Frequency scaling of the RF-parameters in the Muon Collider RCS chain

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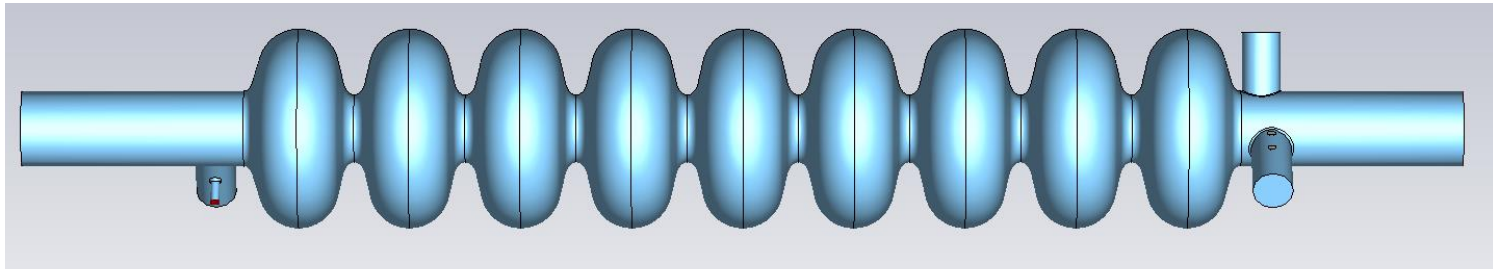
Outline

- Current baseline
- Scaling of different system characteristics
  - R/Q and impedance
  - RF system parameter
  - Transient beam loading
  - Bunch length
  - Phase space
- Conclusion and outlook

Current baseline RF-system (greenfield)



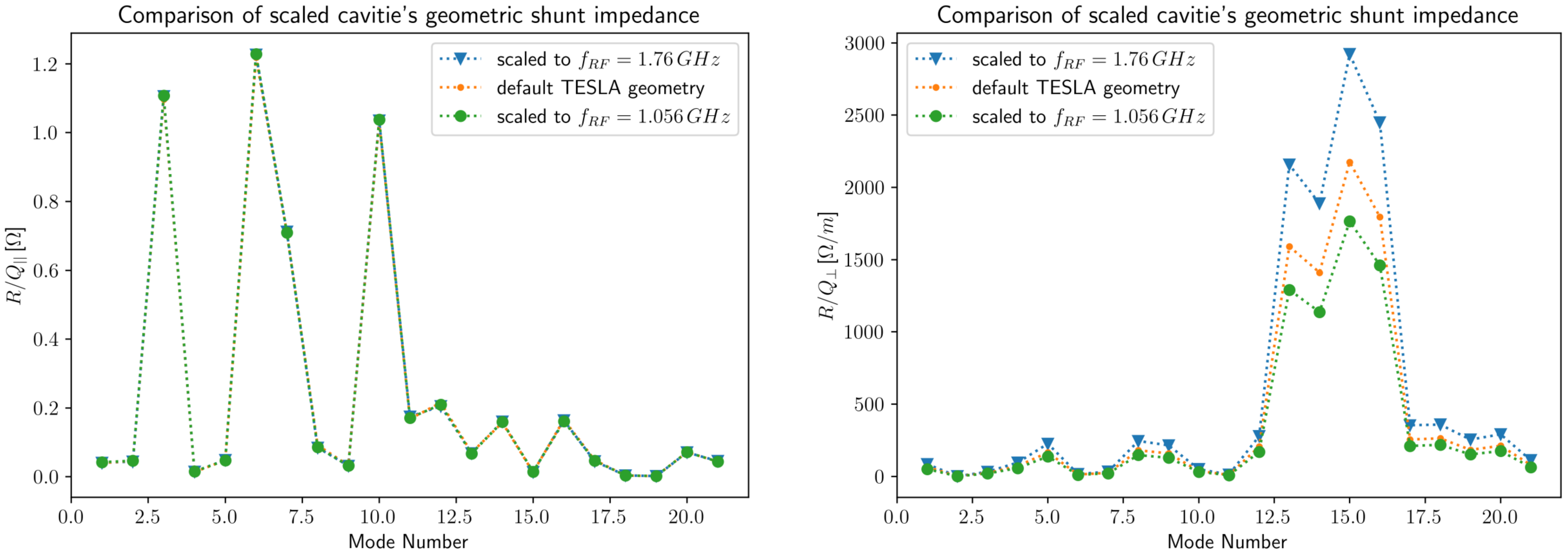
- 1,3 GHz 9-cell TESLA cavity
- $\lambda_{RF} \approx 230\,mm,\ l_{active} = 1026\,mm$
- Gradient is assumed as $30\ MV/m$
- Longitudinal R/Q in FM: $518\ \Omega$
- Very short bunch length
  - 9 mm at injection into RCS1
  - 2.7 mm at ejection from RCS4

		RCS1	RCS2	RCS3	RCS4	All
Combined beam current	mA	43.3	39	19.8	5.49	-
Total RF voltage	GV	20.9	11.2	16.1	90	138.2
Total number of cavities	-	683	366	524	2933	4506
Total RF section length	m	962	519	746	4125	6351
Combined peak beam power	MW	640	310	225	350	-
External Q-factor	10^6	0.696	0.775	1.533	5.522	-
Cavity detuning	kHz	-1.32	-1.186	-0.6	-0.166	-
Beam acceleration time	ms	0.34	1.1	2.37	6.37	-
Cavity filling time	ms	0.171	0.19	0.375	1.352	-
RF duty factor	%	0.19	0.57	1.22	3.36	-
Peak cavity power	kW	1128	1017	516	144	-
Total peak RF power	MW	1020	496	365	561	-
Average WP power	MW	2.95	4.38	6.811	29.1	43.25

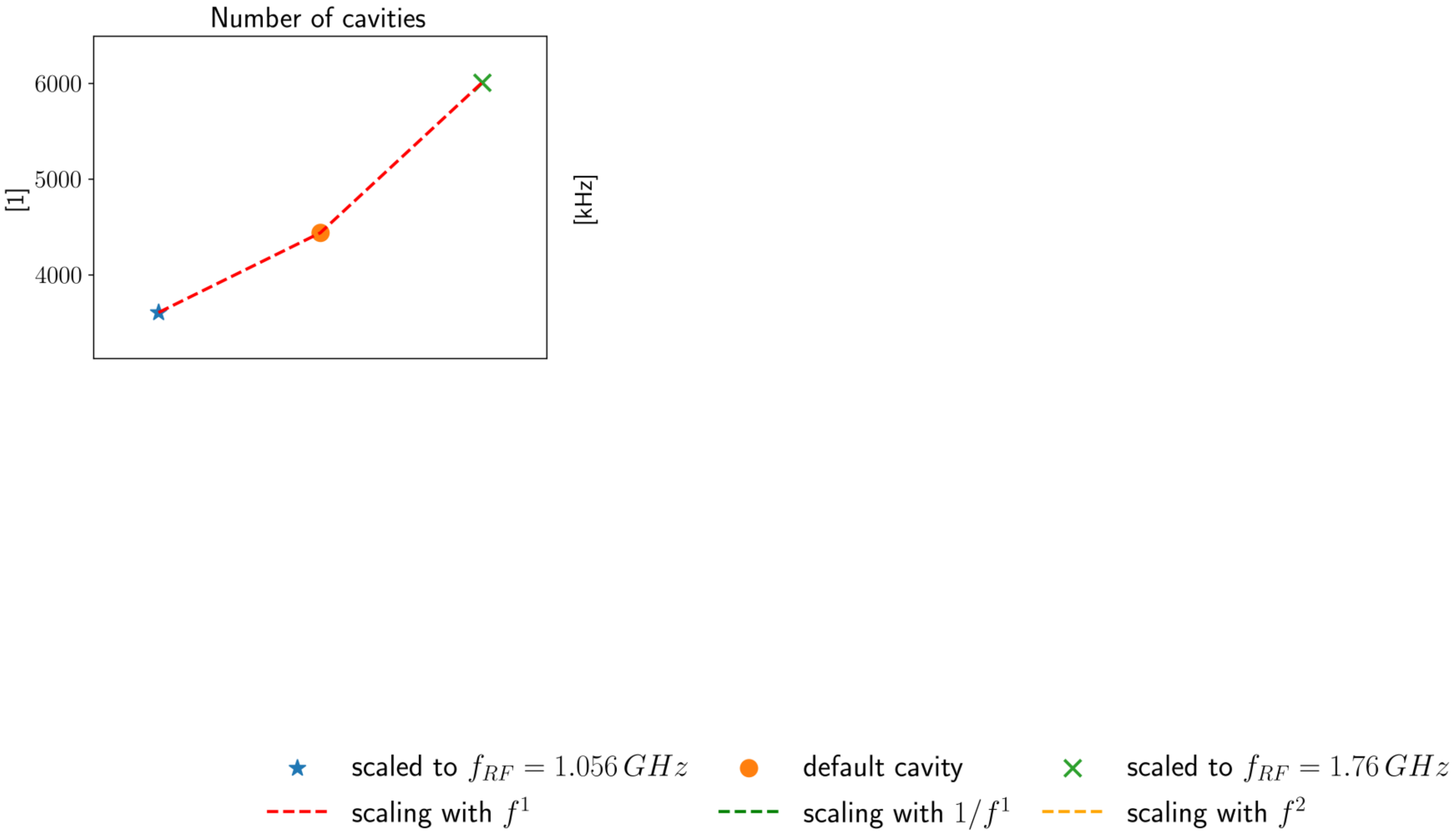
How does this change at different frequencies?

R/Q scaling in superconducting cavities

- Second and third dipole passband in damped TESLA cavity (CST-Model from Sosoho)
- Complete model scaled to different fundamental mode frequencies
  - ➢ 3rd and 5th LEP harmonic

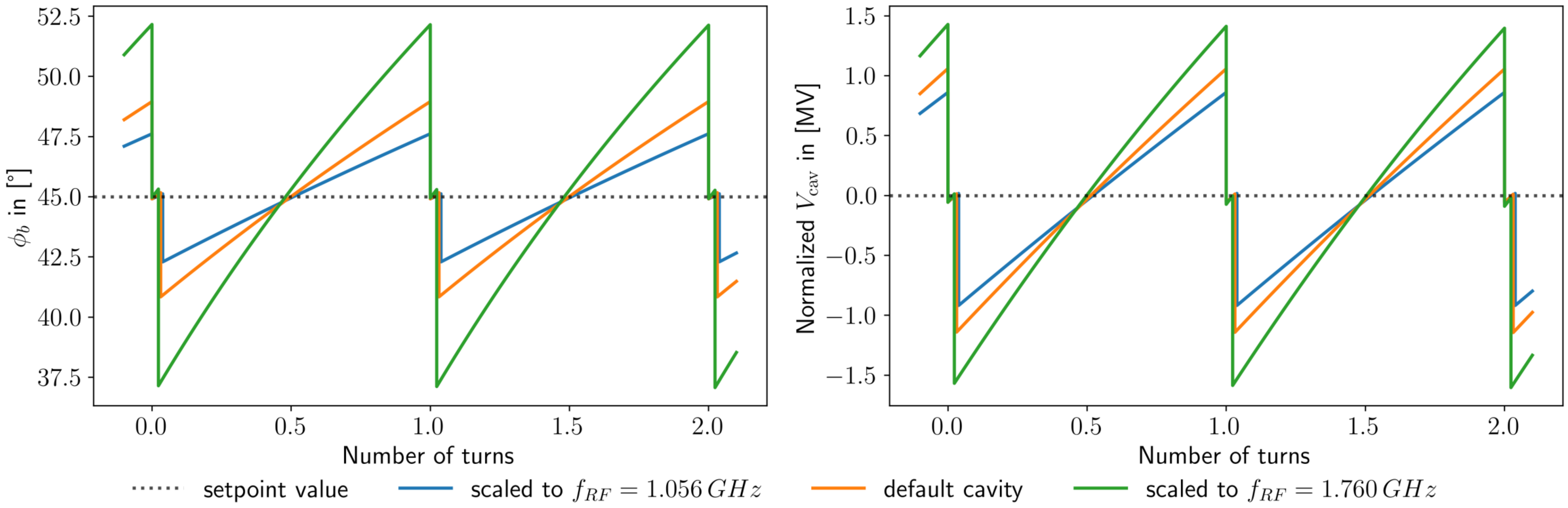


RF-system parameters



Assumption:
Gradient = 30MV/m at all frequencies
FPC: Fundamental Power Coupler
WP: Wall Plug

Transient beam loading simulation

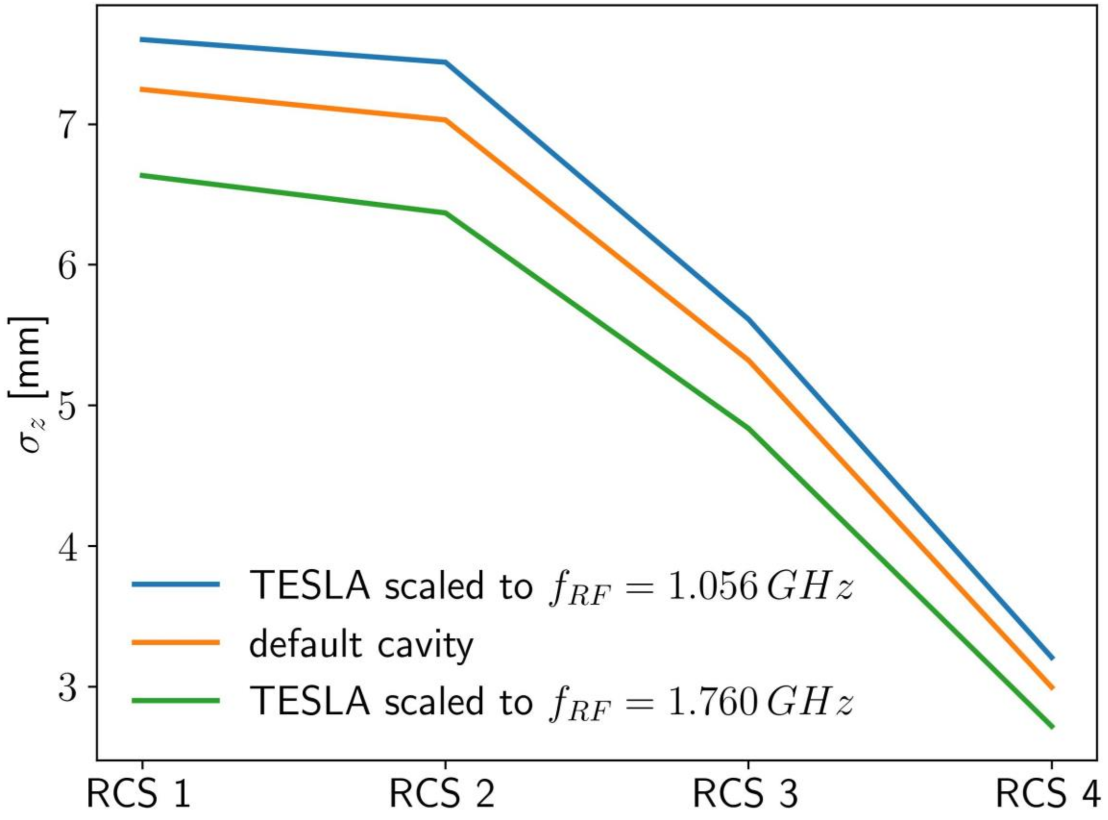


Both ϕ_b and V_{cav} vary more significantly at increased cavity frequency
→ less stored energy in the cavity volume

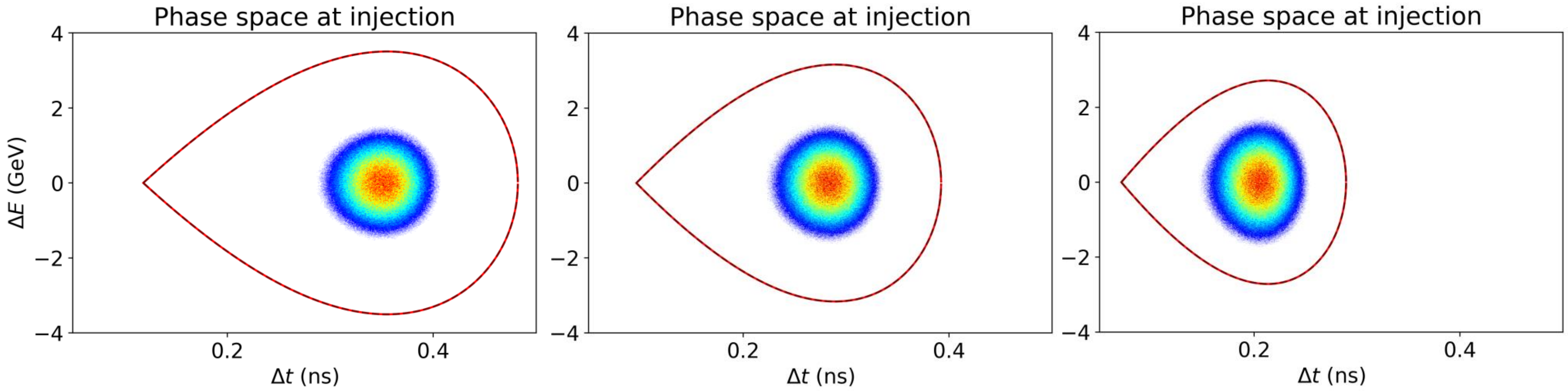
Bunch length considerations

Assumptions:

- Same synchronous phase $\phi_s = 45^o$
- HOM frequencies scaled
- Bunch length at injection after matching
- All other parameters at greenfield baseline



Bunch length considerations

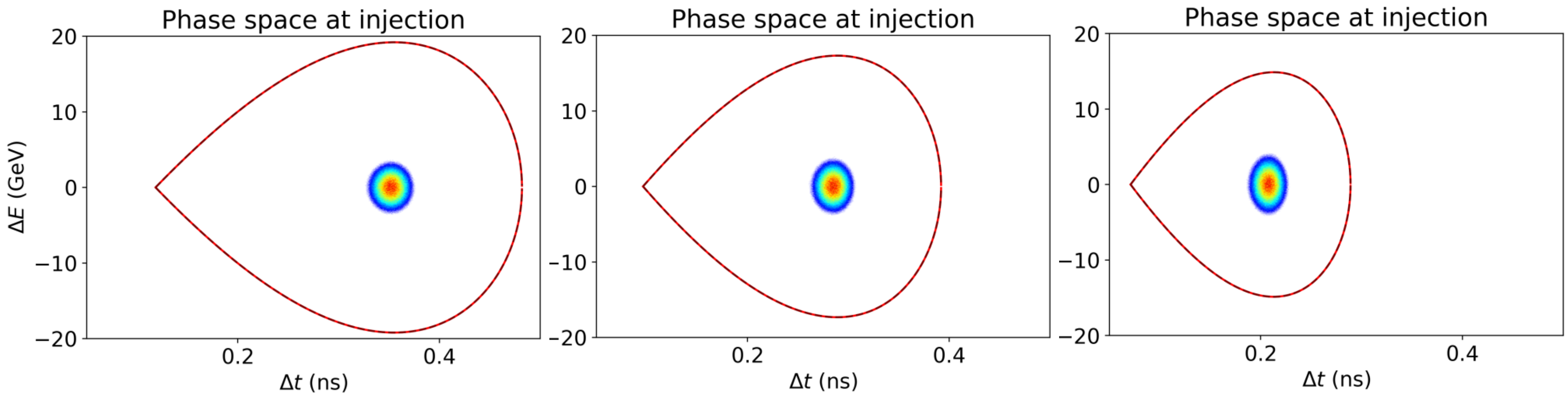


RCS 1

f_{RF} scaled to $1.056\ GHz$

unscaled

f_{RF} scaled to $1.76\ GHz$



RCS 4

Scaling overview

Parameter	Unit	Scaling per cavity	Overall scaling
Achievable gradient	V/m	≈ 1	$-$
Cavity Length	m	$1/f$	~ 1
Cavity Volume	m^3	$1/f^3$	$1/f^2$
Number of cavities	1	$-$	f
$R/Q_{\|\|}$	Ω	1	f
$R/Q_{\perp}$	Ω/m	f	f^2
FPC power	W	$1/f$	$-$
WP power	W	$-$	$< 1/f$
Optimum Q_L	1	$1/f$	$-$
Optimum Δf	Hz	$1/f^2$	$-$

Conclusion and Outlook

- Higher frequency would be preferential, especially in later RCS
  - Lower power consumption
  - Smaller cryomodules
  - Better suited to shorter bunch length
  - Increased total impedance through number of cavities
  - Potentially higher gradient

➢Impedance might be limiting

Open Questions:

- What are the impedance limits in the longitudinal & transverse planes?
- How does the HOM power change at different frequencies?

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Possible drawbacks

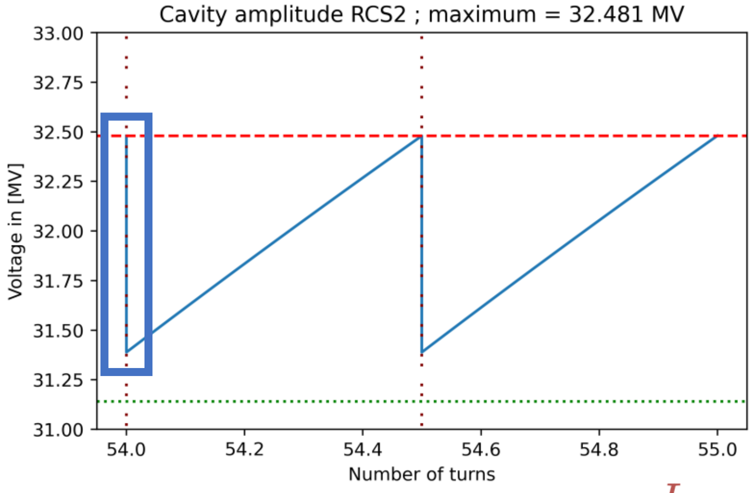
Higher frequency:

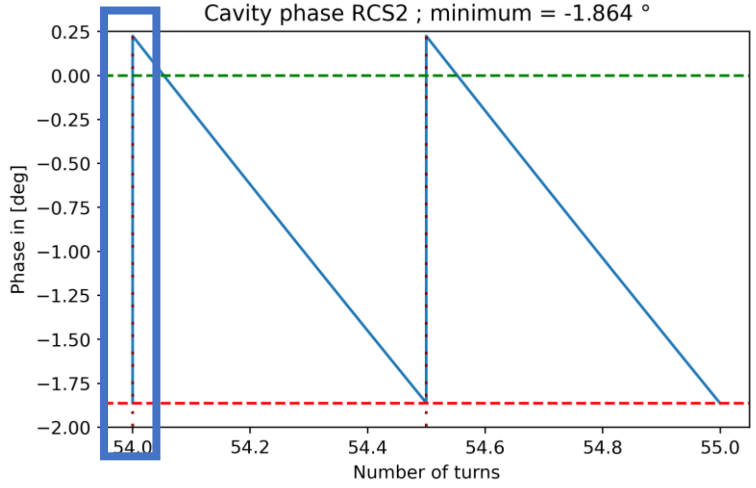
- Impedance limitation
  - Increased number of cavities
  - ➢ Additional transverse and longitudinal short-range wakefields
  - ➢ Where is the stability limit in both planes?
  - ➢ Potentially higher gradient

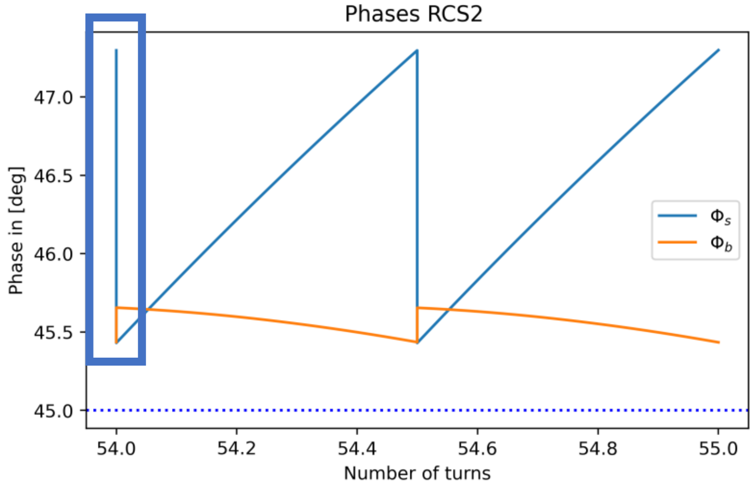
Lower frequency:

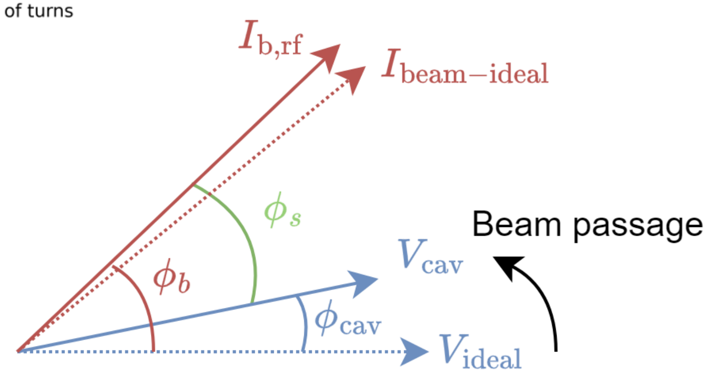
- Cryomodule size & necessary He budget
- Surface treatment of large RF structures?
- Additional manufacturing and alignment tolerance
- With the same bunch length:
  - ➢ Relative to the FM, bunch will induce voltage in more HOMs → until ~38 GHz

Changing cavity voltage (last turn of RCS2)





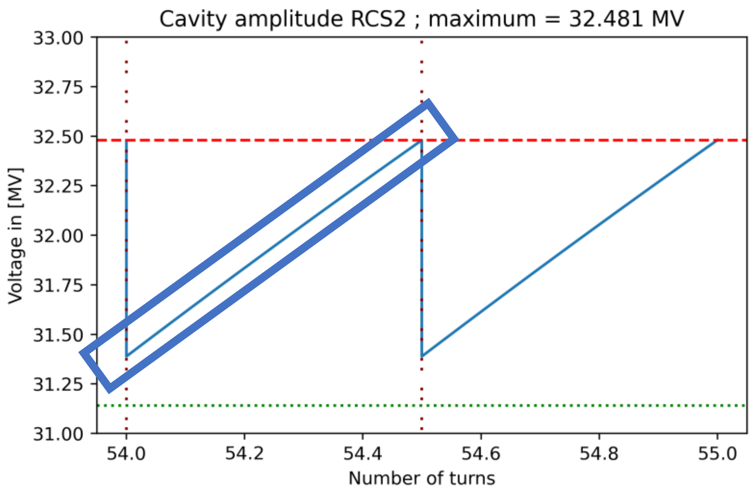


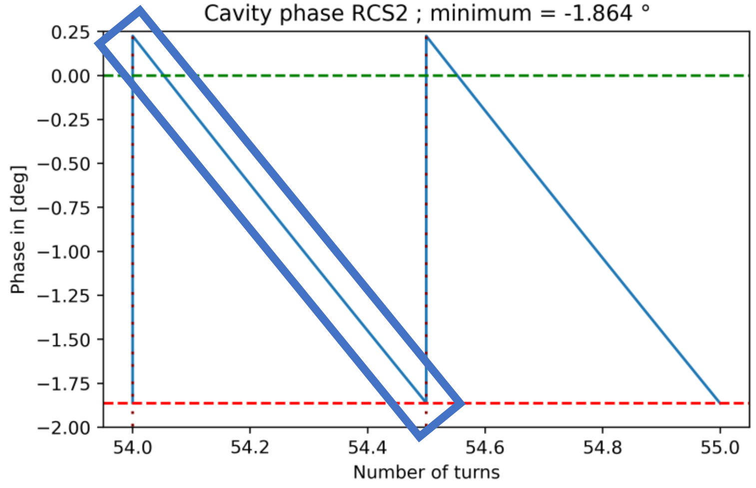


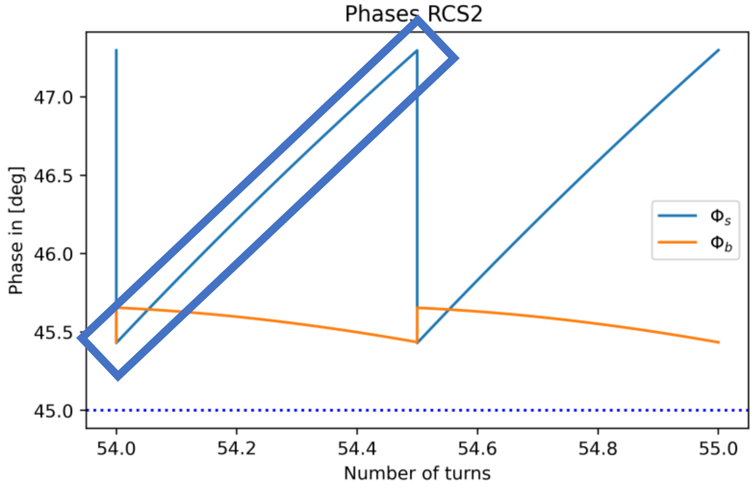
In order to keep the same energy gain, a change in the beam phase is necessary:

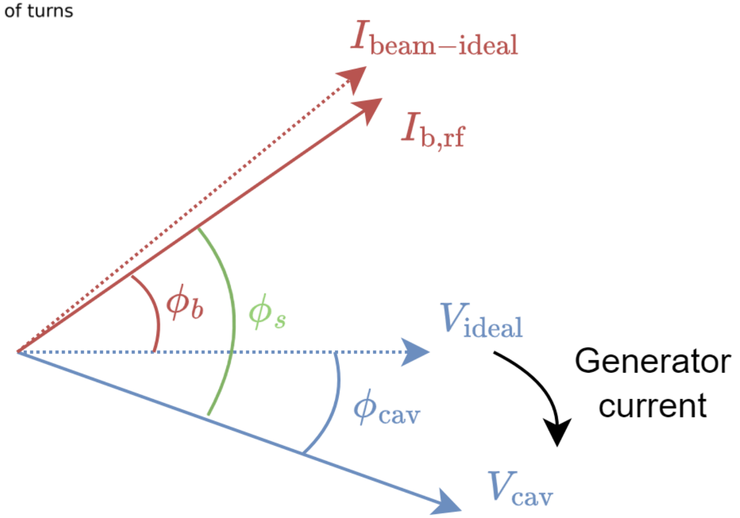
$$\Phi_b = \arccos\left(\frac{\Delta E}{A(t)}\right) + \Phi_{\mathrm{cav}}(t)$$

Changing cavity voltage (last turn of RCS2)









Generator current

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

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

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