RF parameter optimization in the high energy muon acceleration chain

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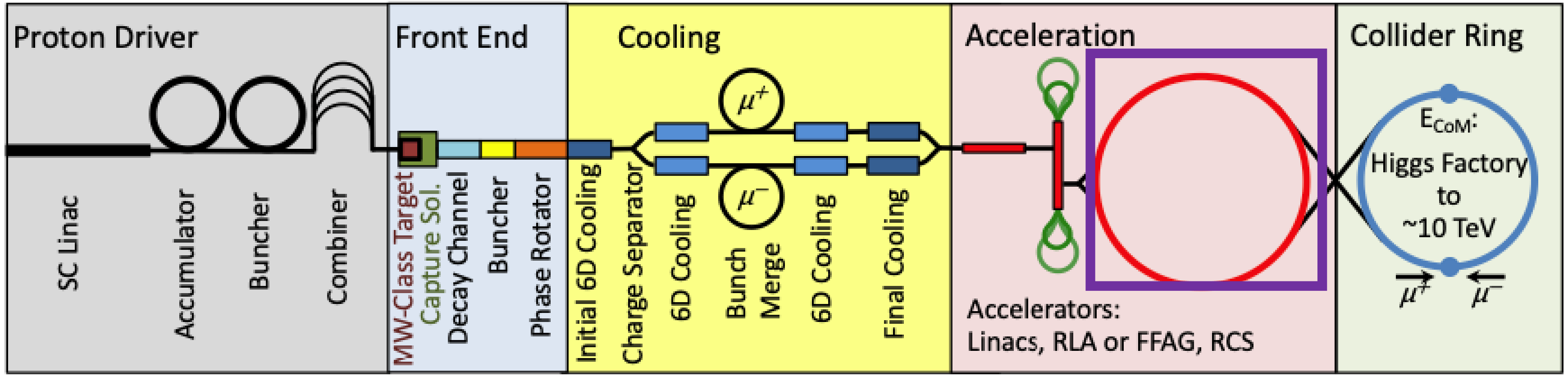
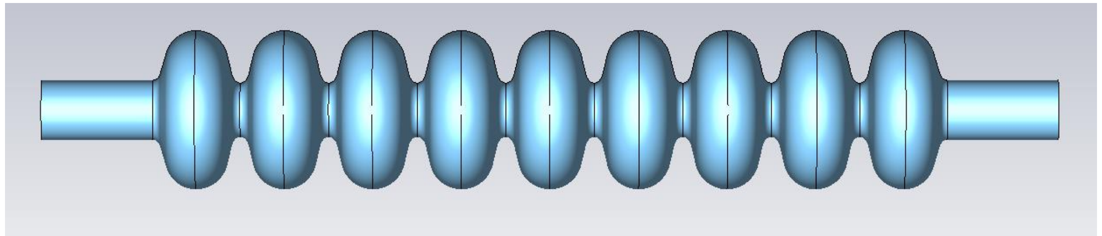


General design criteria for RF systems I

f_{rf} defines:
- The cell-size of the cavity ($\lambda/2$)
- Achievable gradients
- Possible bunch lengths as the bunch has to fit into one cell in elliptical multicell cavities

Baseline 1.3 GHz 9-cell TESLA cavity



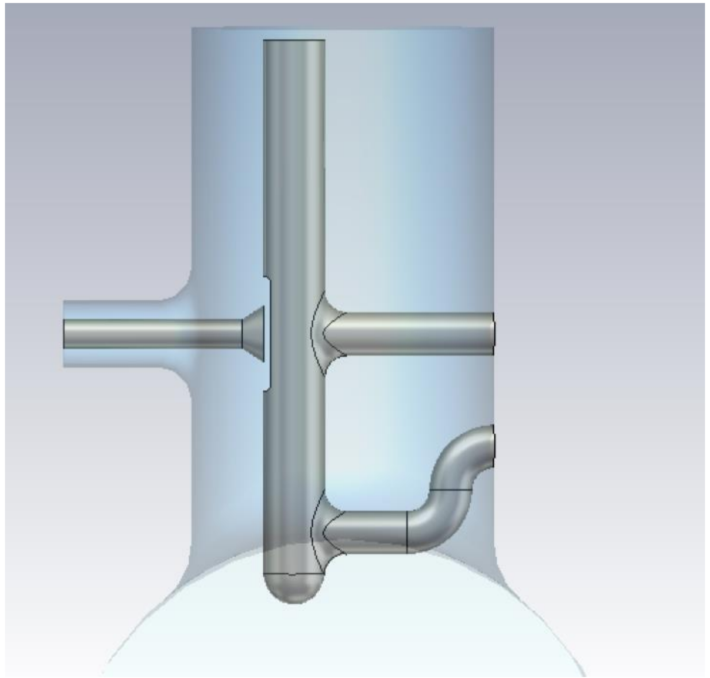
N_{cells}: Changes the requirements on the couplers, both fundamental power coupler and higher order mode couplers

R/Q (geometric impedance):
- Transverse and longitudinal parameters
- Determine the **interaction between the cavity fields and the particles**.
- For fundamental accelerating mode
  - ➢ high R/Q desired
- For higher order modes
  - ➢ reduction of R/Q desired
- Purely dependent on the **cavity shape**.

General design criteria for RF systems II

- Higher order modes (HOM) are unwanted resonances at higher frequencies which occur inside the cavity and are induced by the beam passage
- Higher order mode **quality factors** are controlled through the design of (multiple) **HOM couplers** to reduce the negative impact on the beam (longitudinal and transverse)
- Multiplication of R/Q and the quality factor yields the impedance and therefore magnitude with which the beam induces voltage

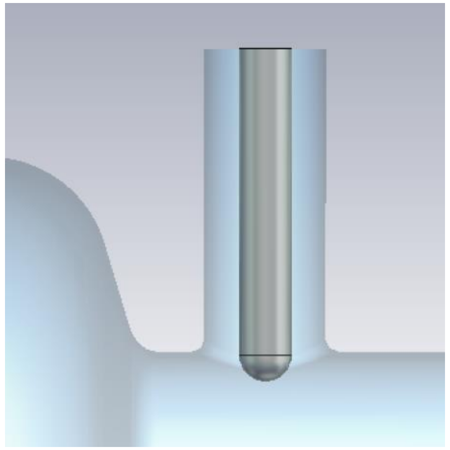
→ Requirements from transverse and longitudinal beam dynamics necessary as input for the design process of the cavity and couplers



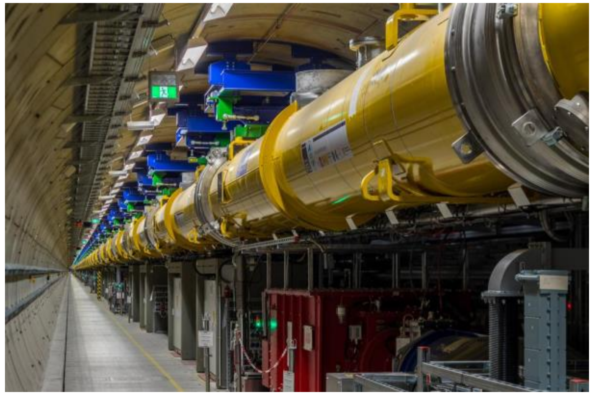
General design criteria for RF systems III

Fundamental mode quality factor is dominated by the design of the **fundamental power coupler (FPC):**

- Impacts long. beam dynamics via decay time of the beam induced field
- Impacts power requirements and filling time of the cavity



MW class pulsed **Klystrons** and systems of waveguides to drive the cavities;
Klystron efficiency and distribution losses will add to the power consumption



From [4]

Cryomodules and cryogenic plants to cool the cavities; integration into the tunnel/surface

RF system requirements

- Two counter-rotating beams with a single **high-intensity bunch**
  - High transient beam loading
- **High energy gain** to preserve muon lifetime
  - High voltage per turn → high cavity gradient & large number of cavities
- **Short acceleration time**
  - Cavities will be operated in pulsed mode (duty cycle of a few %)
- Beams must be kept stable during acceleration despite large synchrotron tune
  - Separation of RF system into **multiple stations** all around the ring
- **RF-frequency swing** will be required to compensate for changing orbit lengths in hybrid RCSs
  - Fast reactive tuners necessary
- Non-linear energy gain leads to the requirement for **additional cavities**
  - The maximum number of cavities has to be installed but is not required during the full acceleration time.

Beam loading compensation I

- Two free parameters can be used and adjusted to reach optimum RF power efficiency:

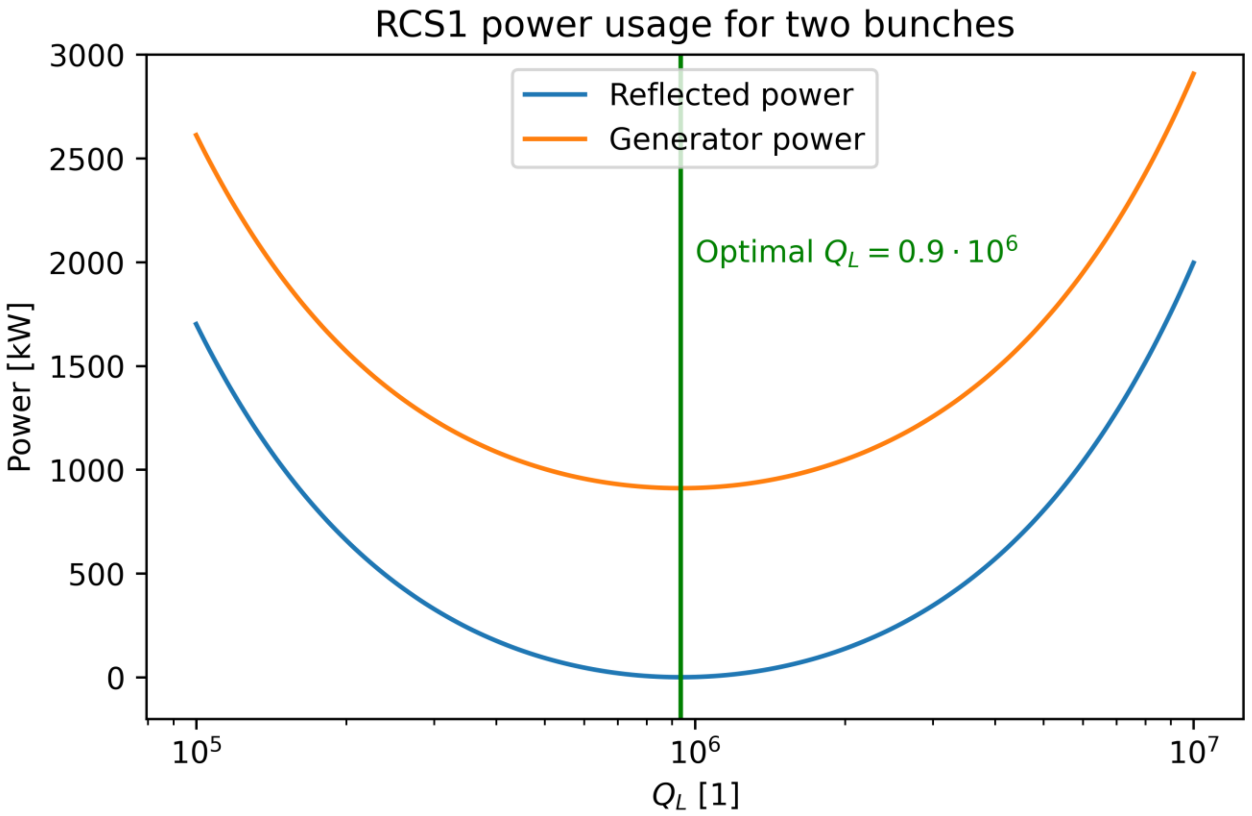
Loaded quality factor $\boldsymbol{Q_L}$ and cavity detuning $\boldsymbol{\Delta\omega}$

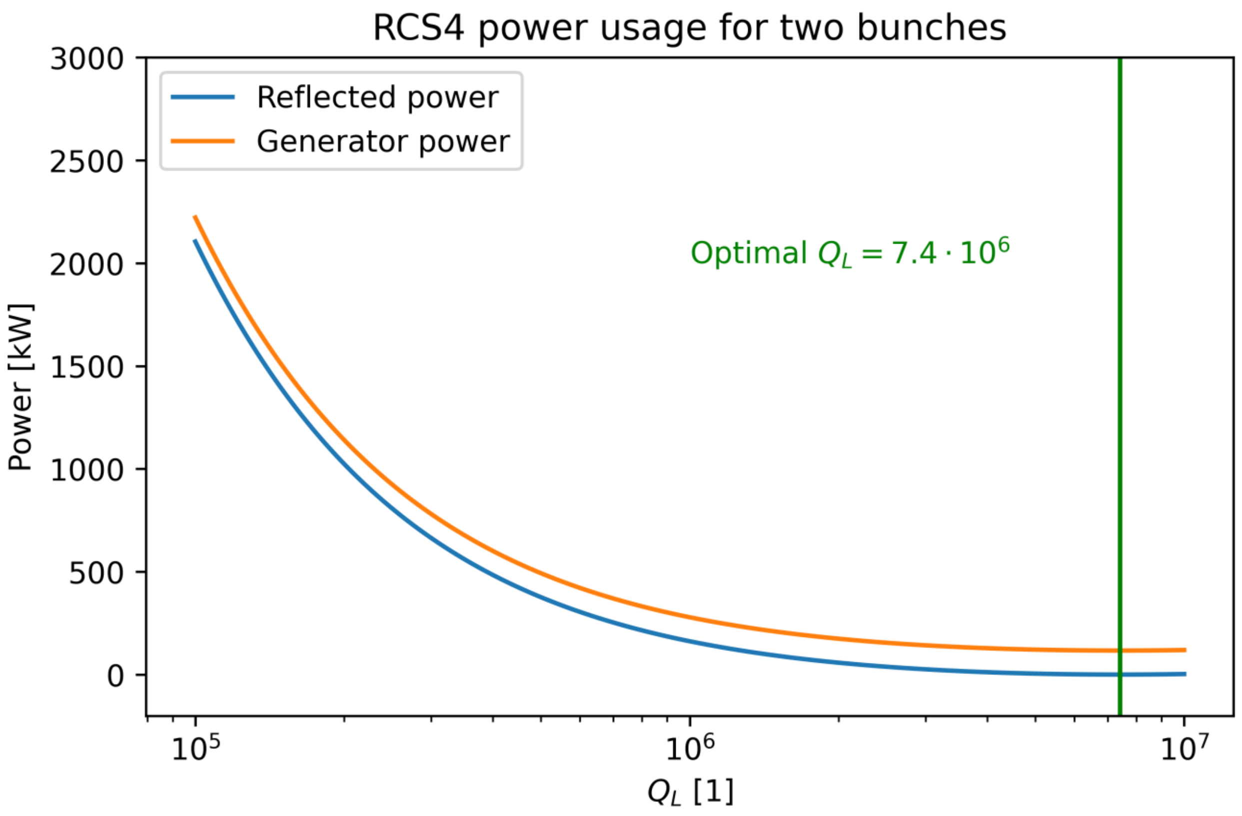
Reduces real part of reflected and generator power

Reduces imaginary part of reflected and generator power

- The values depend on the beam and cavity parameters and will be different for each RCS.
- Deviating from these leads to higher power consumption and parts of the power being reflected back towards the generator.
- BUT: deviation might be desirable from long. beam dynamics standpoint

Beam loading compensation II





The power consumption is calculated based on the formulas derived in [1].

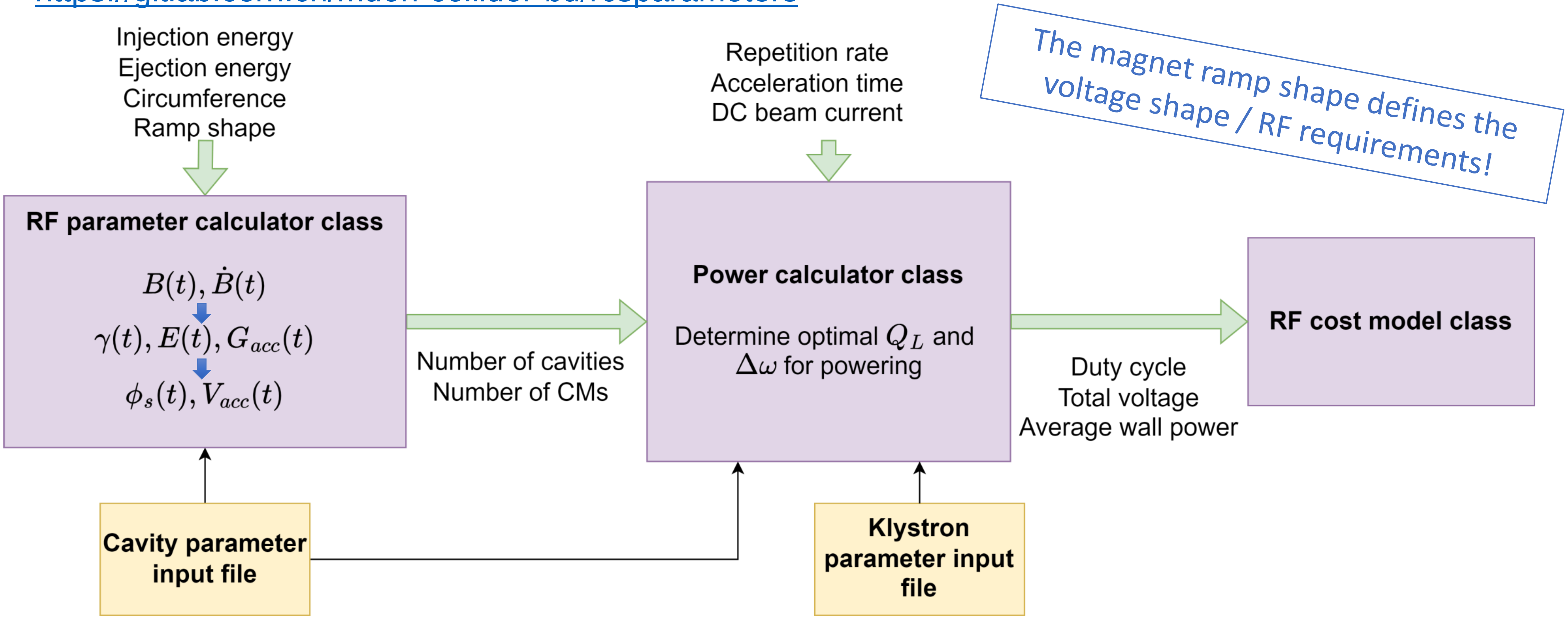
RF parameters in the high-energy chain
Cavity powering

- Assuming optimal quality factor and frequency detuning of the cavity
- Assuming ideal, linear energy ramp (sinusoidal ramp will require additional cavities)

	Unit	RCS1	RCS2	RCS3	RCS4
Beam acceleration time	[ms]	0.34	1.1	2.37	6.37
Cavity filling time	[ms]	0.23	0.25	0.50	1.81
RF pulse length	[ms]	0.57	1.35	2.87	8.18
FPC peak power	[kW]	911	818	416	297
Total peak RF power	[MW]	850	410	300	460
Average wall plug power	[MW]	3.72	4.25	6.56	29.2
Number of klystrons	-	88	42	30	47
Cavities per klystron	-	8	9	18	64
Number of cavities	-	700	380	540	3000

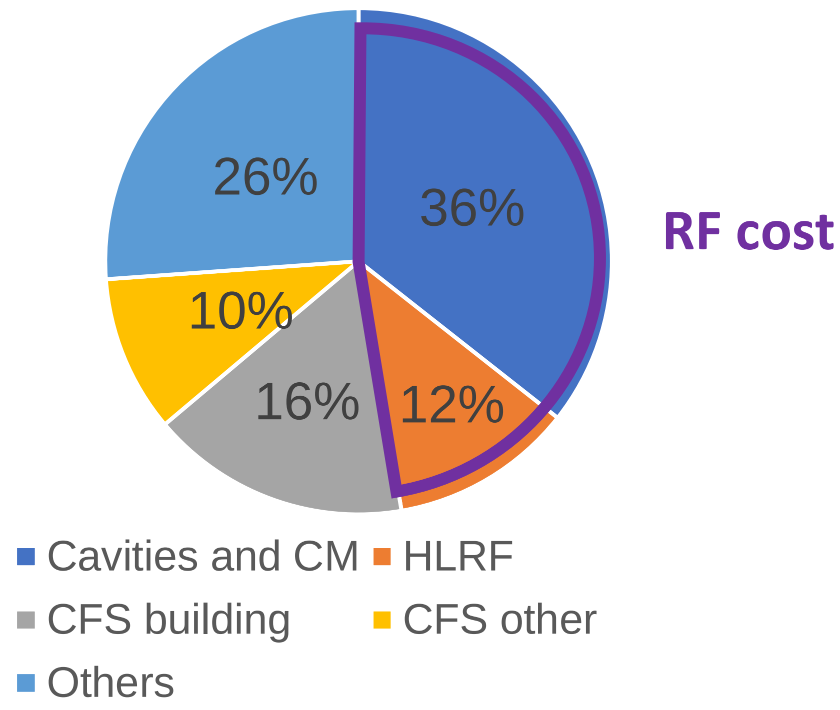
Tools to optimize RF parameters of high-energy acceleration chain

- **Integrated software package for combined optimization of energy ramp and RF parameters** https://gitlab.cern.ch/muon-collider-bd/rcsparameters



ILC TDR cost distribution

ILC 500 cost distribution



Values from [2]

	ILC 500	MuCol HEMAC
Number of cavities	~ 15000	~ 5000
Beam current [mA]	5.8	~ 50 … 5
Bunch intensity	5×10^{10}	$\sim 2 \times 10^{12}$
FPC peak power [kW]	190	910

- Increased high level RF cost due to higher beam current
- Additional dependance on other parameters like the number of required HOM couplers

→ **In RCS chain: Present, preliminary estimates indicate that RF and NC magnet costs are in the same order of magnitude.** [5]

Summary

- Muon survival and beam dynamics require a large, distributed RF system on a comparable scale to the ILC
- 1.3 GHz TESLA cavities are used as a baseline to study beam dynamics
  - For the Muon Collider, an improved design is planned to be developed
- Preliminary estimates: RF system cost is comparable to NC magnet system
  - Optimization is necessary to determine how the most efficient solution looks like
- Changes in the ramp shape will require additional cavities, which are not necessary during the entire ramp
- High impact on transverse and longitudinal beam dynamics
  - Iterations on coupler/cavity design necessary
- Cavity powering impacts beam dynamics through fundamental mode quality factor
  - Amplitude and decay of induced voltage is changing

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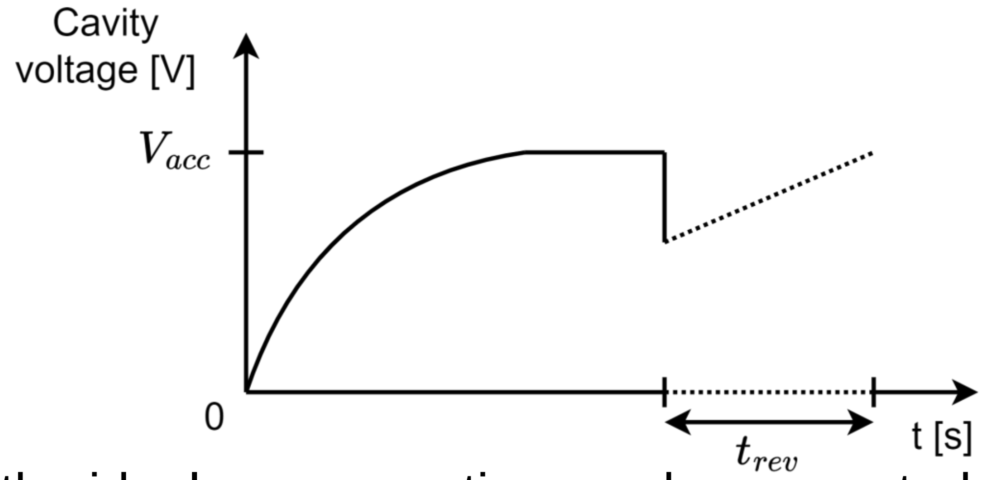
RF parameters in the RCSs

- Estimates using linear acceleration

	Unit	RCS1	RCS2	RCS3	RCS4
Synchronous phase	[°]	135	135	135	135
Bunch population at injection	[1 x 10^{12}]	2.7	2.4	2.2	2.0
Combined avg. beam current (μ^+ and μ^-)	[mA]	43.3	39.0	19.8	5.49
External *Q*-factor	[1 x 10^{6}]	0.94	1.04	2.05	7.42
Optimal cavity detuning	[kHz]	-0.69	-0.62	-0.32	-0.09

Introduction to beam loading in RF cavities

- After filling the cavity with a certain generator current, a voltage will build up.
- The bunch passage will then decrease this voltage as parts of the energy are transferred to the bunch.
- This effect has to be compensated for, as otherwise, the beam will see less voltage on the next passage → **Beam loading compensation**



- The input power for the ideal compensation can be computed from an equivalent circuit model [1] J. Tückmantel, CERN-ATS-Note-2011-002 TECH

Appendix
Generator and reflected current

$$I_g = \left[\frac{V}{2(R/Q)}\left(\frac{1}{Q_{ext}} + \frac{1}{Q_0}\right) + I_{b,DC}F_b \sin(\phi_s)\right] + i\left[I_{b,DC}F_b \cos(\phi_s) - \frac{V\Delta\omega}{\omega(R/Q)}\right]$$

$$I_r = \left[\frac{V}{2(R/Q)}\left(\frac{1}{Q_{ext}} - \frac{1}{Q_0}\right) - I_{b,DC}F_b \sin(\phi_s)\right] - i\left[I_{b,DC}F_b \cos(\phi_s) - \frac{V\Delta\omega}{\omega(R/Q)}\right]$$

Aims when specifying the modifiable parameters

- Set the imaginary part of both formulas to 0 → $\frac{\Delta\omega_{opt}}{\omega} = \frac{I_{b,DC}F_b\cos(\phi)(R/Q)}{V}$
- Set the real part of the reflected current to 0 → $Q_{ext,opt} = \frac{V}{2I_{b,DC}F_b\sin(\phi_s)(R/Q)}$

The formulas used were derived in [1]

References

[1]: Cavity-Beam-Transmitter Interaction Formula Collection with Derivation: http://cds.cern.ch/record/1323893/files/CERN-ATS-Note-2011-002%20TECH.pdf

[2]: ILC TDR: https://linearcollider.org/files/images/pdf/Acceleratorpart2.pdf

[3]: https://www.desy.de/xfel-beam/mlin_klyst.html

[4]: https://www.xfel.eu/news_and_events/news/index_eng.html?openDirectAnchor=1772

[5]: https://indico.cern.ch/event/1356899/