Transient beam loading in the RCS chain

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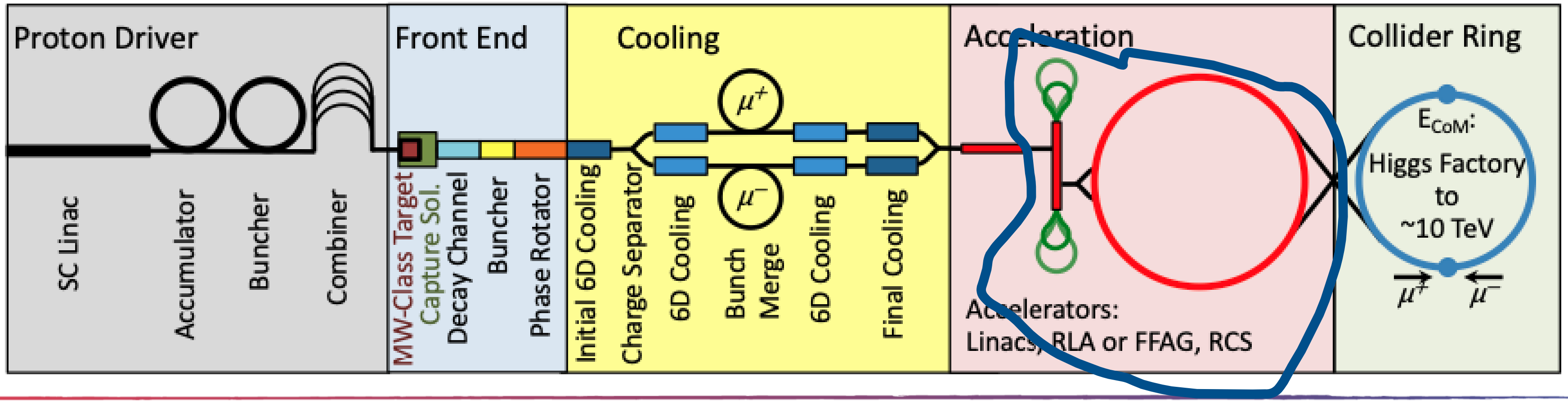
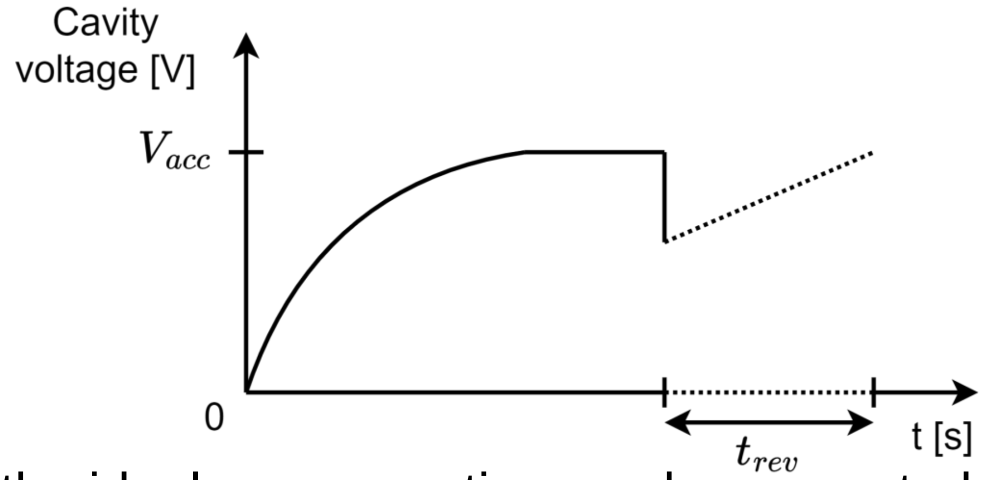
- Summary and outlook



Introduction to beam loading in RF cavities

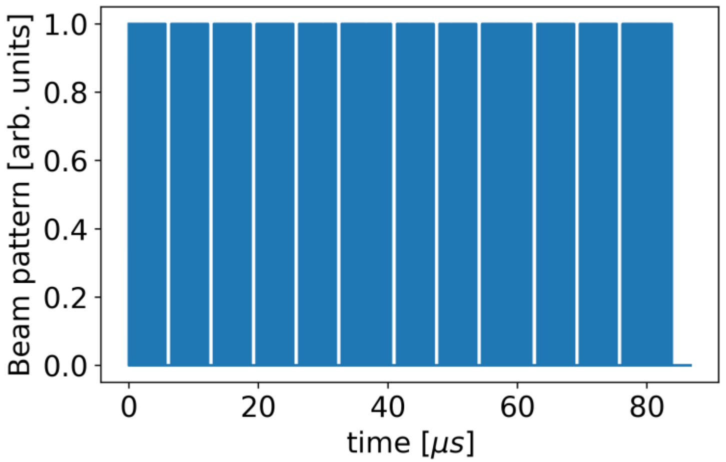
- After filling the cavity with a certain generator current, a voltage will build up.
- The bunch passage will then decrease this voltage as parts of the energy are transferred to the bunch.
- This effect has to be compensated for, as otherwise, the bunch encounters less voltage on the next passage →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

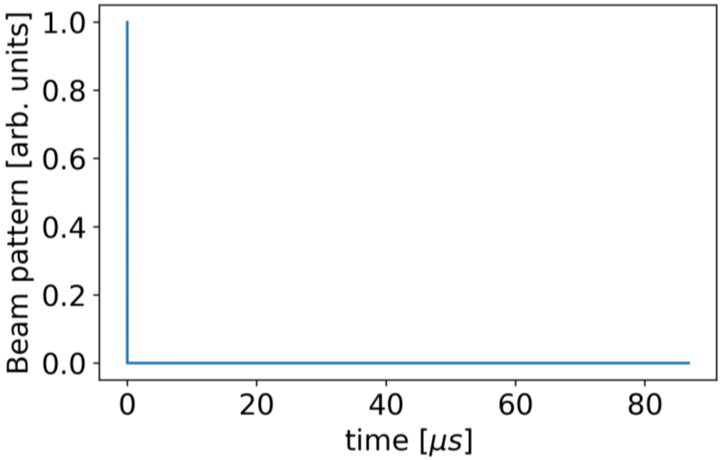
Transient beam loading in the Muon Collider

- In the Muon Collider, the entire beam charge is concentrated in 2 bunches, leaving the rest of the ring empty.
  - The ratio between maximum beam current and average beam current is high.
  - ➢ Transient beam loading will impact the voltage noticeably.
- If the counter-rotating beam then encounters a lower voltage, the energy gain will be smaller, resulting in a lower muon transmission.



← LHC-like bunch pattern

MuCol bunch pattern →



Beam loading compensation

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

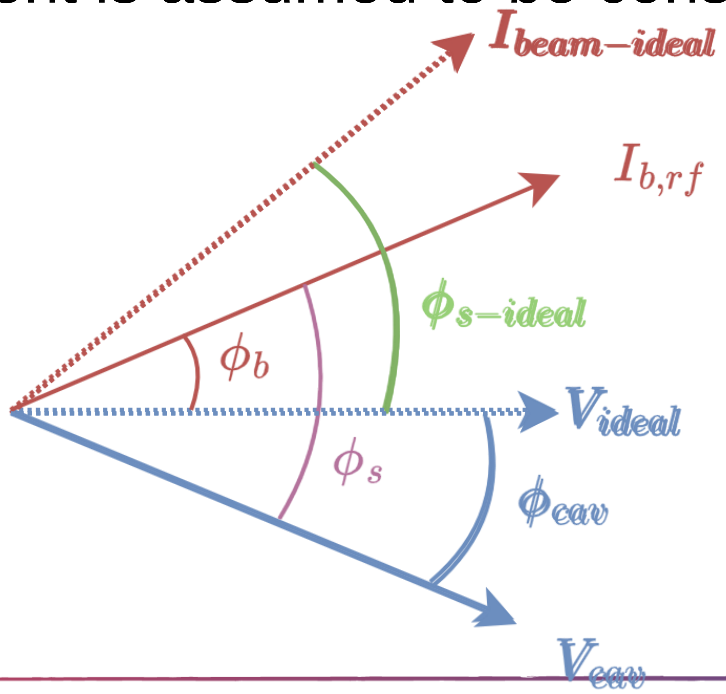
  Loaded quality factor $\boldsymbol{Q_L}$ and cavity detuning $\boldsymbol{\Delta\omega}$
- Both parameters have an optimum point, for which the generator power and reflected power are minimised.
- Deviating from these leads to significantly higher power consumption and parts of the power being reflected back towards the generator.
- Without loops, the beam will not be Robinson stable with the optimum parameters. [2]

➢ Stronger detuning required:

$$\Delta\omega_s = \frac{\Delta\omega_{opt}}{\sin(\Phi_s)^2} \approx \Delta\omega_{opt} * 2$$

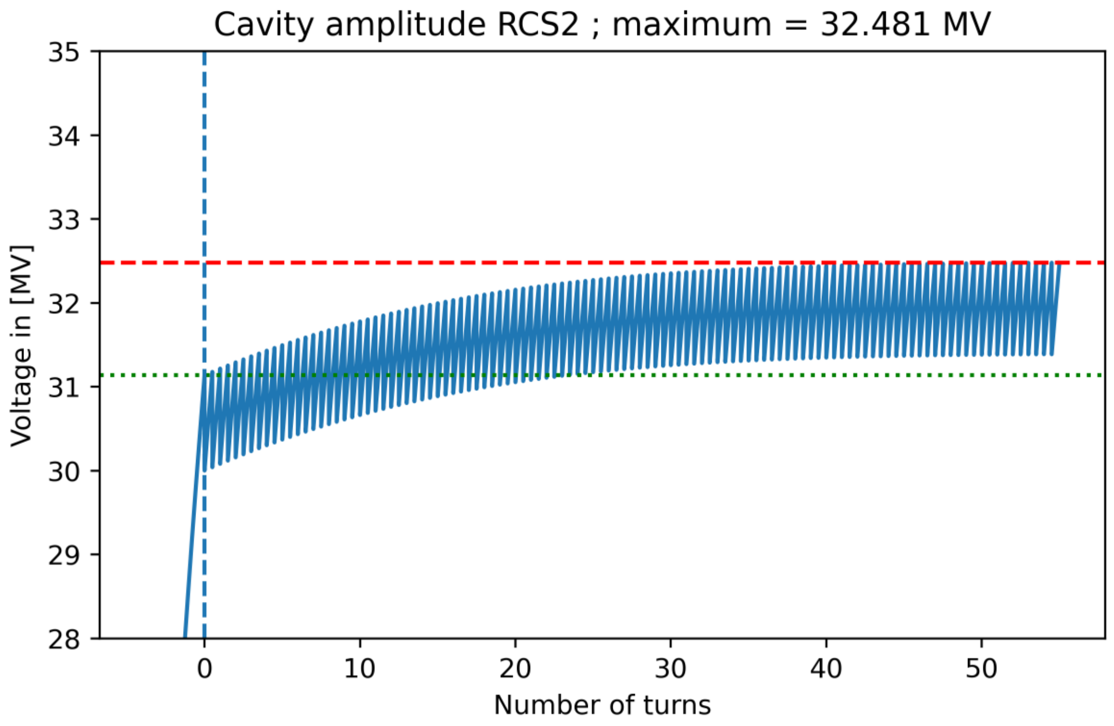
Assumptions to simulate transient beam loading

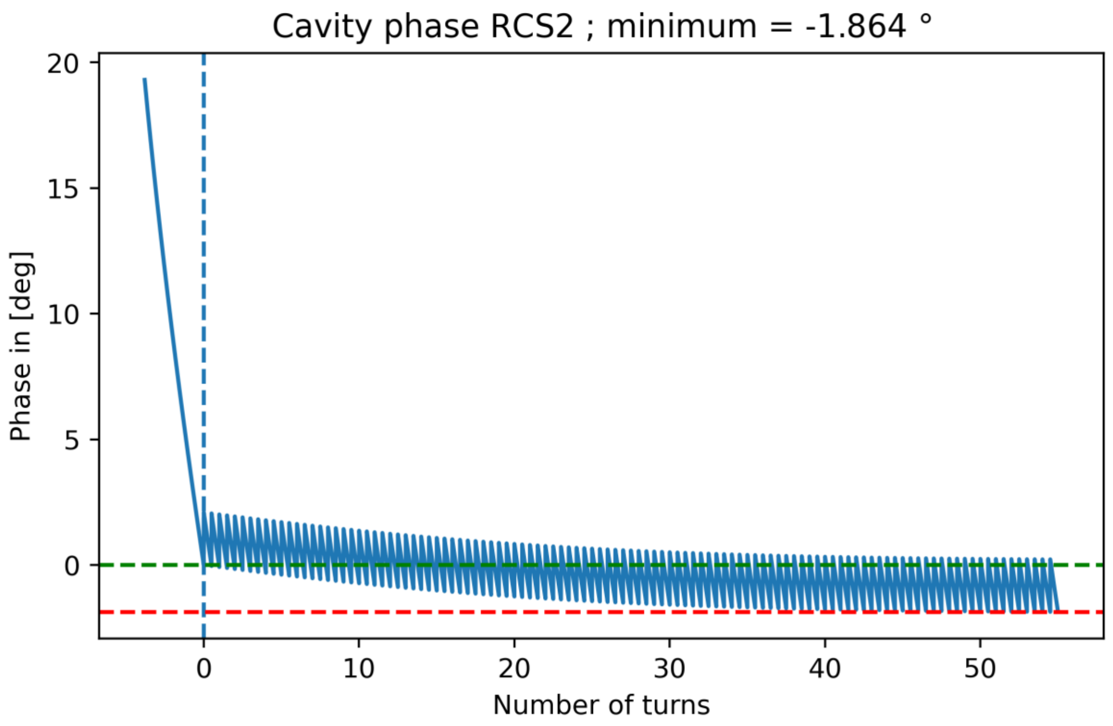
- Due to the short acceleration time, the cavity voltage and cavity phase are allowed to be altered by the beam without a controller loop present.
- The phase at which the beam passes to get the desired energy gain will, therefore, also change.
- The generator current is assumed to be constant.



Cavity voltage amplitude/phase modulation during the acceleration

All plots with stronger detuning and optimal loaded quality factor Q_L.

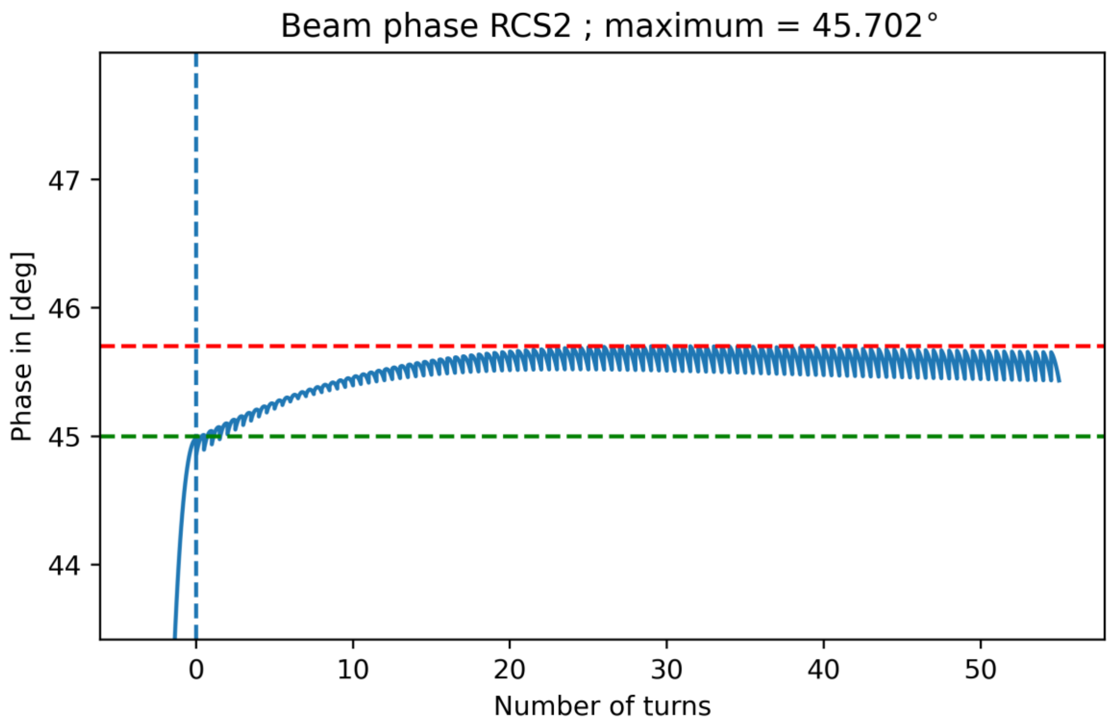


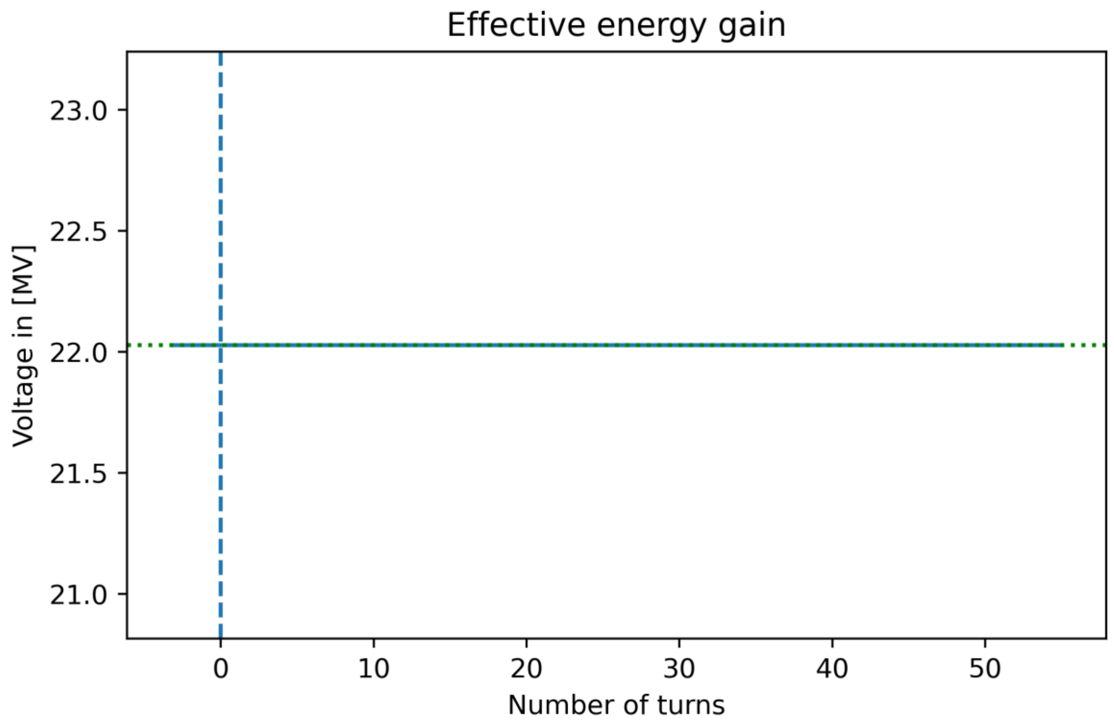


Implementation follows the description in [2] I. Karpov, “Transient beam loading and rf power evaluation for future circular colliders”

Beam phase modulation during the acceleration

- Beam phase is given in electron machine convention
- Phase is modulated, to get the correct energy gain, considering the change in cavity phase and voltage.





RF parameters in the high-energy chain
Cavity powering “stable” detuning

	Unit	RCS1	RCS2	RCS3	RCS4
Duty factor	[%]	0.21	0.59	1.26	3.52
Optimum cavity detuning	[kHz]	-0.64	-0.58	-0.3	-0.08
Stable cavity detuning	[kHz]	-1.29	-1.16	-0.59	-0.16
FPC peak power	[kW]	954	860	435	120
FPC peak power	[kW]	1191	1072	543	151
Average wall plug power (incl. klystron eff.)	[MW]	2.7	3.7	6	25
Average wall plug power (incl. klystron eff.)	[MW]	3.3	4.7	7.2	31
Number of klystrons	-	96	45	31	47
Number of klystrons	-	112	52	40	58

Parameters with optimum detuning

Parameters with stronger detuning

Summary

- Usage of non-optimal cavity detuning leads to higher power consumption.
- The phase at which the beam sees the correct voltage changes during the acceleration.
- The transient beam loading simulation shows that the cavity voltage reaches its equilibrium above the current baseline of 30 MV/m.
  - This indicates, that a higher surface field would be present during the acceleration.
  - Try to adjust RCS parameters in order to change the equilibrium voltage.

Outlook

- Implement non-linear ramping and investigate the impact on the energy gain.
- Optimize the frequency detuning of the cavity to reduce the power consumption of the cavity.
- Integration of cavity voltage evolution into BLonD beam dynamics simulations.
- Quantify energy gain difference between μ^+ and μ^- bunches.
- Investigate the impact of using different cavities and/or frequencies on the cavity powering.
  - R/Q in HOMs is believed to be too high for transverse stability (see talk by D. Amorim)

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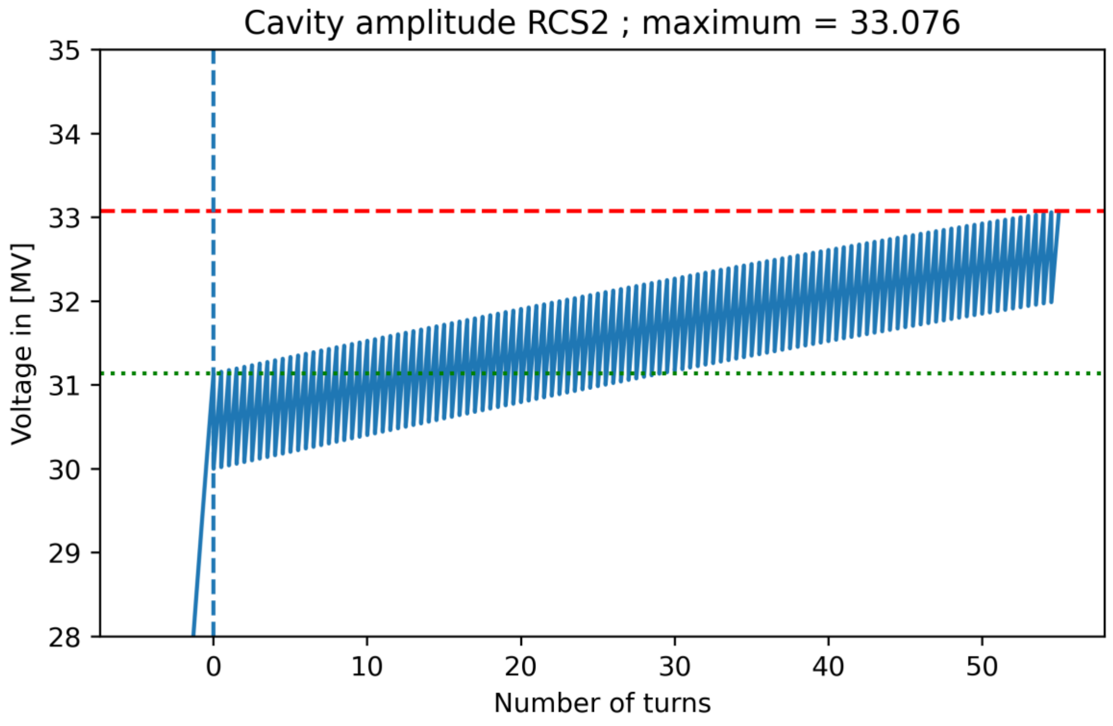
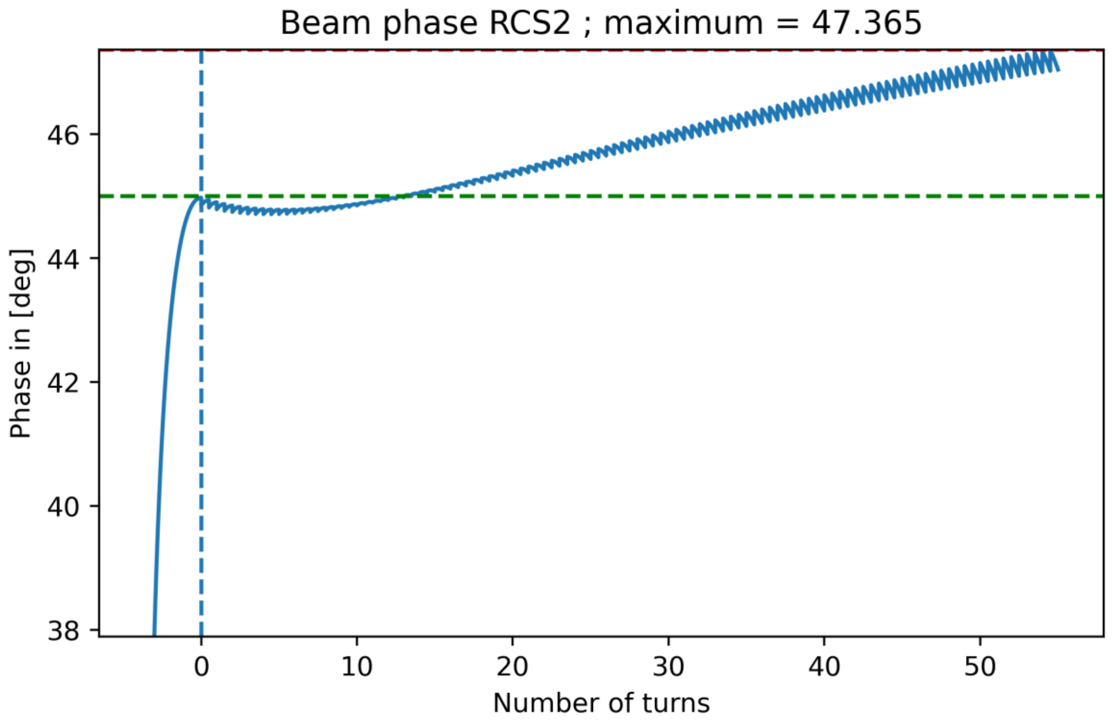
Cavity voltage with optimal detuning

- Cavity amplitude is continuously rising, not reaching equilibrium within the simulation time
- Acceleration is not stable in this regime





RF parameters in the high-energy chain
Cavity powering “stable” detuning

	Unit	RCS1	RCS2	RCS3	RCS4
Beam acceleration time	[ms]	0.34	1.10	2.36	6.42
Cavity filling time	[ms]	0.25	0.27	0.54	1.94
RF pulse length	[ms]	0.59	1.37	2.90	8.36
Duty factor	[%]	0.21	0.59	1.26	3.52
Cavity detuning	[kHz]	-1.294	-1.164	-0.590	-0.164
FPC peak power	[kW]	1191	1072	543	151
Total peak RF power (incl. power distribution losses)	[MW]	1630	794	575	891
Average wall plug power (incl. klystron eff.)	[MW]	3.3	4.7	7.2	31
Number of klystrons	-	112	52	40	58
Cavities per klystron	-	6	7	13	50

RF parameters in the high-energy chain
Cavity powering – optimum detuning

	Unit	RCS1	RCS2	RCS3	RCS4
Beam acceleration time	[ms]	0.34	1.10	2.36	6.42
Cavity filling time	[ms]	0.25	0.27	0.54	1.94
RF pulse length	[ms]	0.59	1.37	2.90	8.36
Duty factor	[%]	0.21	0.59	1.26	3.52
Cavity detuning	[kHz]	-0.64	-0.58	-0.3	-0.082
FPC peak power	[kW]	954	860	435	120
Total peak RF power (incl. power distribution losses)	[MW]	1304	629	466	717
Average wall plug power (incl. klystron eff.)	[MW]	2.7	3.7	6	25
Number of klystrons	-	96	45	31	47
Cavities per klystron	-	7	8	17	62

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