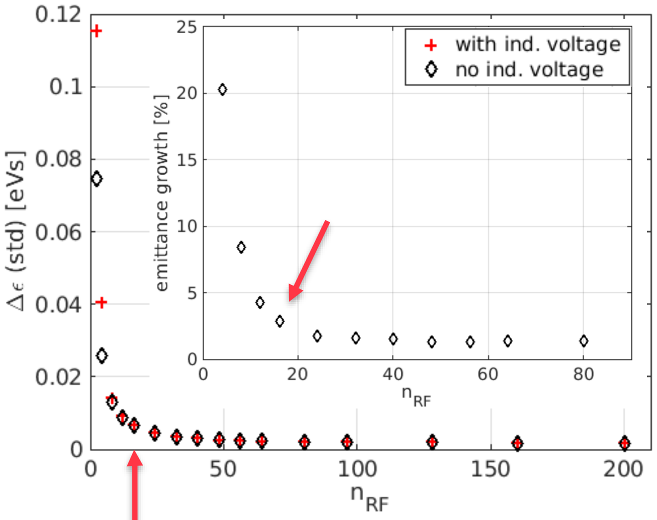


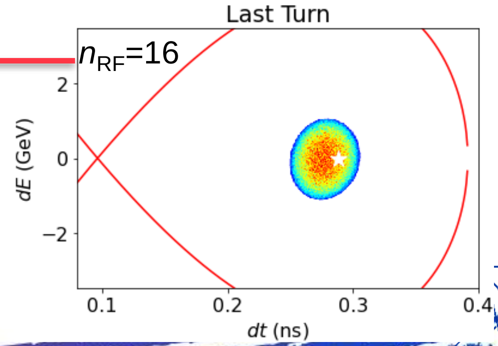
RCS2, $\Delta\varepsilon$ (std)





RCS3, $\Delta\varepsilon$ (std)





Similar behaviour for RCS 2&3, no change for n_{RF} > 48

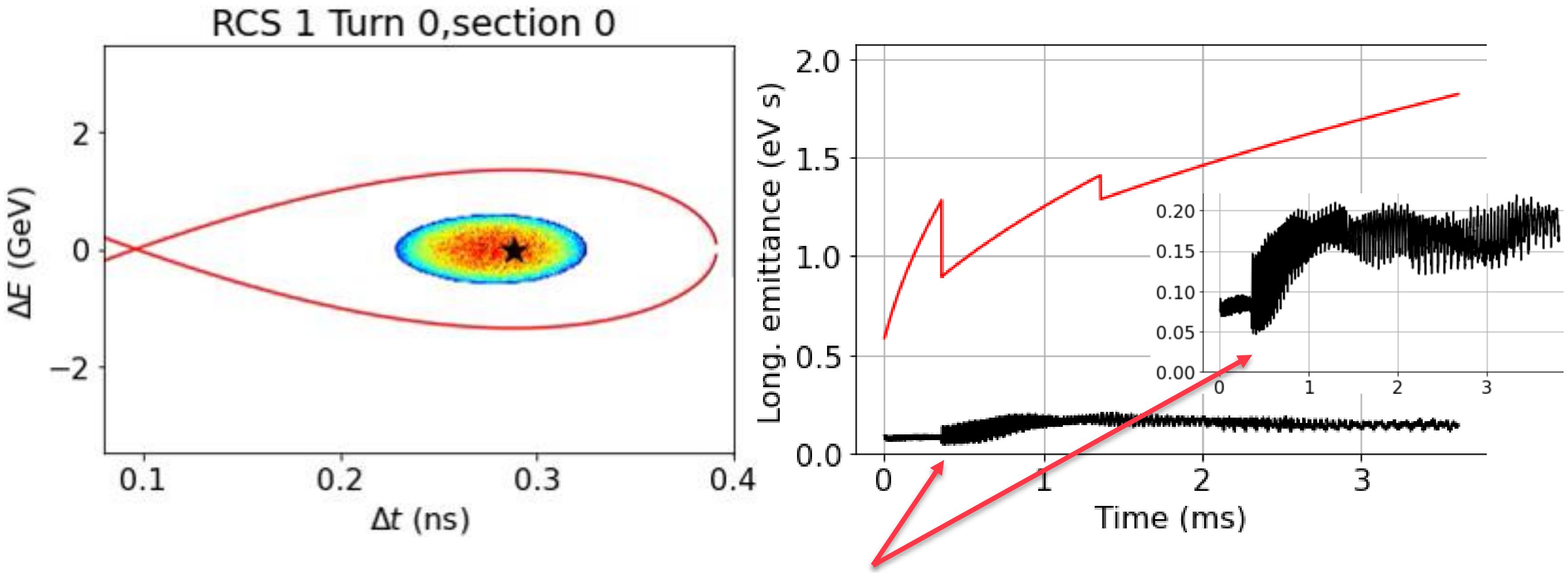
Lower Q_s allows for slightly smaller number in RCS 2&3, e.g. n_{RF} = 24 and 16

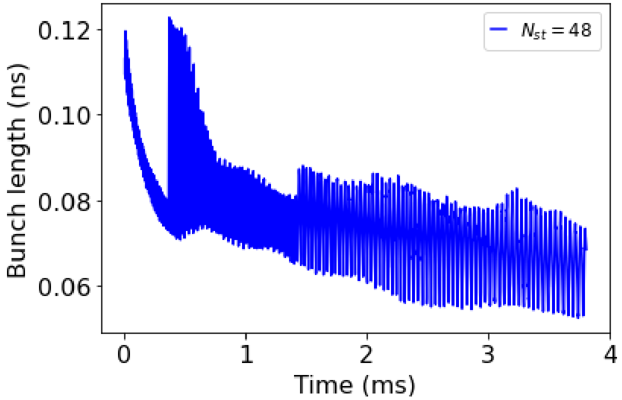
- **Influence of small n_{RF} on two bunches to be investigated**

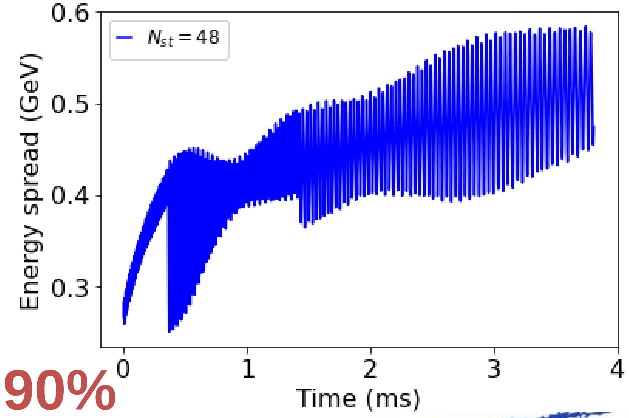
Beam transport though the RCS chain: Evolution of bunch parameter

How do the bunch length, energy spread and emittance evolve when propagating the bunch through not one, but all RCS?

All RCS with n_{RF}=48







- **Unmatched bunch remains main problem, emittance growth 90%**

F. Batsch

Mode stability prediction
Transverse stability in RCS 1

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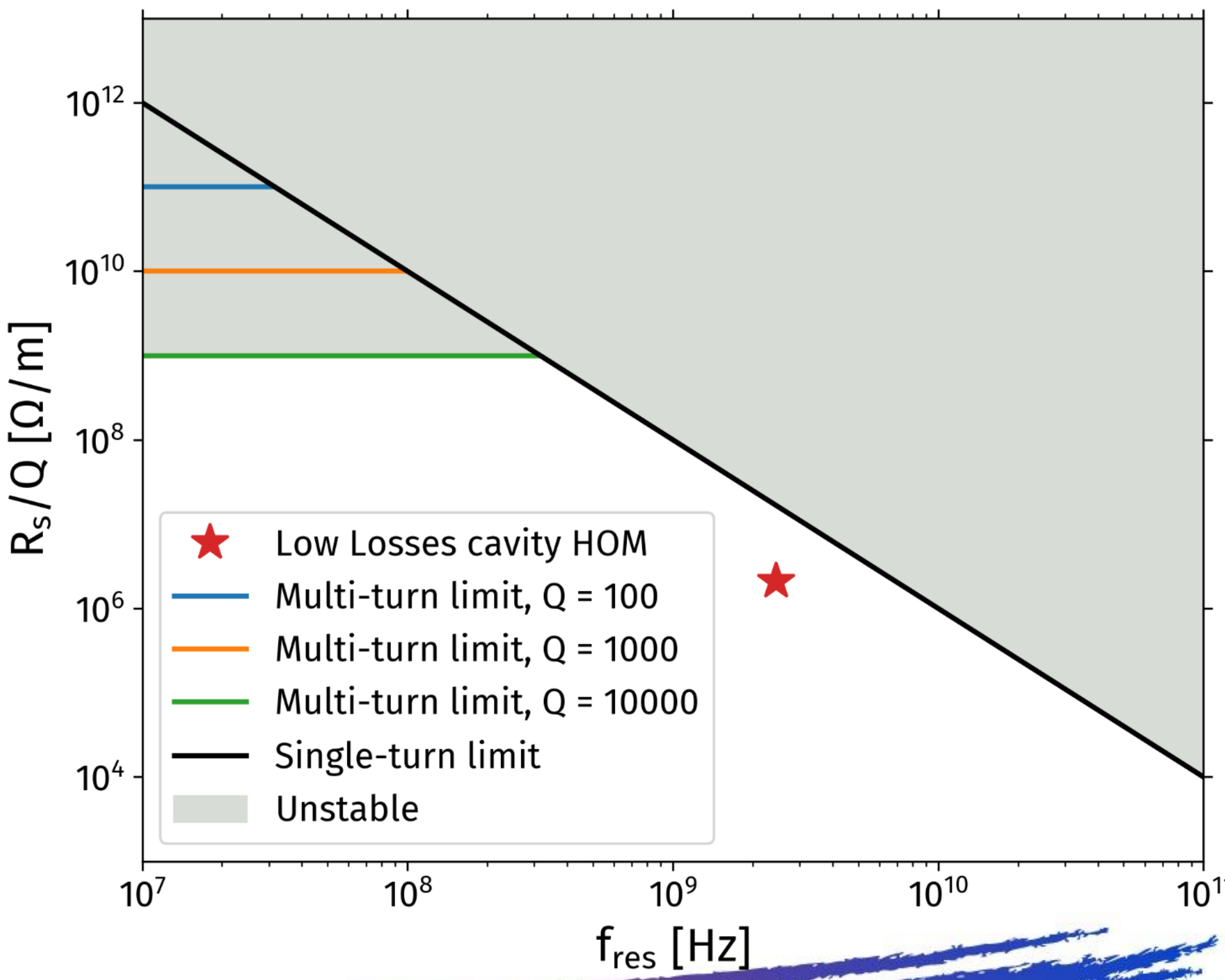
Courtesy: David Amorim

- Stability threshold (single turn) $R_s/Q \sim 100$ [MΩ/m] / f^2 [GHz^2]
- This **HOM** at **2.45 GHz:**
  - **$[R_s/Q]_{threshold}$** = $100/2.45^2$ = **16.7MΩ/m**
  - **$[R_s/Q]_{total}$ = 2.1 MΩ/m**

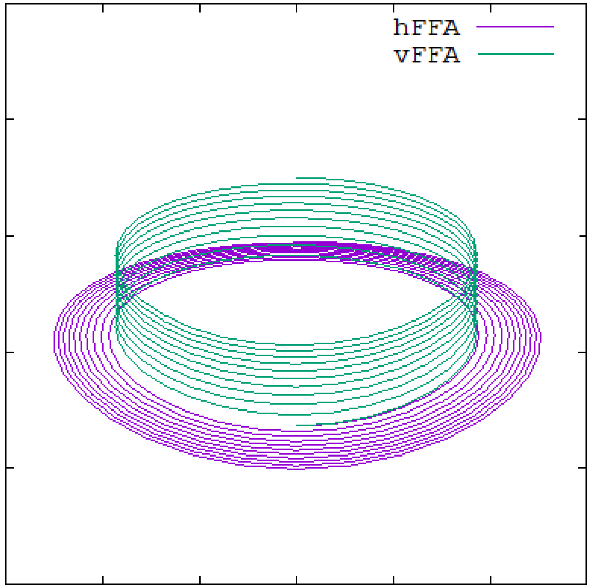
- HOM below the predicted stability limit by factor 8

Stability limit versus resonator parameters

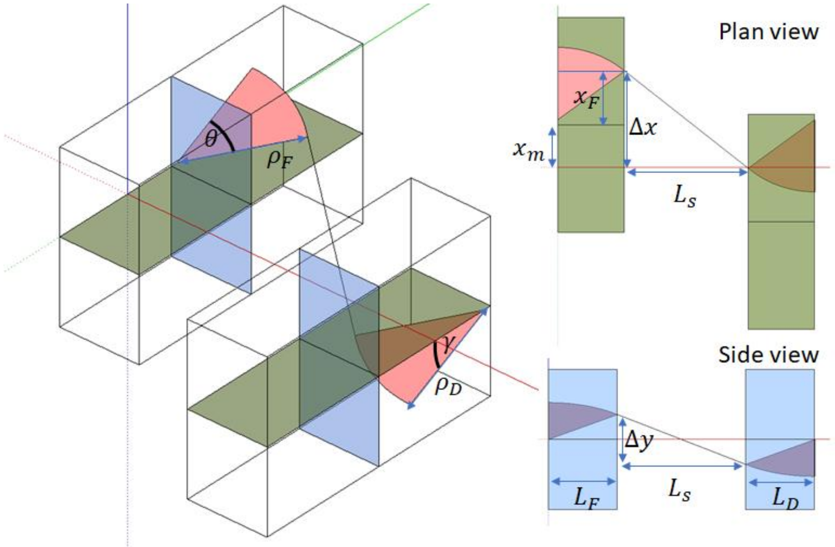


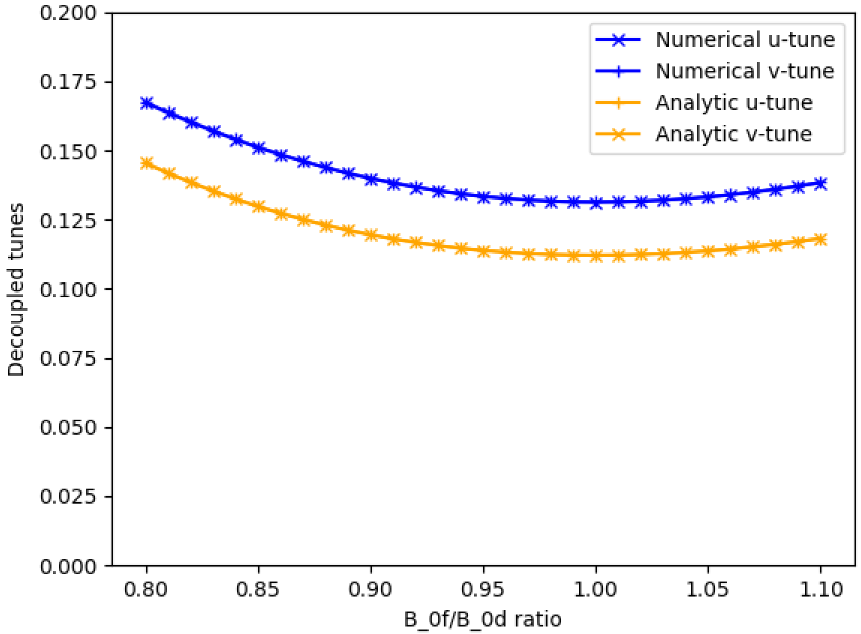
Alternatives to RCS
vFFA

Courtesy: Max Topp-Mugglestone



- Development of analytic tools to modelize the 3D orbit





- Promising steps towards an analytic model of the vFFA have been made!

10 TeV collider

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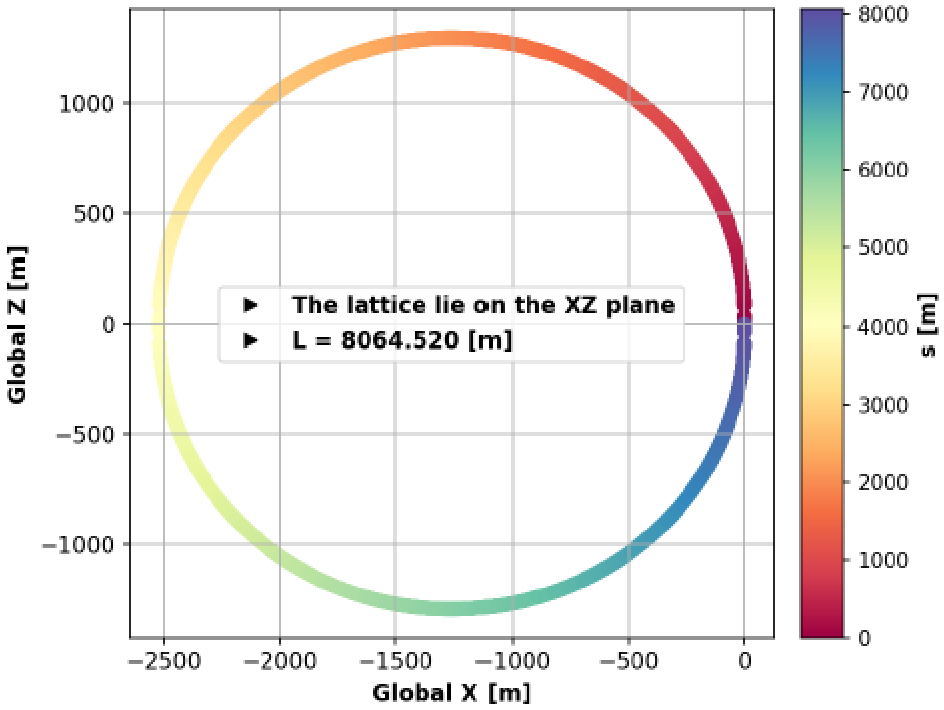
Courtesy: Kyriacos Skoufaris

10TeV Muon Collider

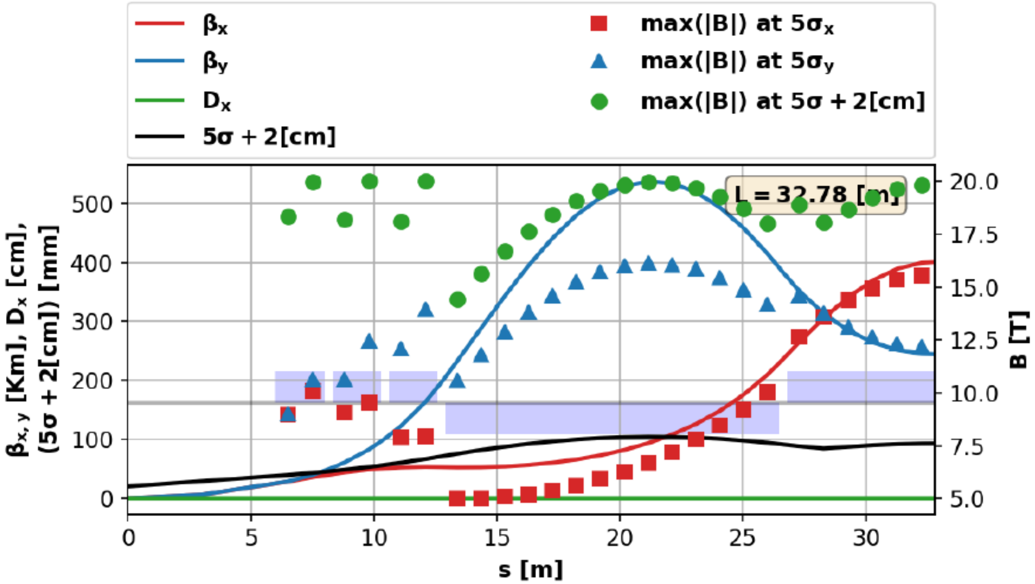
TABLE I. 10 TeV center of mass energy muon collider.

Parameters	Symbol	Unit	10TeV com mc
Particle energy	E	GeV	5000
Particle momentum	P_0	GeV c^{-1}	5000
Luminosity	$\mathcal{L}$	10^{34} cm^{-2} s^{-1}	20
Bunch population	N_p	10^{12}	1.8
Transverse normalized rms emittance	$\varepsilon_{nx} = \varepsilon_{ny}$	μm	25
Longitudinal emittance ($4\pi\ \sigma_E\ \sigma_T$)	ε_l	eVs	0.314
Rms bunch length	σ_z	mm	1.5
Relative rms energy spread	δ	%	0.1
Beta function at IP	$\beta_x^\star = \beta_y^\star$	mm	1.5
Beam power with 10 Hz repetition rate	P_{beam}	MW	14.4

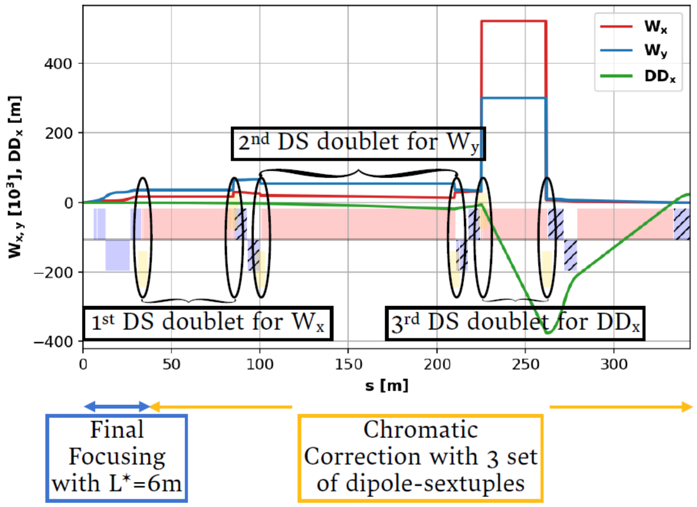


Collider: a tremendous chromatic correction scheme

Courtesy: Kyriacos Skoufaris



10TeV Muon Collider - Chromatic Correction Scheme



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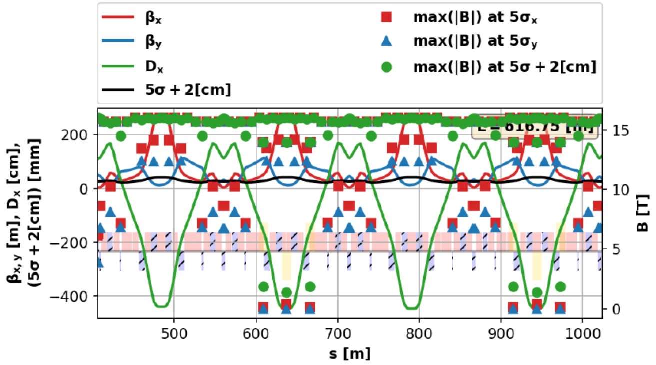
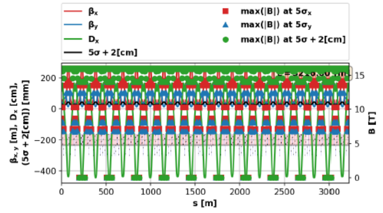
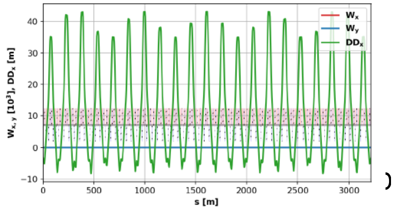
10TeV Muon Collider - Arc







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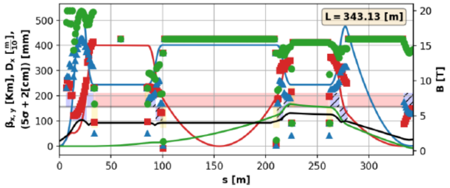
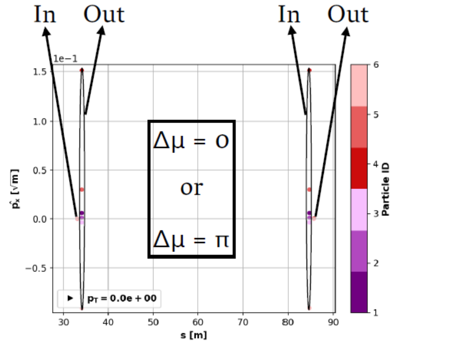
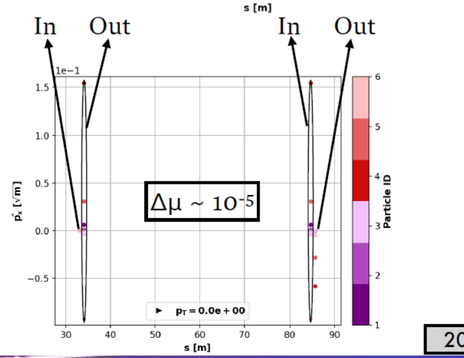
10TeV Muon Collider - Tracking Studies

- Due to very large beta values at the IRs, small variations of the phase advance (~10⁻⁵) can be detrimental for the particle dynamics (beam lifetime) thus, the compensation of sextupolar aberrations are quite demanding.







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Neutrino Radiation for a realistic Collider

Courtesy: Christian Carli

Numerical evaluations
Simple cases

- Divergence of muon beam neglected, peak dose rate
  - Straight section Δs, using $C = 2\pi\gamma E_{\mu}/(ceB)$ and $L_s \approx 2R_e h$ with $R_e \approx 6.38\cdot 10^6$ m the earth radius

$$\frac{dH_s}{dt} = \left(6.85\cdot 10^{-11}\,\frac{\mathrm{Sv}}{\mathrm{T}}\right) f_r N_\mu \left(\frac{E}{5\,\mathrm{TeV}}\right)^3 \frac{\Delta s B}{h}$$ for beam energies around $E \approx 5$ TeV

  - Bending magnet – integration w.r.t s using $\vartheta_\mu - \hat{\vartheta}(s) - (eB/(\gamma E_\mu/c))s$

$$\frac{dH_B}{dt} = \left(6.85\cdot 10^{-11}\,\frac{\mathrm{Sv}}{\mathrm{T}}\right) f_r N_\mu \left(\frac{E}{5\,\mathrm{TeV}}\right)^3 \frac{B}{h}\int ds \exp\left(-3\left(\frac{eBc}{E_\mu}s\right)^2\right) = \left(2.47\cdot 10^{-11}\,\mathrm{Sv\,m}\right) f_r N_\mu \left(\frac{E}{5\,\mathrm{TeV}}\right)^3 \frac{B}{hB}$$

  - Integrated peak equivalent dose per muon beam for one year operation (5000 h = 18 10⁶ s) without mitigation measures
    - $N_\mu = 1.8\cdot 10^{12}$ muons per bunch,
    - $f_r = 5$ Hz repetition,
    - $E \approx 5$ TeV beam energy,
    - $C = 10000$ km circumference and
    - $B = 10.42$ T average field

Contribution only from of the two muon beams

Mitigation mandatory!!

h (m)	L_s (km)	H_s (mSv) for Δs = 0.3 m	H_B (mSv) for B = 8 T
100	35.7	3.5	0.52
200	50.5	1.75	0.26
500	79.7	0.70	0.105
784	100	0.45	0.067

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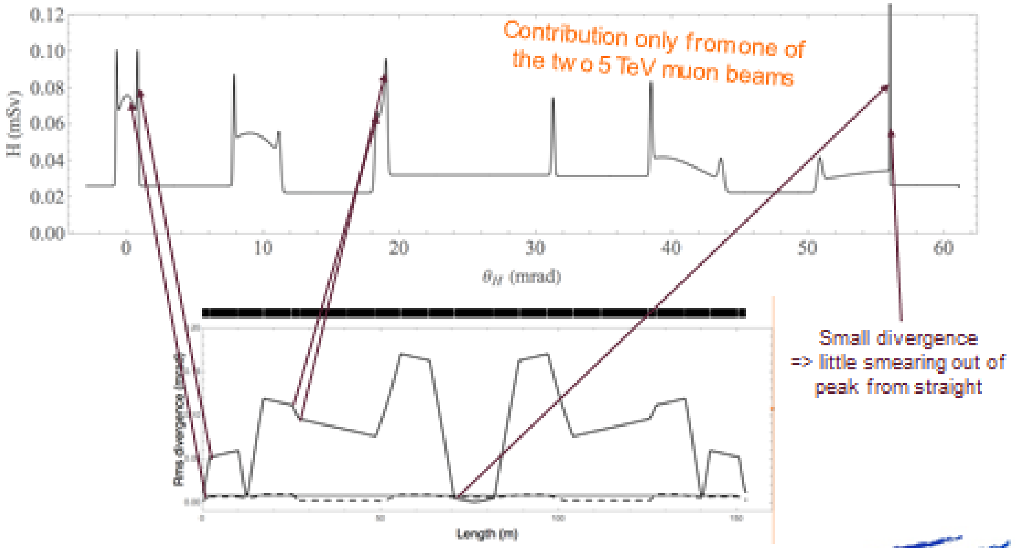
Numerical evaluations
equivalent dose from arc cell at 100 km

- Integrals evaluated for present (work in progress by K. Skoufaris) 10 TeV collider arc half cell
  - In collider mid-plane as function of ϑ_μ (i.e., $\vartheta_y = 0$) for one year (5000 h operation)



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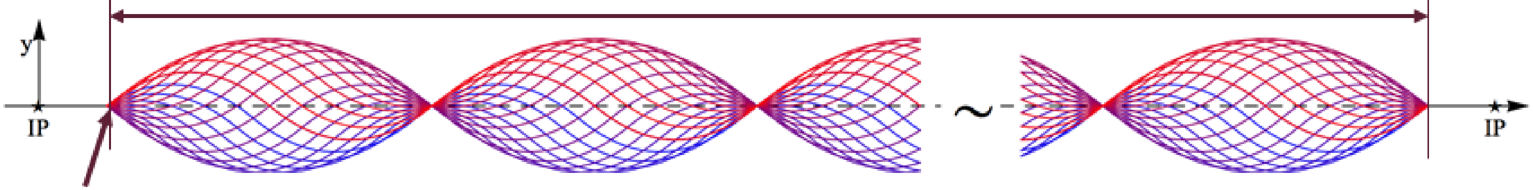
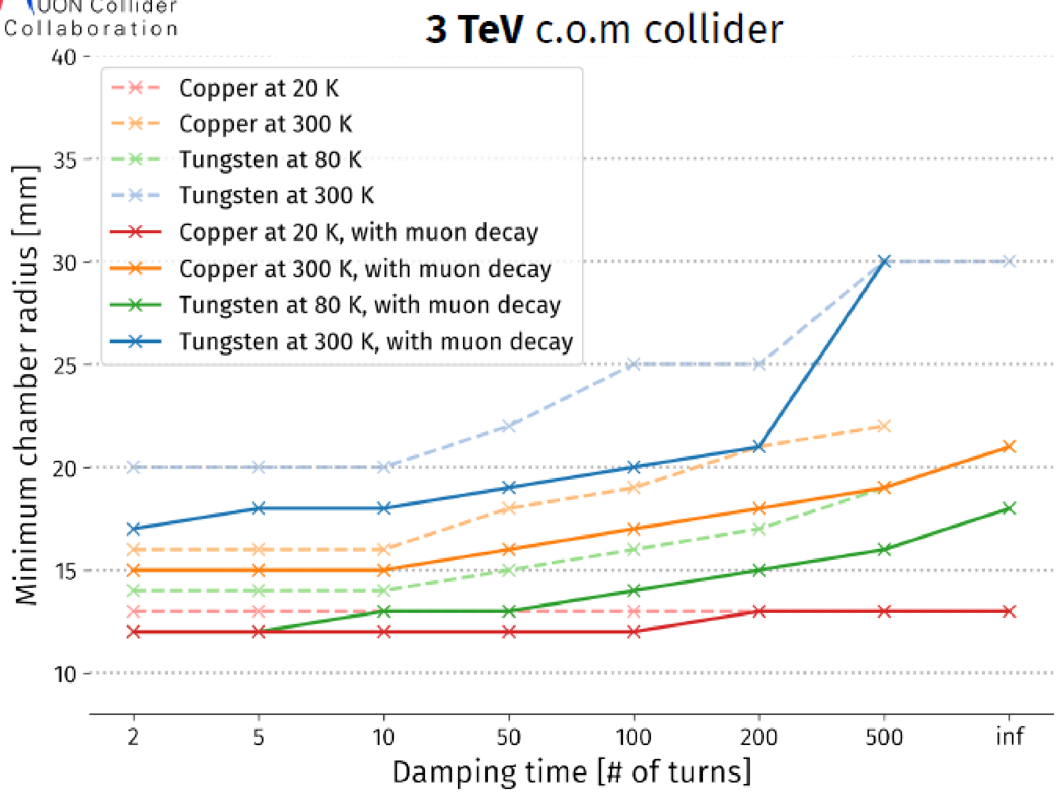
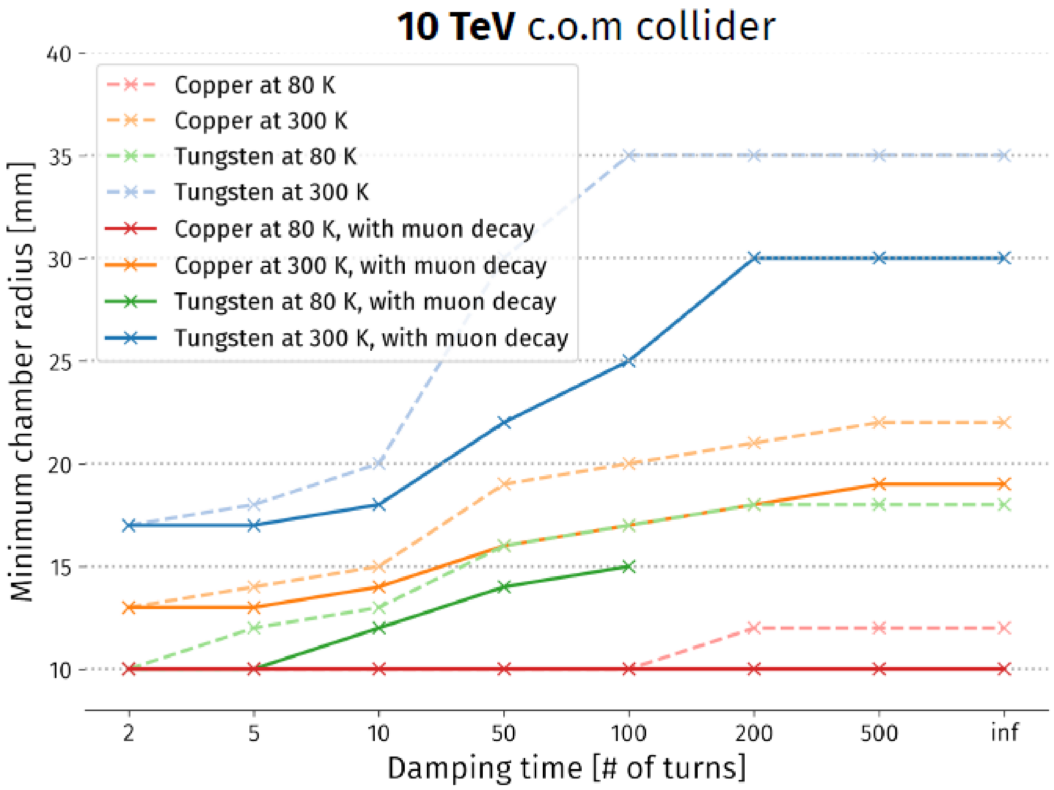
Wobbling: first proposals to generate some parabola pieces with a cycled vertical dipoles.



Transverse impedances for & 3 TeV and 10 TeV collider

Courtesy: David Amorim





- Overall the 10 TeV collider requires larger apertures than the 3 TeV collider with Tungsten at 300 K
- Muon decay helps gaining some margin on the minimum chamber radius required for transverse stability

Conclusion
Pulsed synchrotron and FFA

- **The design of resistive magnets has begun. Shaping correctly the reference field ramp is essential** to optimize the maximum power to be delivered. **Optimization with RF has started**.
- First longitudinal studies show that **1.3 GHz TESLA Cavity is suited for muon acceleration** in the RCSs. **Short-range wakefields and beam loading** are **huge** but **seem manageable**. **A large number of RF stations is needed** to ensure a sufficiently low synchrotron tune between the stations. If done, **beam is transported with % level emittance growth** in each RCS.
- A **parametric model is under development** to make easier the coupling between magnet, RF, optics, stability constraints.
- **One Low losses SRF cavity was investigated** from transverse stability for RCS1. **The most critical HOM remains below the stability threshold** with a margin factor ~8 for this single mode.
- **Analytic vFFA modelling is close to a solution** under a set of approximations and to be applied to a muon ring resign.

Conclusion
Collider

- **Extensive use of combined function magnets** with independent control of their multipolar components in order to evenly distribute the muon decay products and to minimize the collider length.
- **Different designs for the Final Focusing scheme** that aim to mitigate the BIB. **The BIB reduction due to dipolar components was so far found lower than expected**, but the study is still ongoing.
- **The Chromatic Correction scheme has been designed**. **Arc design with Flexible Momentum Compaction cells** that control the momentum compaction factor, the linear chromaticity and the 2π closing of the trajectory with independent knobs.
- Dose generated at earth surface due to **showers generated by nu interactions is a serious issue**.
- **Time-dependent vertical deformation of the whole arc** proposed as mitigation measure.
- With a 100-turn damper transverse beam stability would require at least **25 mm radius with Tungsten at 300 K for the 10 TeV collider.**

Next steps

- **A lot of parameters for the RCS need to be optimized:**
  - Decay rate: RF voltage and ramp rates better distributed between the different rings
  - Synchronous phase ⇔ higher voltage ⇔ emittance budget.
  - Beam optics: dedicated arc cells integrating RF cavities.
  - Magnet's ramping functions to reduce power consumption.
  - Better Matching between the different rings to reduce emittance growth.
- **The transverse stability study will continue** (more detailed cavity models, same studies for other RCS, adding counter-rotating beam, impact of chromaticity correction and needs for mitigation).
- **Completion of vFFA analytic tools** to go to a design of vFFA ring.
- Magnet design for FETS-vFFA ring has been carried out. **Prototype magnet due for construction over the next few months.**

Next steps
Collider

- The **next steps for the collider** is to refine the location of the straight sections, the Final Focusing design for a better control of the Beam Induced Background and the Chromatic Correction scheme.
- **Estimation of key parameters as well their tolerances** for the: minimum aperture, maximum allowed magnetic fields, maximum beta values out of the IR, chromaticity values, etc…
- Feasibility of the **Time-dependent vertical deformation** to be studied.
- Collective effects: Include additional instability mitigation measures to help reach tighter chamber radii (positive chromaticity, Landau damping with octupoles).Simulate a more detailed vacuum chamber when available. Include the second, counter-rotating, beam effects. Investigate other potential shielding materials
- **Collider and RCS relie on a close interaction between WP2/5/6/7.**
- **A lot of technical issues are addressed but still a lot of work before saying that such a complex is feasible but that is why MuC is motivating ;-).**

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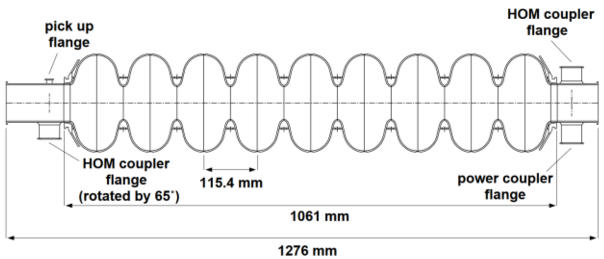
Thank you for your attention

Backup

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



From design report

Parameters and tools:
RF – The TESLA cavity

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- **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	TM_{011}
$\pi/9$ $(R/Q)/$ frequency	80 Ω/2454 MHz
$2\pi/9$ $(R/Q)/$ frequency	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

Parameters and tools: General parameter

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Courtesy: Fabian Batsch

- **Detailed parameter table: https://cernbox.cern.ch/index.php/s/l9VpITncUeCBtiz**

	RCS1→314 GeV	RCS2→750 GeV	RCS3→1.5 TeV
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	2.5×10^{12}	2.3×10^{12}	2.2×10^{12}
Survival rate per ring	90%	90%	90%
Acceleration time [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	30	30
Max. RF voltage for ϕ_s=45° [GV]	20.9	11.2	16.1

				Stage 1		Stage 2		Stage 3
13				Stage 1		Stage 2		Stage 3
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_B	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^l_n	[eVs]	0.025	7.5 MeV m	0.025		0.025
95	Longitudinal emittance (phase space area)	ε^l_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