Updates on transient beam loading in the RCS chain

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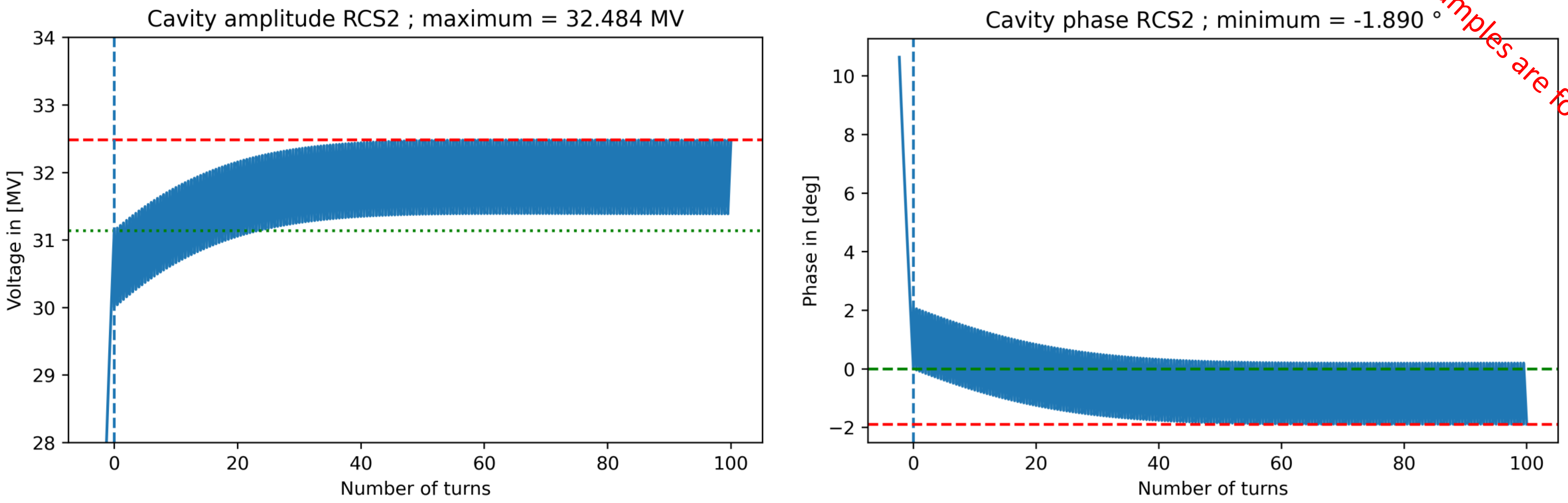
Cavity voltage amplitude/phase modulation during the acceleration

Last meeting: transient beam loading with stronger detuning and "Optimal Quality factor"

All examples are for RCS2



Injection at nominal Voltage and 0 cavity phase leads to a **non-nominal equilibrium voltage**

→ **Why is this the case?**

Implementation follows the description in [2] I. Karpov, "Transient beam loading and rf power evaluation for future circular colliders"

Beam loading compensation

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

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

- Both parameters have an optimum point, for which the generator power and reflected power are minimised.

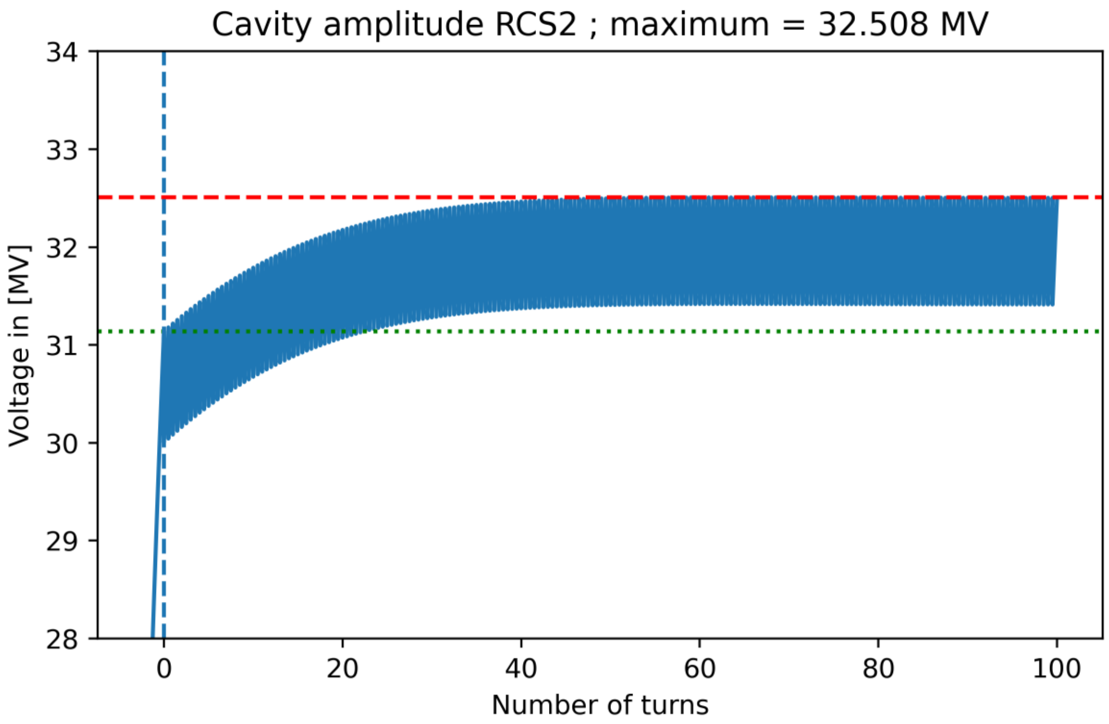
$$I_g = \left[\frac{V}{2(R/Q)Q_L} + I_{b,DC}F_b\sin(\phi_s)\right] + i\left[I_{b,DC}F_b\cos(\phi_s) - \frac{V\Delta\omega}{\omega(R/Q)}\right] \qquad \Delta\omega_{opt} = \omega_{rf}\frac{(R/Q)|F_b|I_{b,DC}\cos(\Phi_s)}{V_{cav}} \quad (12)$$

$$I_r = \left[\frac{V}{2(R/Q)Q_L} - I_{b,DC}F_b\sin(\phi_s)\right] - i\left[I_{b,DC}F_b\cos(\phi_s) - \frac{V\Delta\omega}{\omega(R/Q)}\right] \qquad Q_{L,opt} = \frac{V_{cav}}{2(R/Q)|F_b|I_{b,DC}\sin(\Phi_s)} \quad (13)$$

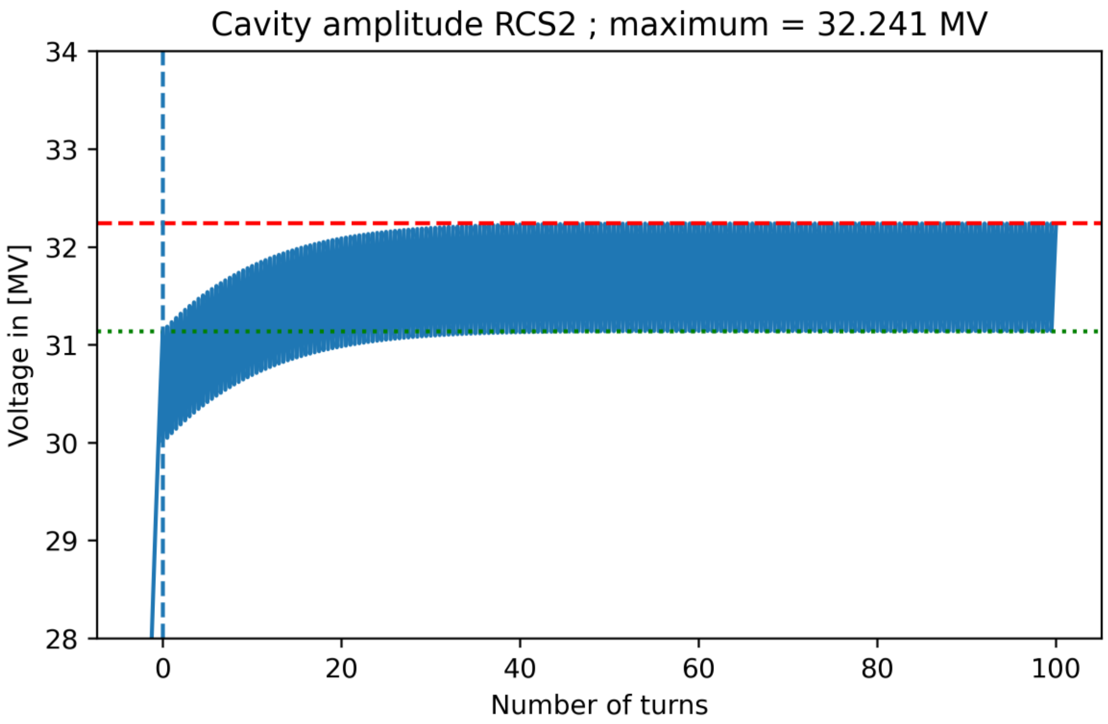
- BUT: the optimum of Q_L is dependent on the chosen $\Delta\omega$
- Since we will change the $\Delta\omega$ to make the acceleration stable, the Q_L must be adjusted as well.

Cavity voltage amplitude/phase modulation during the acceleration

“Optimal” Quality factor



Corrected Quality factor

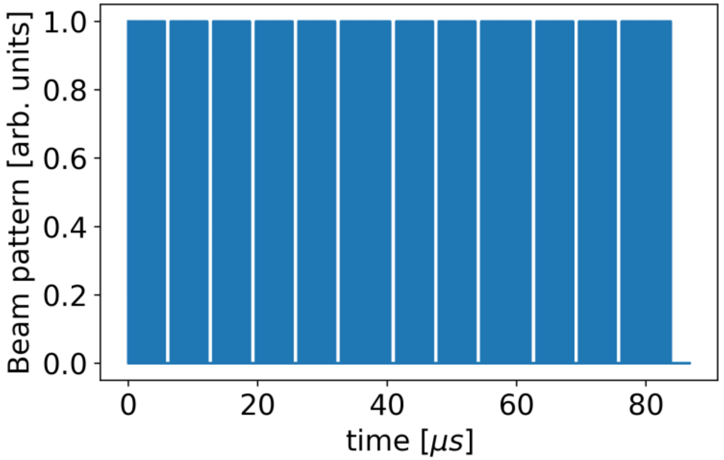


Equilibrium is closer to the setpoint (green dashed line), but not oscillating around it.

Implementation follows the description in [1] I. Karpov, “Transient beam loading and rf power evaluation for future circular colliders”

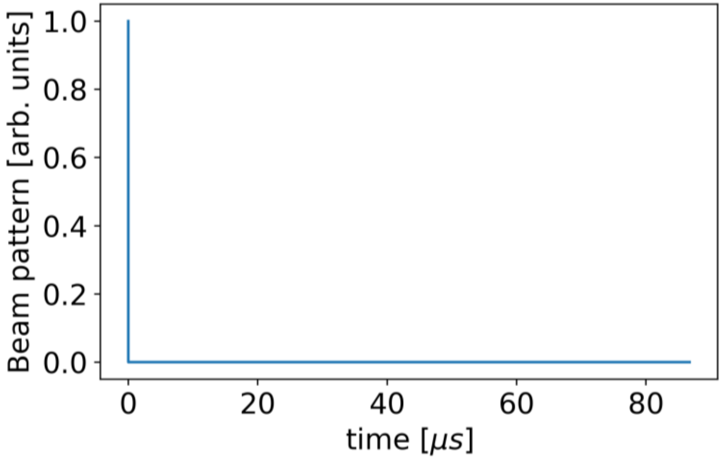
Transient beam loading in the Muon Collider

- In the Muon Collider, the entire beam charge is concentrated in 2 bunches, leaving the rest of the ring empty.



← LHC-like bunch pattern over one turn

MuCol bunch pattern →



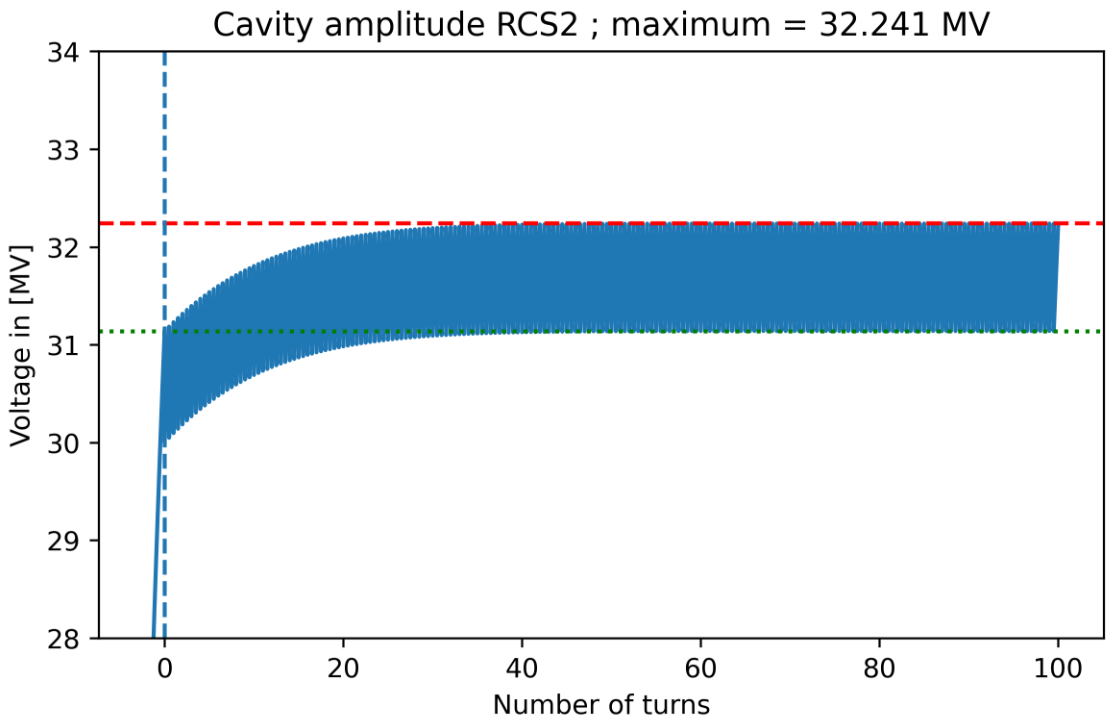
- High difference between average and peak current in the MuCol.
- Simulation assumes only slow changes of the beam current per simulation step

→ not the case for MuCol.

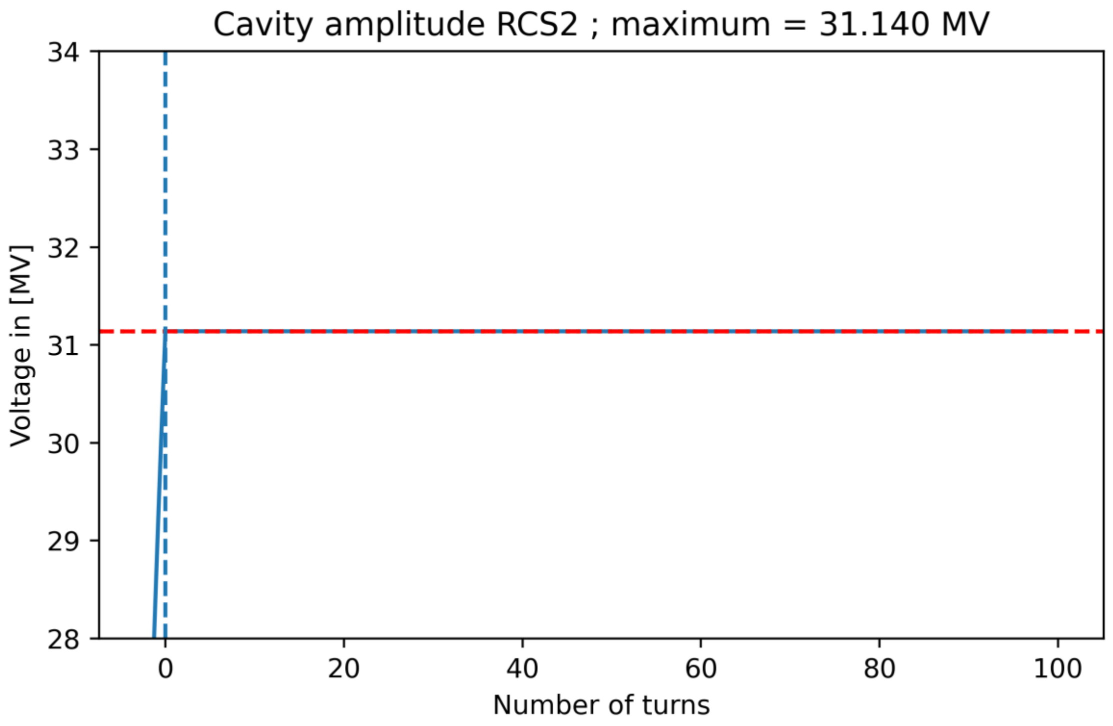
- Solution: → increase time resolution of the simulation from $1\ t_{rf}$ to $0.1\ t_{rf}$

Cavity voltage amplitude/phase
Distributed beam

Corrected Quality factor; Time resolution = 1 t_{rf}



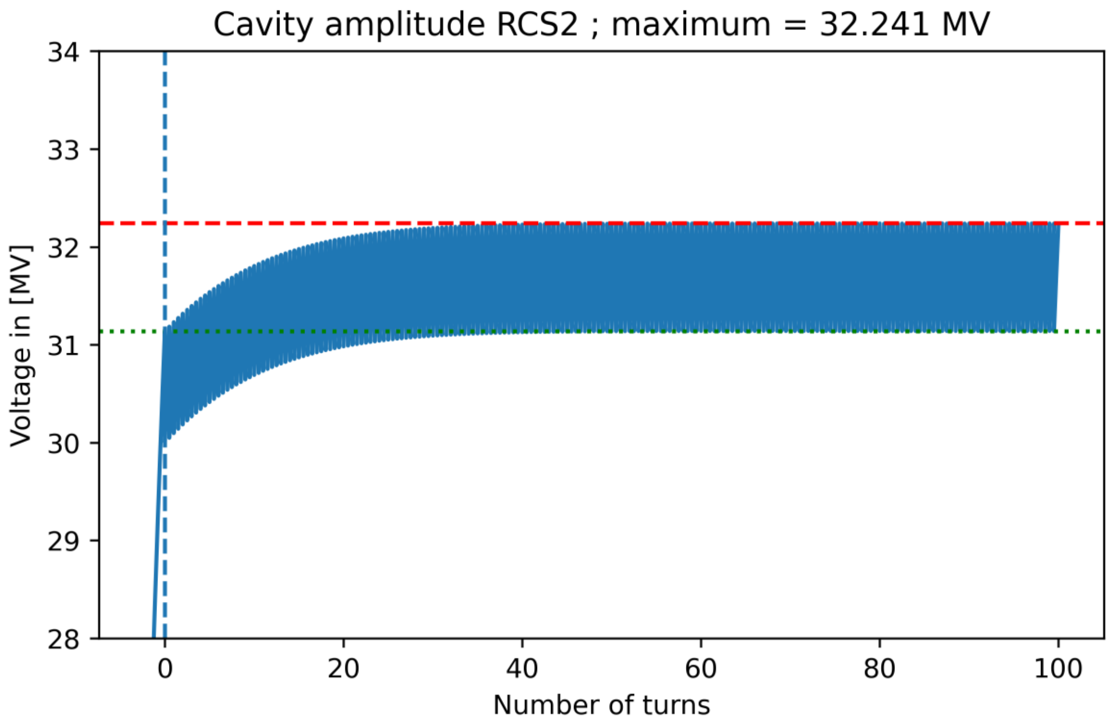
Spread out beam



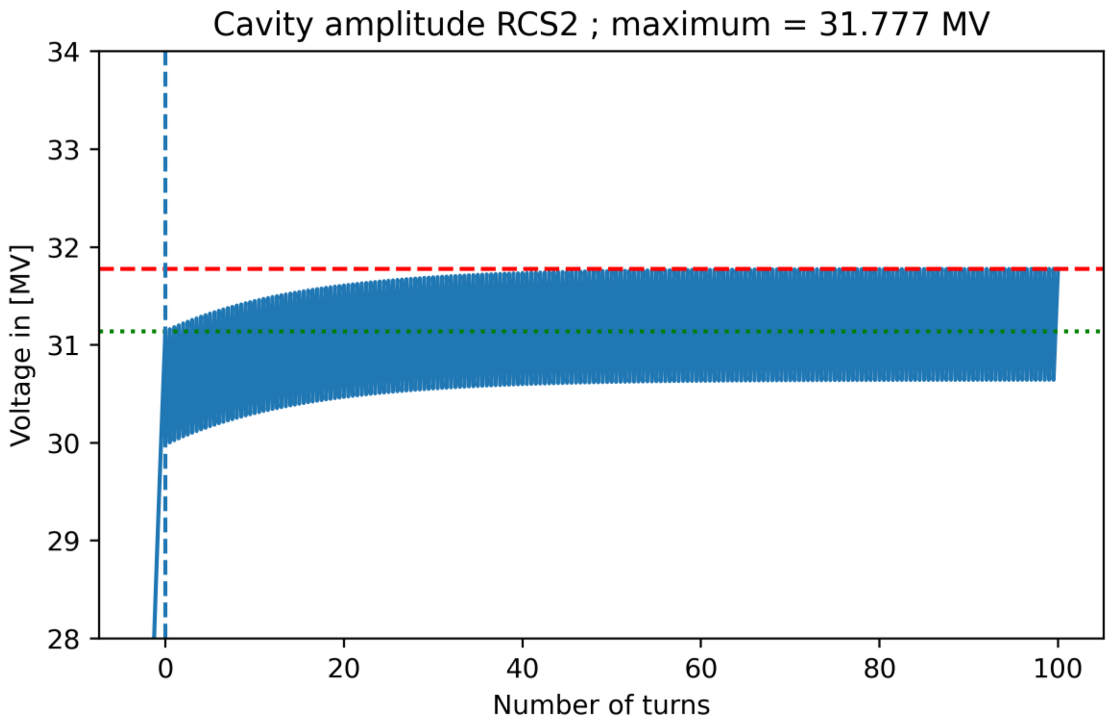
With an averaged beam, the amplitude is exactly on the setpoint voltage

Cavity voltage amplitude/phase increased time resolution

Corrected Quality factor; Time resolution = $1\ t_{rf}$



Time resolution = $0.1\ t_{rf}$

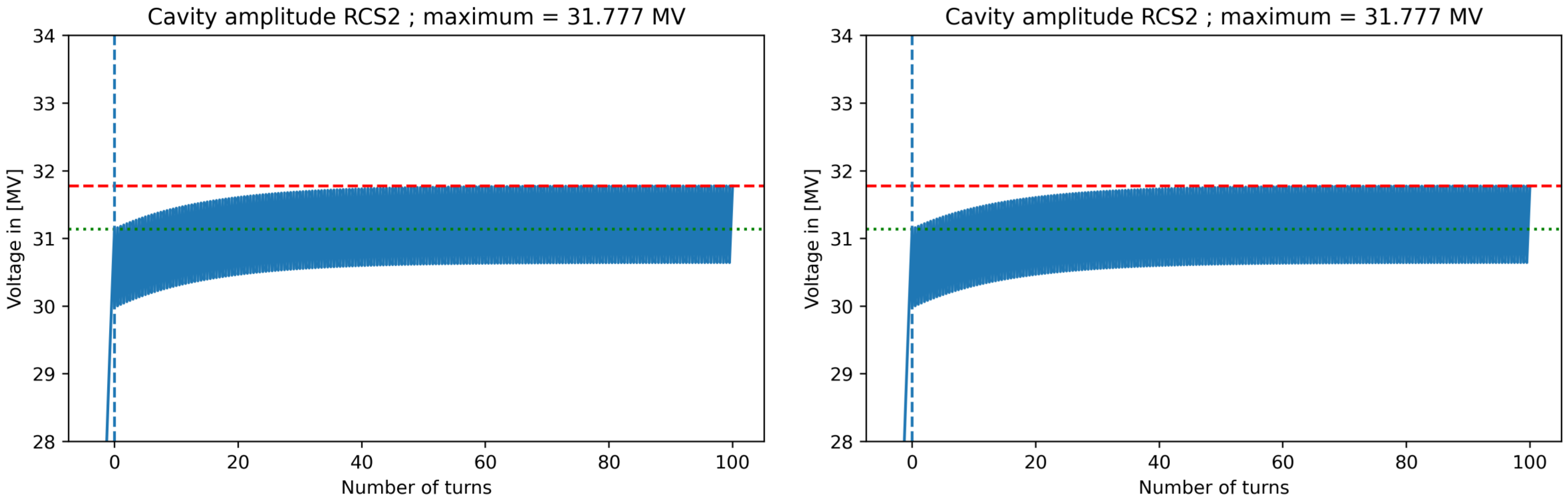


Now, the voltage amplitude is oscillating around the setpoint, as expected

Cavity voltage amplitude/phase increased time resolution

Time resolution = $0.1\ t_{rf}$

Beam in 10 rf buckets and Time resolution = $1\ t_{rf}$

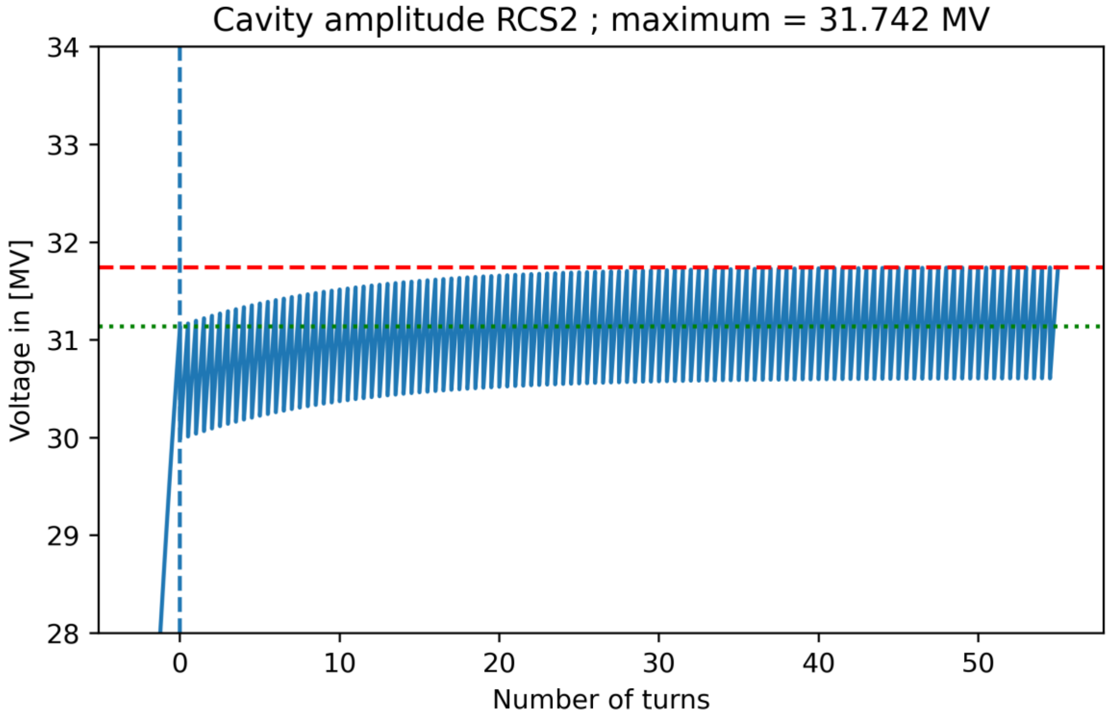


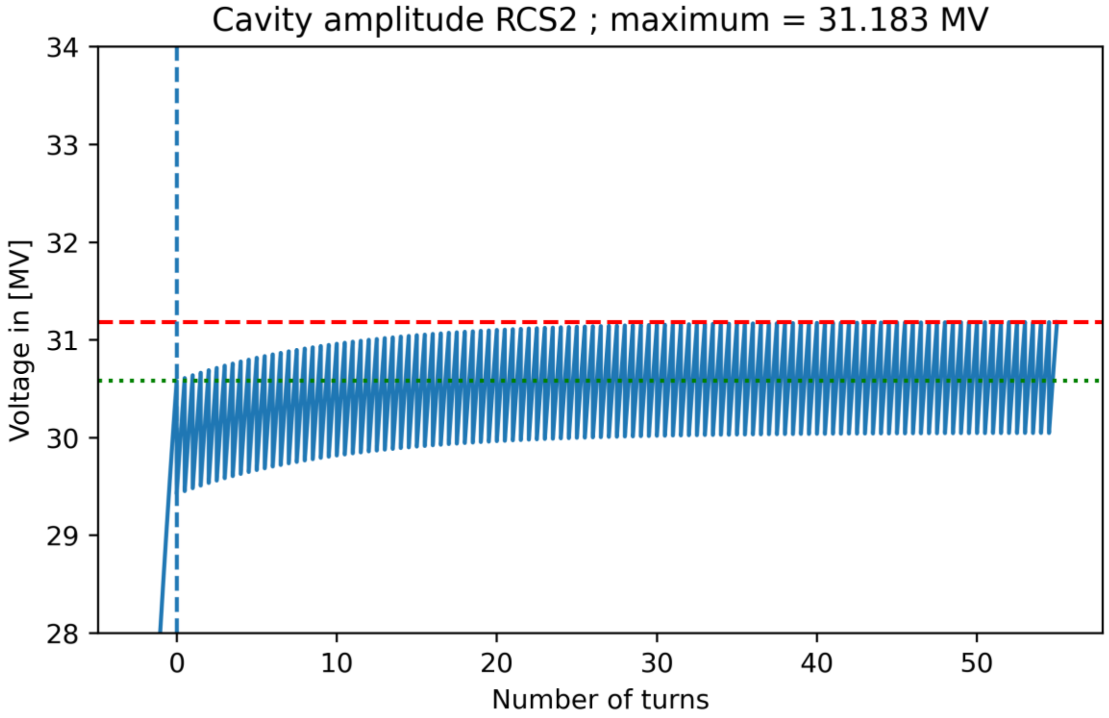
Having the beam spread out over 10 buckets has the same effect as increasing the time resolution by a factor of 10 **BUT**: saves simulation time

The formulas of the cav. phase and amplitude are coupled: the per-timestep change cannot be too large

Cavity voltage amplitude/phase
Lowering the setpoint

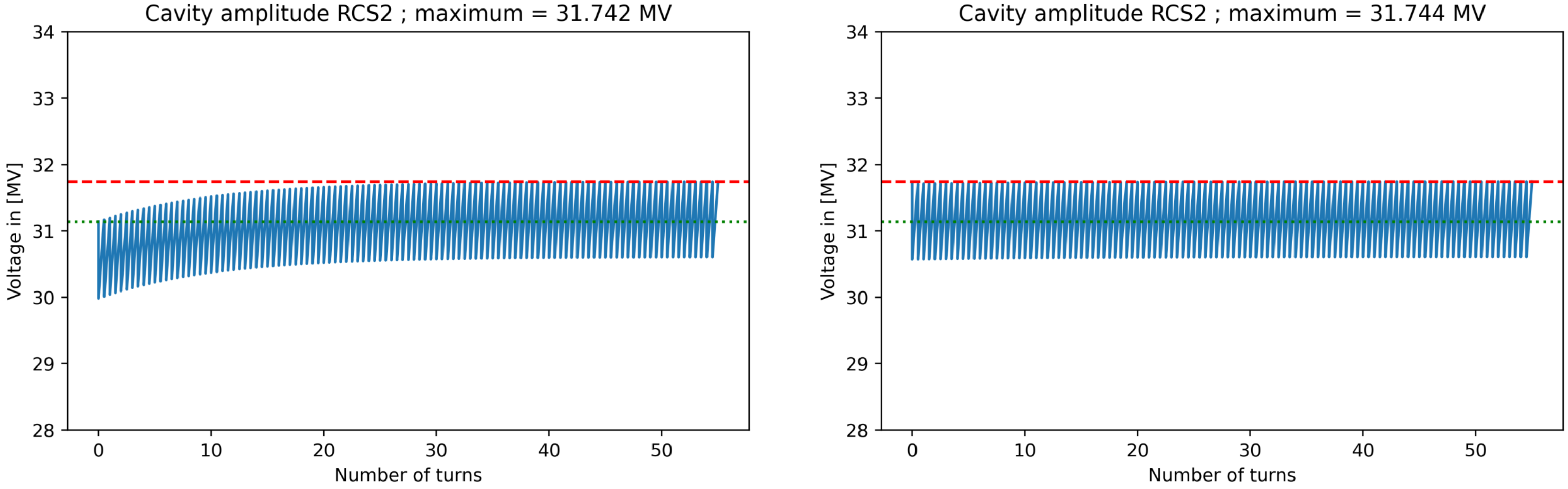
- As the cavity voltage is partially above the setpoint during parts of the acceleration, the setpoint needs to be lowered
- → slightly more cavities are required





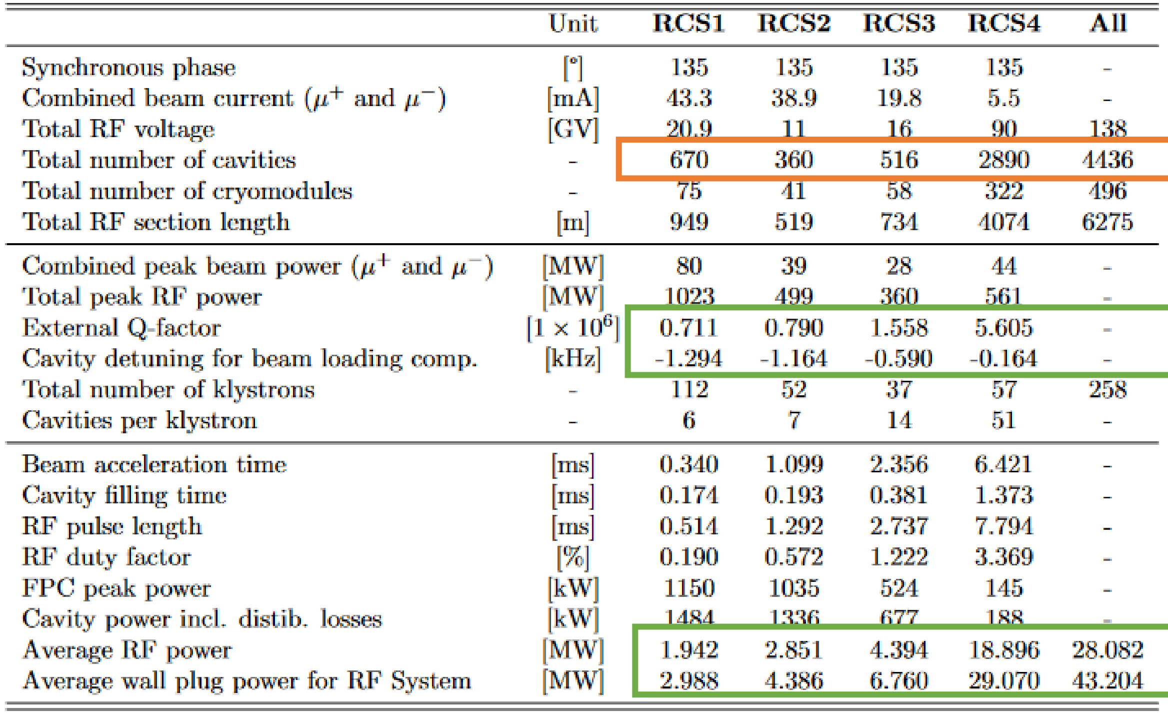
Cavity voltage amplitude/phase
Injecting at equilibrium

- To avoid the voltage change at the beginning of the acceleration, one can inject at the equilibrium voltage directly.



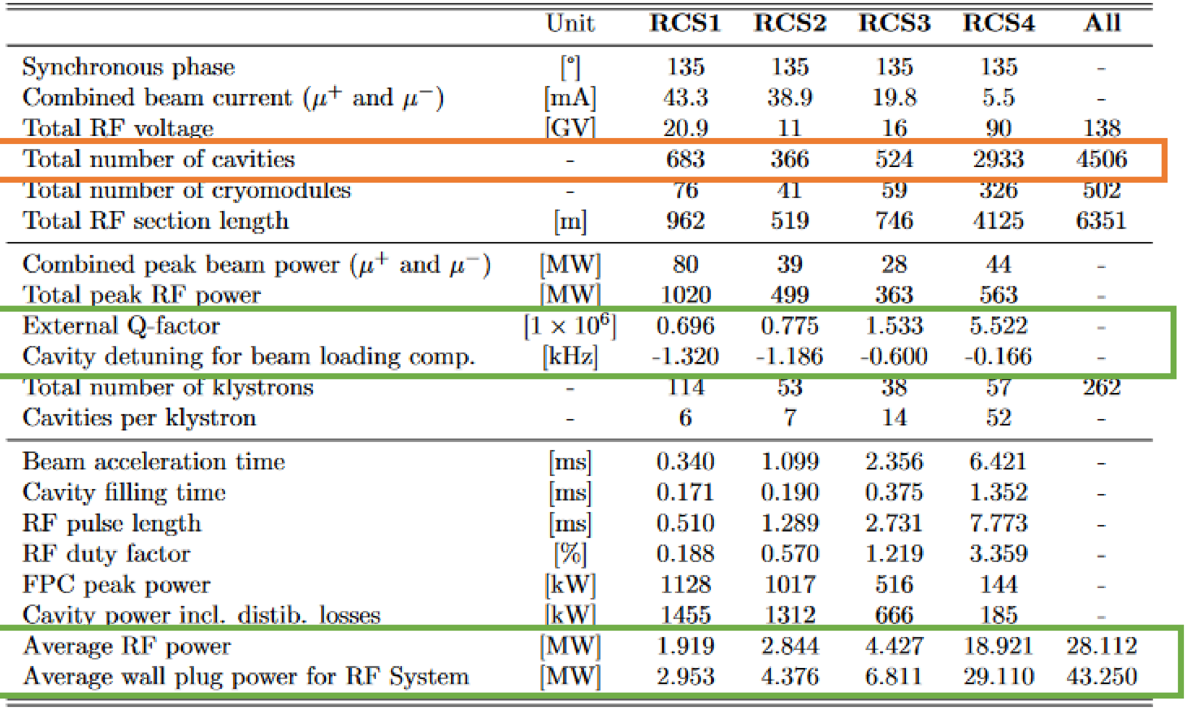
Resulting parameter changes

RF powering parameters before the changes



	Unit	RCS1	RCS2	RCS3	RCS4	All
Synchronous phase	[°]	135	135	135	135	-
Combined beam current (μ^+ and μ^-)	[mA]	43.3	38.9	19.8	5.5	-
Total RF voltage	[GV]	20.9	11	16	90	138
Total number of cavities	-	670	360	516	2890	4436
Total number of cryomodules	-	75	41	58	322	496
Total RF section length	[m]	949	519	734	4074	6275
Combined peak beam power (μ^+ and μ^-)	[MW]	80	39	28	44	-
Total peak RF power	[MW]	1023	499	360	561	-
External Q-factor	[1×10^6]	0.711	0.790	1.558	5.605	-
Cavity detuning for beam loading comp.	[kHz]	-1.294	-1.164	-0.590	-0.164	-
Total number of klystrons	-	112	52	37	57	258
Cavities per klystron	-	6	7	14	51	-
Beam acceleration time	[ms]	0.340	1.099	2.356	6.421	-
Cavity filling time	[ms]	0.174	0.193	0.381	1.373	-
RF pulse length	[ms]	0.514	1.292	2.737	7.794	-
RF duty factor	[%]	0.190	0.572	1.222	3.369	-
FPC peak power	[kW]	1150	1035	524	145	-
Cavity power incl. distib. losses	[kW]	1484	1336	677	188	-
Average RF power	[MW]	1.942	2.851	4.394	18.896	28.082
Average wall plug power for RF System	[MW]	2.988	4.386	6.760	29.070	43.204

RF powering parameters including adjustments



	Unit	RCS1	RCS2	RCS3	RCS4	All
Synchronous phase	[°]	135	135	135	135	-
Combined beam current (μ^+ and μ^-)	[mA]	43.3	38.9	19.8	5.5	-
Total RF voltage	[GV]	20.9	11	16	90	138
Total number of cavities	-	683	366	524	2933	4506
Total number of cryomodules	-	76	41	59	326	502
Total RF section length	[m]	962	519	746	4125	6351
Combined peak beam power (μ^+ and μ^-)	[MW]	80	39	28	44	-
Total peak RF power	[MW]	1020	499	363	563	-
External Q-factor	[1×10^6]	0.696	0.775	1.533	5.522	-
Cavity detuning for beam loading comp.	[kHz]	-1.320	-1.186	-0.600	-0.166	-
Total number of klystrons	-	114	53	38	57	262
Cavities per klystron	-	6	7	14	52	-
Beam acceleration time	[ms]	0.340	1.099	2.356	6.421	-
Cavity filling time	[ms]	0.171	0.190	0.375	1.352	-
RF pulse length	[ms]	0.510	1.289	2.731	7.773	-
RF duty factor	[%]	0.188	0.570	1.219	3.359	-
FPC peak power	[kW]	1128	1017	516	144	-
Cavity power incl. distib. losses	[kW]	1455	1312	666	185	-
Average RF power	[MW]	1.919	2.844	4.427	18.921	28.112
Average wall plug power for RF System	[MW]	2.953	4.376	6.811	29.110	43.250

- Slightly higher number of cavities
- Different Q-factor and detuning
- Resulting power consumption is not differing by a lot

Conclusion and Outlook

- Adjustment of Q_{L-opt} in dependence of $\Delta\omega$ was performed.
- Time resolution of the simulation was increased to reach the anticipated equilibrium voltage.
- Voltage setpoint was lowered, which led to a slight increase in required cavities.

- Integrate transient beam loading calculation into beam dynamics simulation.
- Perform simulations for CERN-site based options.
- Perform simulations with different cavities.

International
MUON Collider
Collaboration

MuCol

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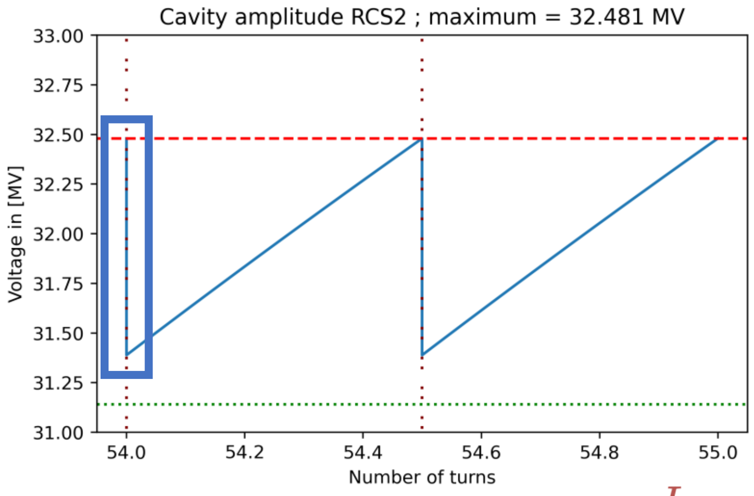
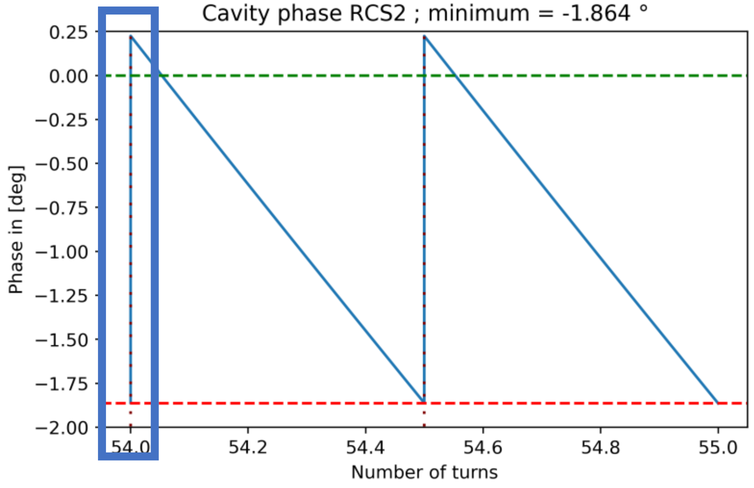
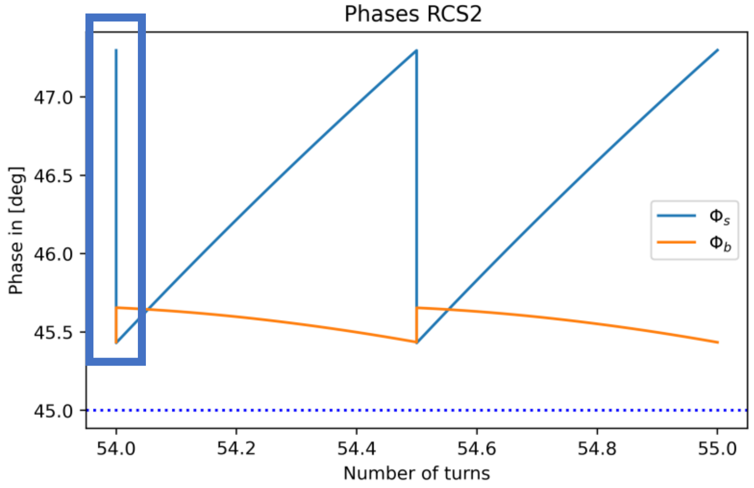
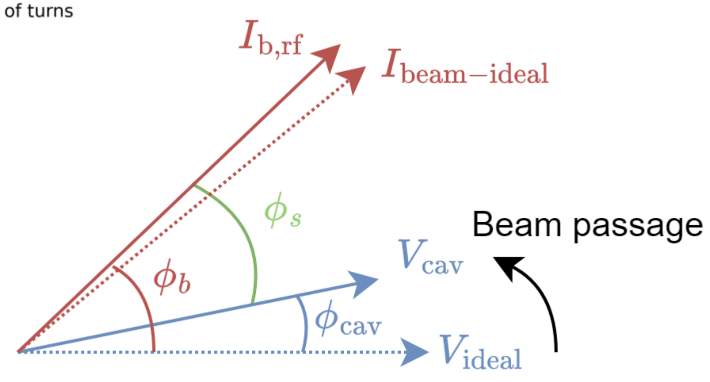
Changing cavity voltage (last turn of RCS2)





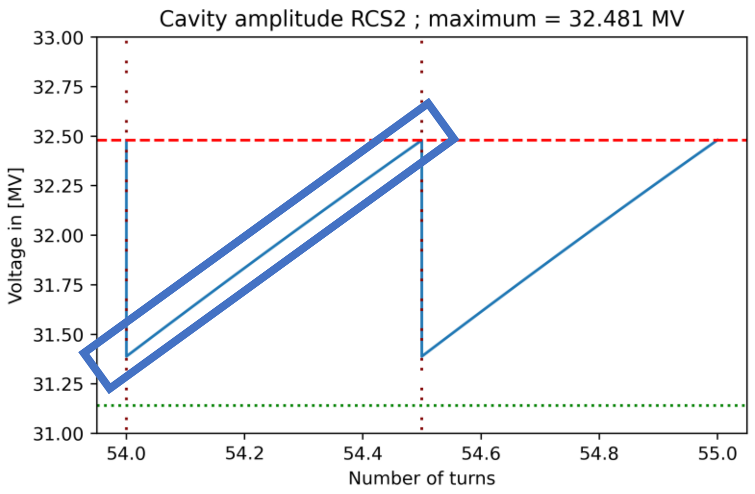


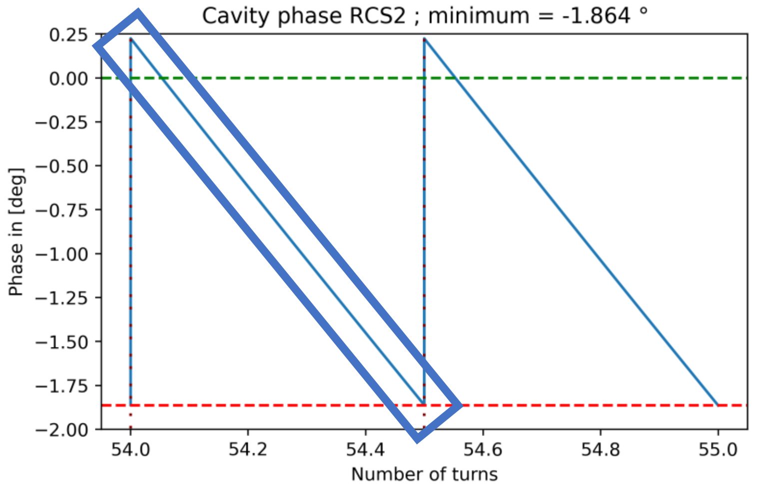


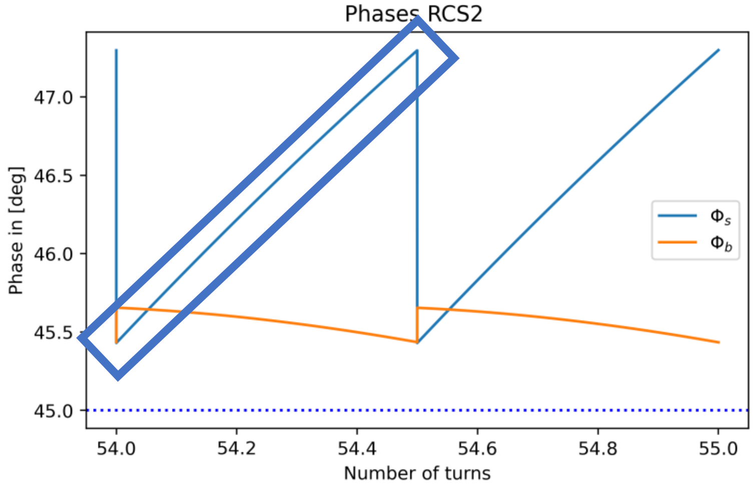
In order to keep the same energy gain, a change in the beam phase is necessary:

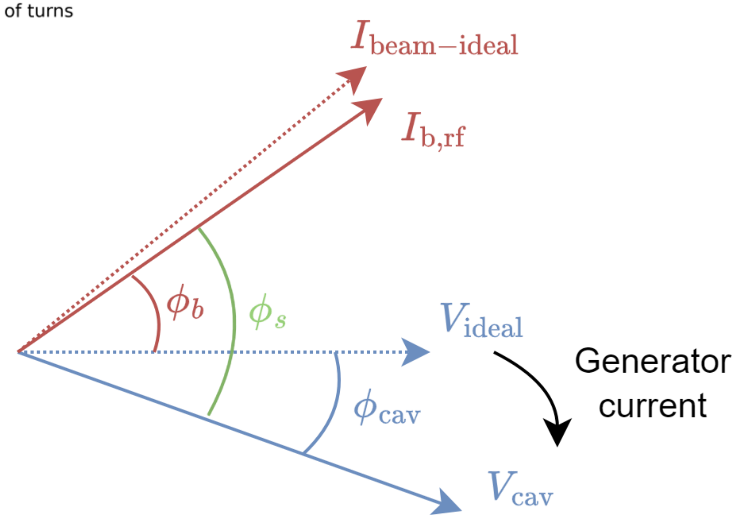
$$\Phi_b = \arccos\left(\frac{\Delta E}{A(t)}\right) + \Phi_{\mathrm{cav}}(t)$$

Changing cavity voltage (last turn of RCS2)


Cavity amplitude RCS2 ; maximum = 32.481 MV


Cavity phase RCS2 ; minimum = -1.864 °


Phases RCS2



In order to keep the same energy gain, a change in the beam phase is necessary:

$$\Phi_b = \arccos\left(\frac{\Delta E}{A(t)}\right) + \Phi_{\text{cav}}(t)$$

Forumla collection

$$\frac{dA(t)}{dt} = -\frac{A(t)}{\tau} + (R/Q)\omega_{\mathrm{rf}} \times \left\{ I_{g,c}\cos[\phi_L - \phi(t)] - \frac{A_b(t)\cos[\phi_s - \phi_b(t) + \phi(t)]}{2} \right\}, \qquad (7)$$

$$\frac{d\phi(t)}{dt} = \Delta\omega + \frac{(R/Q)\omega_{\mathrm{rf}}}{A(t)} \times \left\{ I_{g,c}\sin[\phi_L - \phi(t)] + \frac{A_b(t)\sin[\phi_s - \phi_b(t) + \phi(t)]}{2} \right\}, \qquad (8)$$

$$\Delta E = \cos(\Phi_s - \Phi(t)) * A(t) \ (16)$$

for $\Phi_b = \Phi_s = const.$

https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.22.081002

$$I_g e^{i\Phi_L} = \frac{V_{cav}}{2(R/Q)}\left(\frac{1}{Q_L} - 2i\,\frac{\Delta\omega}{\omega_{rf}}\right) + \frac{< I_{b,rf} >}{2} \ (9)$$

$$Q_{L,opt} = \frac{V_{cav}}{R/Q\sqrt{(|F_b| I_{b,dc}\cos(\Phi_s))^2 + \left(|F_b| I_{b,DC}\sin(\Phi_s) + \frac{V_{cav}\,2\Delta\omega}{\omega R/Q}\right)^2}} \ (13)$$

$$\Delta\omega_{opt} = -\omega_{rf}\frac{(R/Q)|F_b| I_{b,dc}\sin(\Phi_s)}{2V_{cav}} \ (12)$$

$$\Phi_s = \arccos\left(\frac{\Delta E}{A(t)}\right) \ (14)$$

$$\Phi_b = \arccos\left(\frac{\Delta E}{A(t)}\right) + \Phi(t) \ (15)$$

References

[1]: I. Karpov, Transient beam loading and rf power evaluation for future circular colliders
https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.22.081002