Intensity Effects in a Chain of Muon RCSs

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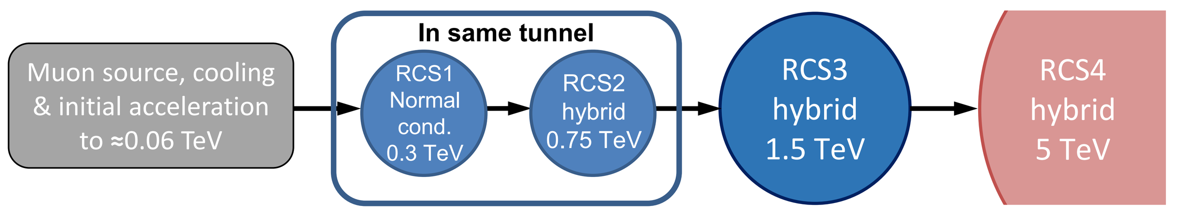
Abstract

The muon collider offers an attractive path to a compact, multi-TeV lepton collider. However, the short muon lifetime leads to stringent requirements on the fast energy increase. While extreme energy gains in the order of several GeV per turn are crucial for a high elevated muon survival rate, ultra-short and intense bunches are needed to achieve large luminosity. The longitudinal beam dynamics of a chain of rapid cycling synchrotrons (RCS) for acceleration from around 60 GeV to several TeV is being investigated in the framework of the International Muon Collider Collaboration. Each RCS must have a distributed radio-frequency (RF) system with several hundred RF stations to establish stable synchrotron motion. In this contribution, the beam-induced voltage in each RCS is studied, assuming a single high-intensity bunch per beam in each direction and ILC-like 1.3 GHz accelerating structures. The impact of single- and multi-turn wakefields on longitudinal stability and RF power requirements is analysed with particle tracking simulations. Special attention is moreover paid to the beam power deposited into the higher-order modes (HOM) of the RF cavities.

Towards a Muon Collider

- **International Muon Collider Collaboration (IMCC)** [1,2] aims at design proposal for a multi-TeV collision muon facility (3 TeV and 10 TeV stage)
- Muon production, 6D cooling and initial acceleration to ~60 GeV
- **High-energy acceleration stage with up to 4 rapid cycling synchrotrons (RCS)**



Hybrid RCS: interleaving normal and super-conducting magnets

- **Muon decay** counteracted by relativistic time dilation, $\tau_{\mu,0}$ = 2.197 µs
  - → Ultrafast acceleration of one **intense** μ^+ and μ^- bunch in **1.3 GHz RF system [2]**
  - → **High synchrotron tunes up to Q_s = 1.5 require distributed RF stations per RCS**
  - → **Strong transient beam loading**, unique RF requirements

→ **Simulations of the longitudinal bunch distribution and HOM power** using the longitudinal macro-particle tracking code **BLonD** [4]

Beam and RF Parameters

- **Example parameters for the muon RCSs assuming a 90% survival rate per RCS and ILC-like RF system at 1.3 GHz. Values for RCS4 are draft parameters:**

	RCS1	RCS2	RCS3	RCS4
Circumference [m], C	5990	5990	10700	35000
Injection energy [TeV], E_{inj}	0.06	0.30	0.75	1.50
Ejection energy [TeV], E_{ej}	0.30	0.75	1.50	5.00
Ejection γ, γ_{ej}	2971	7099	14198	47323
Acceleration time [ms], τ_{acc}	0.34	1.10	2.37	6.4
Revolution period [µs], T_{rev}	20.0	20.0	35.7	117
Number of turns	17	55	66	55
Energy gain per turn [GeV], ΔE	14.8	7.9	11.4	64
Average gradient [MV/m], G_{avg}	2.4	1.3	1.1	1.8
Total RF voltage [GV], $V_{\mathrm{RF}}(\phi_s = 45°)$	20.9	11.2	16.1	90
Acc. gradient in cavity [MV/m], G_{acc}	30	30	30	30
Number of cavities	700	380	540	3000
Bunch intensity [10¹²]	**2.7**	**2.43**	**2.2**	**2.0**
Bunch current [mA]	**21.67**	**19.5**	**9.9**	**3.0**
Bunch duration [1σ, ps]	**<45**	**<33**	**<28**	**<17**
Target 4σ emittance [eVs]	**0.31**	**0.31**	**0.31**	**0.31**

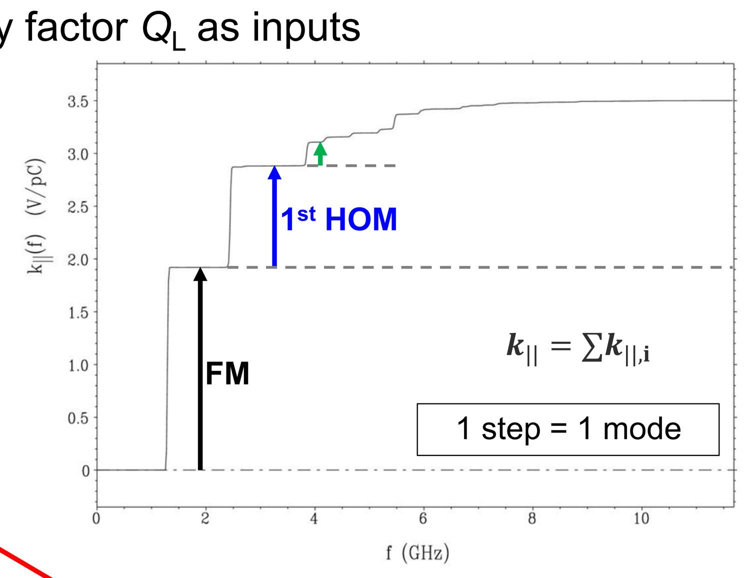
- **Accelerator parameters fully determined through survival rate $N(t)/N_0$ and energy swing:**

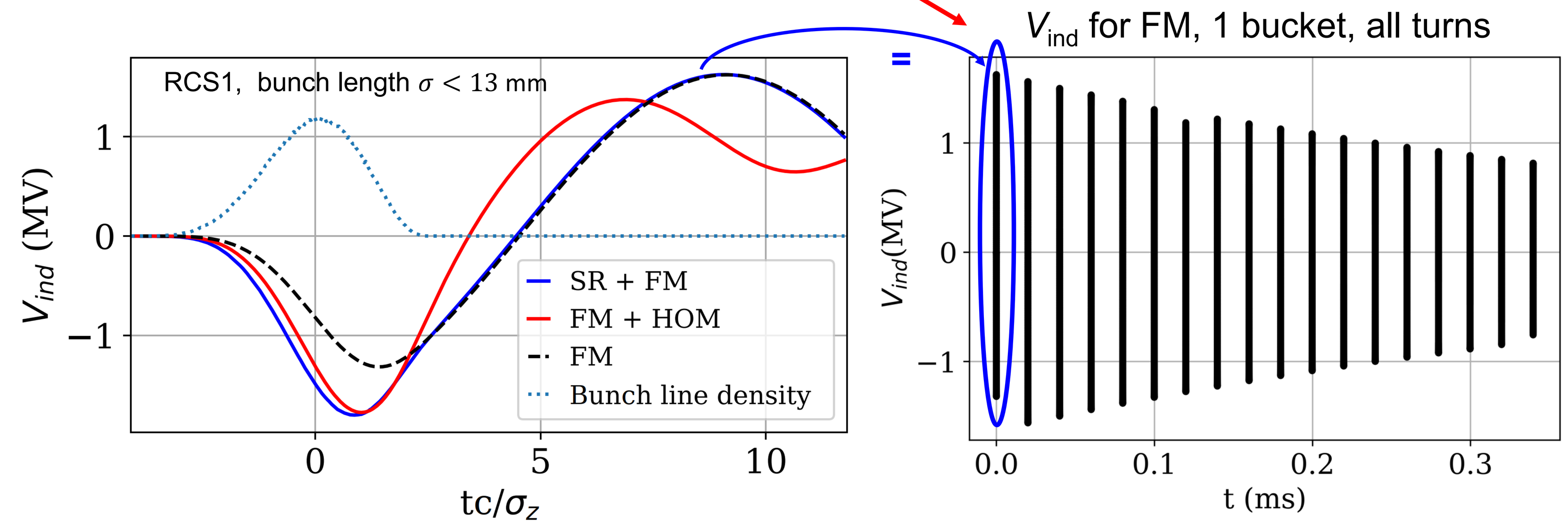
$$\frac{N(\tau_{acc})}{N_0} = \exp\left(-\frac{1}{\tau_\mu}\int_0^{\tau_{acc}} \frac{dt}{\gamma(t)}\right) = \left(\frac{\gamma_{ej}}{\gamma_{inj}}\right)^{-\frac{1}{\tau_\mu}\frac{\tau_{acc}}{\gamma_{ej}-\gamma_{inj}}}$$

$$G_{\mathrm{acc}} = -\frac{1}{\tau_\mu} m_\mu c \ln\left(\frac{\gamma_{\mathrm{ej}}}{\gamma_{\mathrm{inj}}}\right) / \ln\left(\frac{N_{\mathrm{ej}}}{N_{\mathrm{inj}}}\right) \qquad \tau_{\mathrm{acc}} = -\tau_\mu(\gamma_{\mathrm{ej}} - \gamma_{\mathrm{inj}}) \ln\left(\frac{N_{\mathrm{ej}}}{N_{\mathrm{inj}}}\right) / \ln\left(\frac{\gamma_{\mathrm{ej}}}{\gamma_{\mathrm{inj}}}\right)$$

Beam-induced Voltages

- **Fundamental mode** (FM) beam loading computed with a resonator model [5] with total shunt impedance (from *R/Q)* and loaded quality factor Q_L as inputs
- **HOM short-range** (SR) wakefields according to theory of K. Bane [4]
- **Long-range / multi-turn effects** by using resonator model also for HOMs
- Compute intensity effects only at bucket of interest in each turn
- $V_{ind} \approx 1.8$ MV $< 10\%$ of cavity voltage





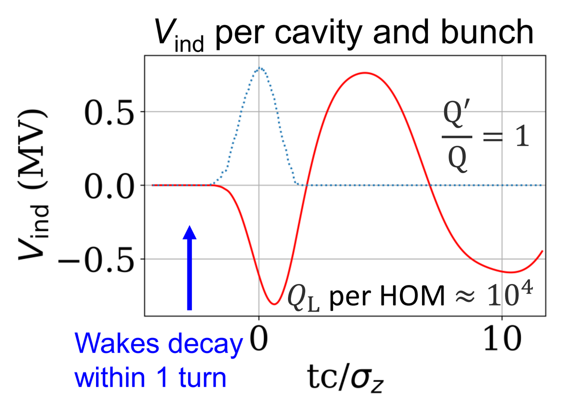
Intensity Effects from HOMs

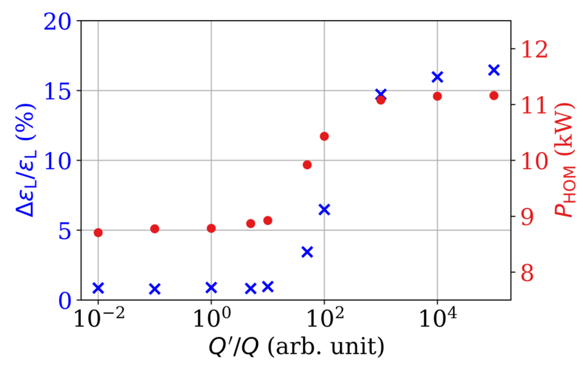
- Average HOM power per bunch during acceleration from multi-turn wakefields and line density $\lambda(t)$:

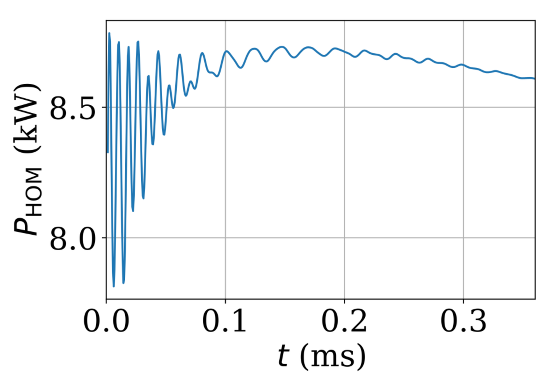
$$P_{\mathrm{HOM}} = -k_{||,\mathrm{SR}} \cdot \frac{q^2}{T_{\mathrm{rev}}}, \quad k_{||,\mathrm{SR}} = \int W_{\mathrm{L,SR}}(t) \cdot \lambda(t)$$

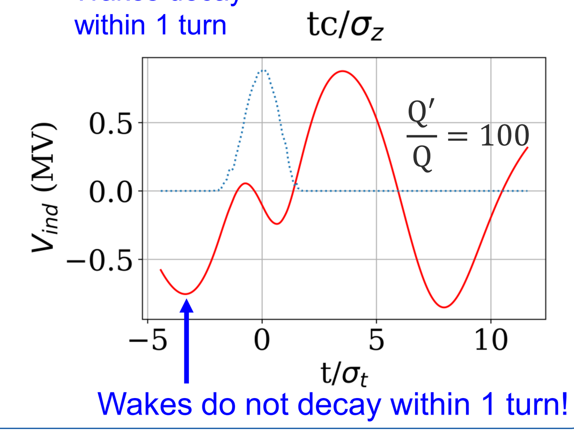
- Included HOMs in frequency range up to 6.7 GHz
- HOM decay within 1 turn and $P_{\mathrm{HOM}} < 9$ kW for $Q_L \approx 10^4$
- Influence of Q_L studied with factors from 10^{-2} to 10^5
- For $Q'/Q > 10^1$, emittance growth and P_{HOM} increase

→ **High-power HOM couplers with well-defined Q_L**









Conclusions

- **Ultra-fast acceleration** of muons in **rapid-cycling synchrotrons** to extend their lifetime → **Unique RF** requirements and longitudinal beam dynamics
- **Up to 2.7·10¹² muons per bunch cause strong transient beam loading**
- Induced voltages from single-turn effects on the order of MV per cavity → Less than 10% of cavity voltage
- Multi-turn effects depend on the loaded quality factors of each HOM, $Q_L \leq 10^5$ needed
- Tens of kW HOM peak power losses expected → high-power HOM couplers
- Future studies will be devoted to the impact of the counter-rotating bunches on the choice of the RF frequency and multi-turn effects

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