RCS transverse stability versus α_p

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Goal of the study

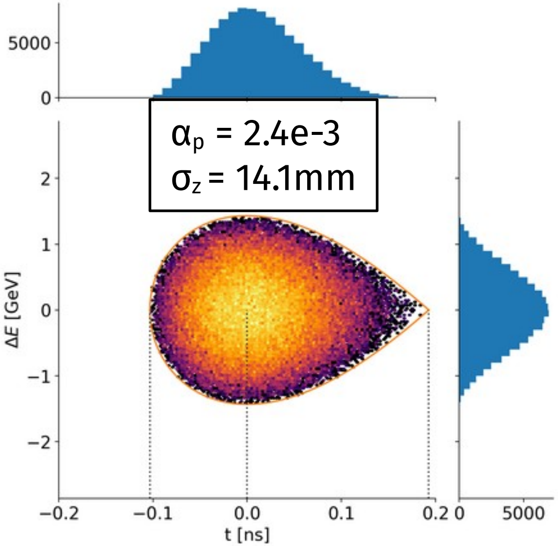
- Check the **effect of momentum compaction factor** on **transverse beam stability** through the RCS chain
- Use the **TESLA cavity transverse HOMs impedance model**
- Scan on damper gain and initial transverse offset of the bunch. Only chromaticity Q'=0 and Q'=+20 will be shown

Machine parameters	**Unit**	**RCS 1**	**RCS 2**	**RCS 3**	**RCS 4**
RF frequency	MHz	1300	1300	1300	1300
Harmonic number		25957	25957	46295	151433
RF voltage	GV	20.9	11.22	16.1	90.0
α_p		**0.0024**	**0.0024**	**0.001**	**0.001**

Reducing α_p has a visible impact on the longitudinal beam profile

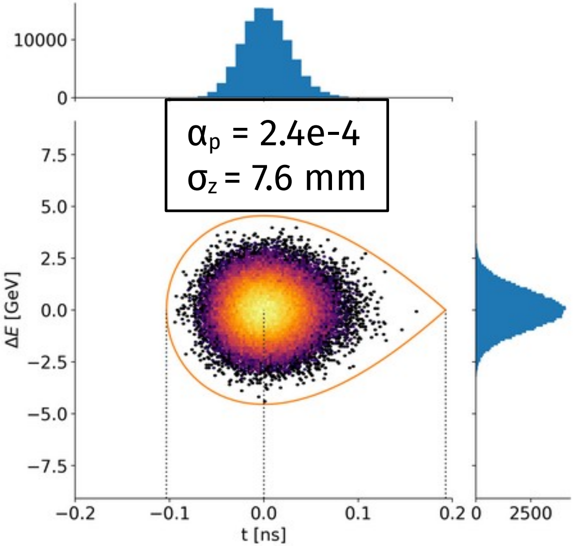
- Bunch length and energy deviation scale with $\eta^{1/4}$ and $\eta^{-1/4}$ respectively
- We have $1/\gamma^2 = 2.8e{-6}$ in RCS 1 at injection, so $\eta = \alpha_p - 1/\gamma^2 \sim \alpha_p$
- If we keep the same longitudinal emittance and RF parameters, the bunch length will be reduced for smaller α_p (assuming the bunch is matched to the bucket)

Longitudinal bunch profile at injection in RCS1



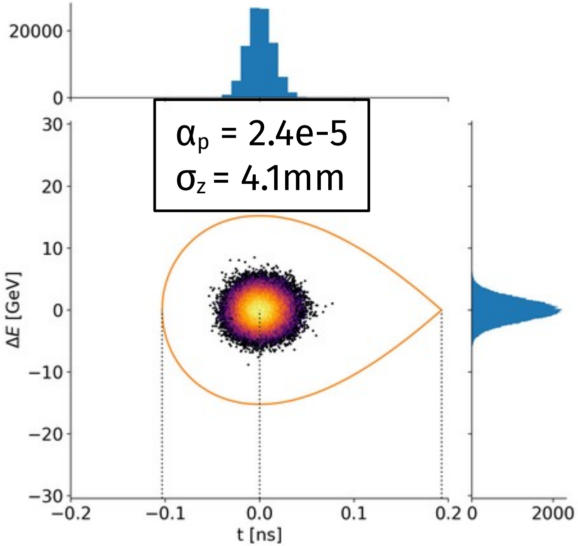
$\alpha_p = 2.4e{-3}$
$\sigma_z = 14.1\text{mm}$

Longitudinal bunch profile at injection in RCS1



$\alpha_p = 2.4e{-4}$
$\sigma_z = 7.6\text{ mm}$

Longitudinal bunch profile at injection in RCS1

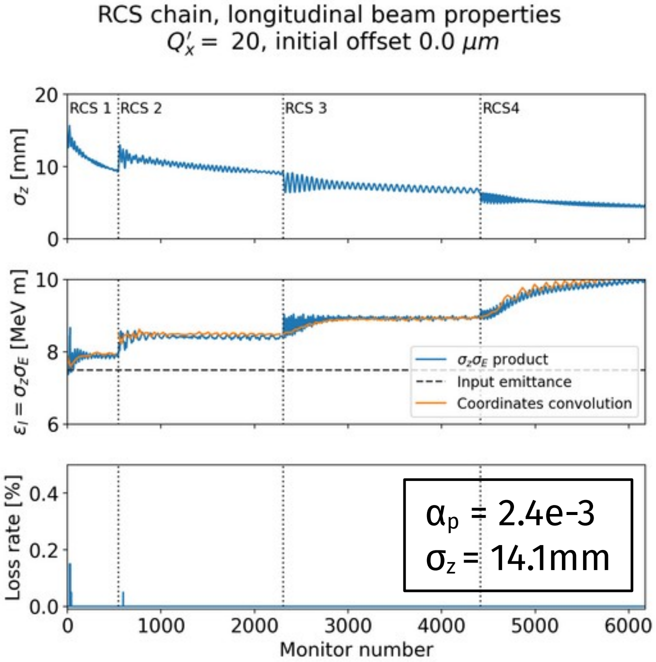


$\alpha_p = 2.4e{-5}$
$\sigma_z = 4.1\text{mm}$

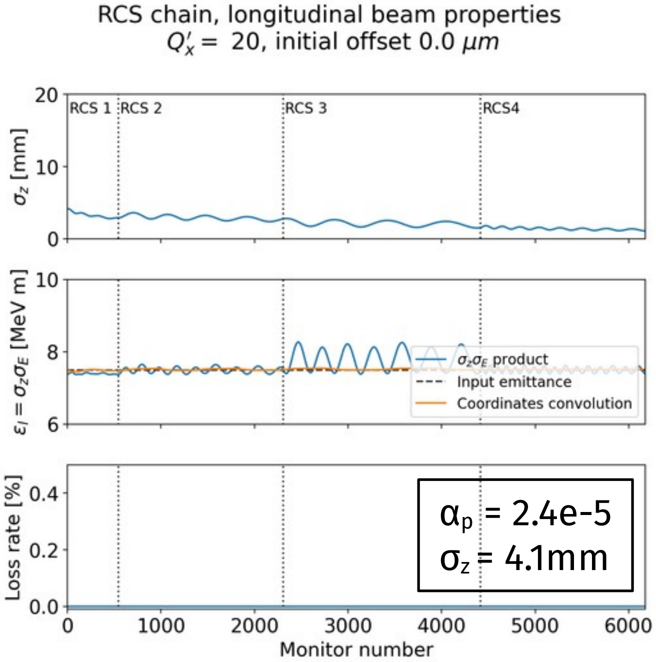
Reducing α_p has a visible impact on the longitudinal beam dynamics

- **Divide α_p by 10 for all RCS**, with Q'=+20, no initial transverse offset, and 20-turn damper

- Changing the momentum compaction factor **reduces the bunch length**
- Beam **losses and blow-up are also reduced**
- Reminder: these simulations don't include beam loading effects, longitudinal impedance…


RCS chain, longitudinal beam properties
$Q'_x =$ 20, initial offset 0.0 μm

α_p = 2.4e-3
σ_z = 14.1mm

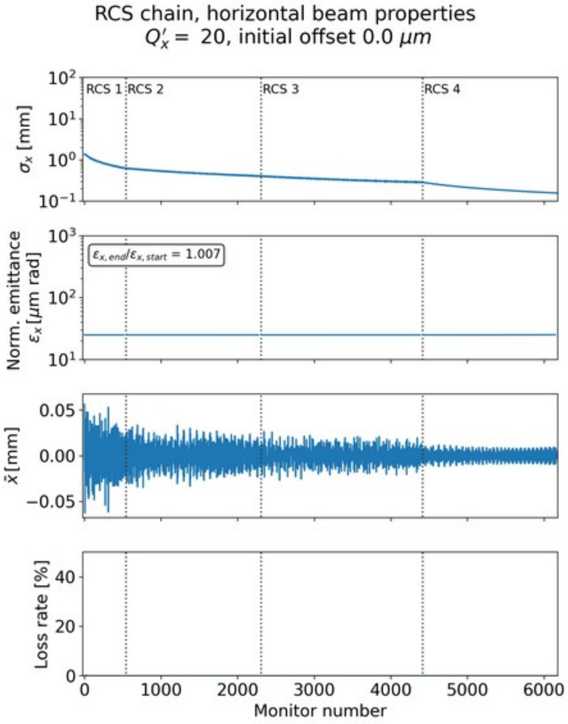

RCS chain, longitudinal beam properties
$Q'_x =$ 20, initial offset 0.0 μm

α_p = 2.4e-5
σ_z = 4.1mm

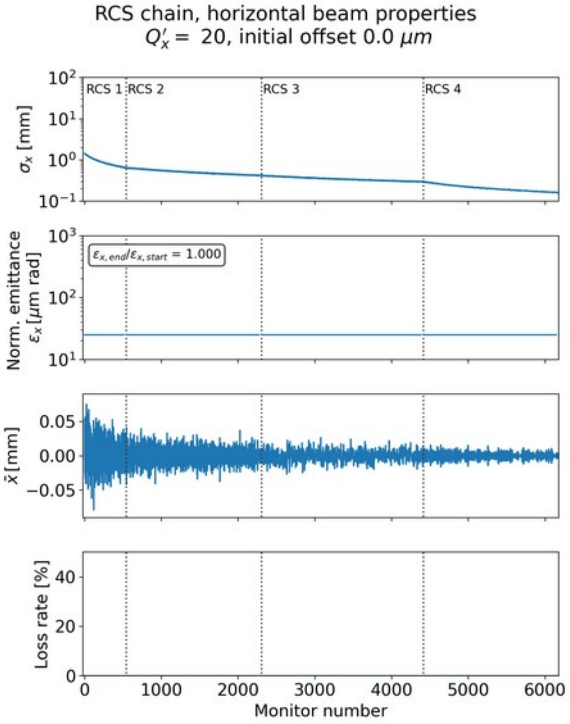
With Q’=20, reducing α_p doesn’t impact transverse beam stability

- **Divide α_p by 10 for all RCS**, with Q’=+20, no initial transverse offset, and 20-turn damper
- Changing the momentum compaction factor doesn’t affect the transverse stability in that case

Nominal α_p



Reduced α_p (factor 100)

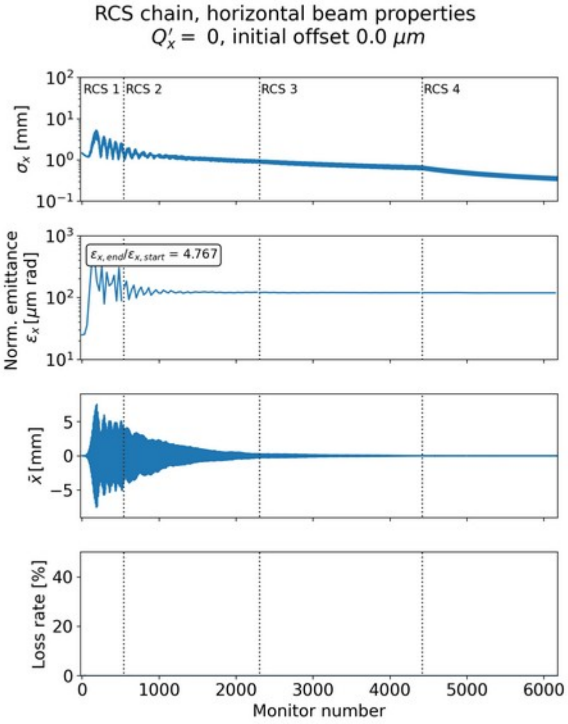


With Q’=0, reducing α_p affects the transverse beam dynamics

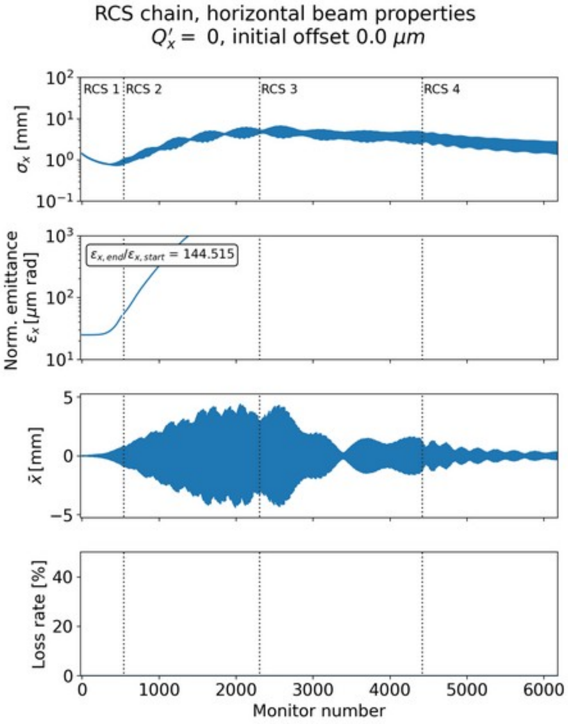
- Even with **nominal α_p the bunch is already unstable**

- Reducing the momentum compaction factor **reduces the synchrotron tune Q_s**
  - This makes the **beam even more unstable** in the transverse plane

Nominal α_p



Reduced α_p (factor 100)



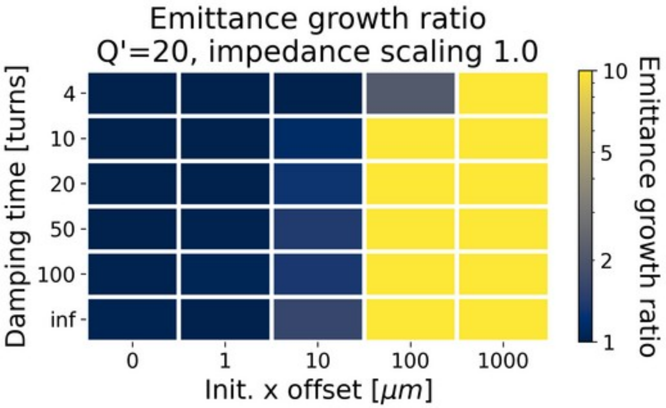
Overall impact on transverse beam stability

- Check the **effect of momentum compaction factor** on **transverse beam stability** through the RCS chain
- Use the **TESLA cavity transverse HOMs impedance model**
- Scan on damper gain and initial transverse offset of the bunch. Only chromaticity Q’=+20 will be shown

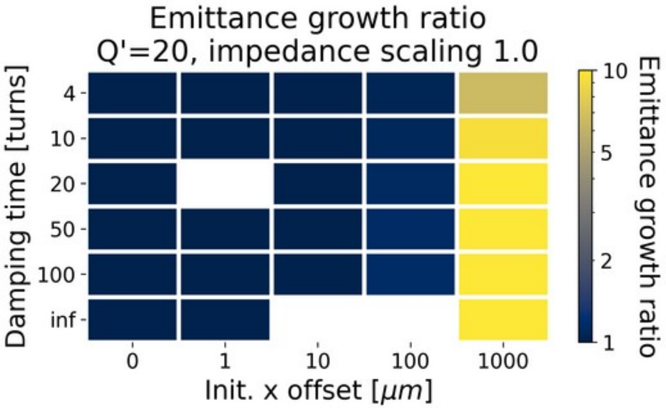
Dividing α_p by a factor 10 (with Q’=+20)

Chromaticity Q’=+20

Nominal α_p
(2.4e-3, 2.4e-3, 1.0e-3, 1.0e-3)



Reduced α_p
(2.4e-4, 2.4e-4, 1.0e-4, 1.0e-4)

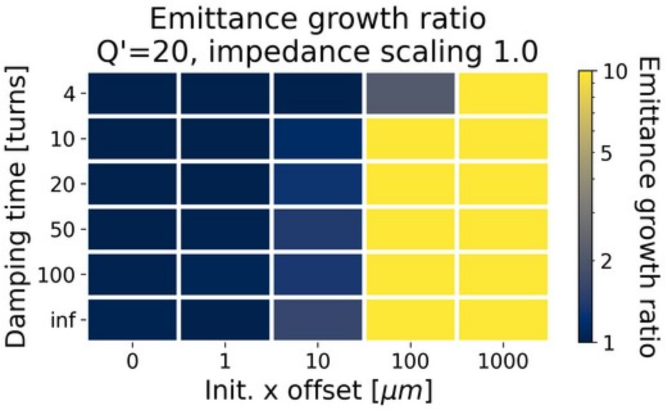


- Reducing the momentum compaction factor doesn’t degrade transverse beam stability
- Situation is even improved for the case with 100 μm offset
- Cases with 1 mm initial offset still have large emittance blow-up

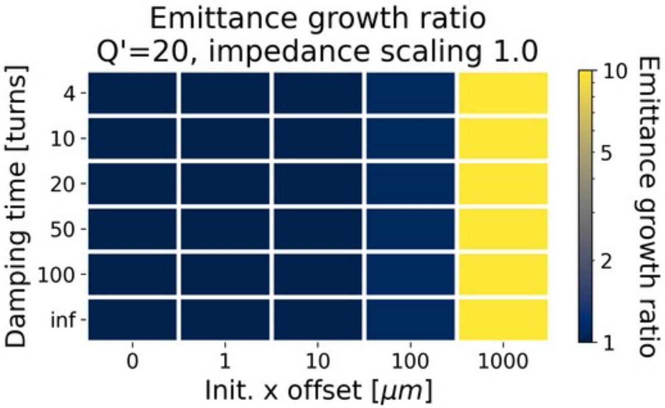
Dividing α_p by a factor 100 (with Q’=+20)

Chromaticity Q’=+20

Nominal α_p (2.4e-3, 2.4e-3, 1.0e-3, 1.0e-3)



Reduced α_p (2.4e-5, 2.4e-5, 1.0e-5, 1.0e-5)



- Same as the previous picture: no strong degradation of transverse coherent stability
- Reduction of α_p is even beneficial for the 100 μm case

Conclusion

- **Positive chromaticity** is still **needed** to stabilize the beam
- Reducing the α_p with Q'=+20 doesn't degrade transverse coherent stability
- The situation is quite different with Q'=0, since transverse instability threshold scales with Q_s, and therefore $\alpha_p^{1/2}$

Thank you !

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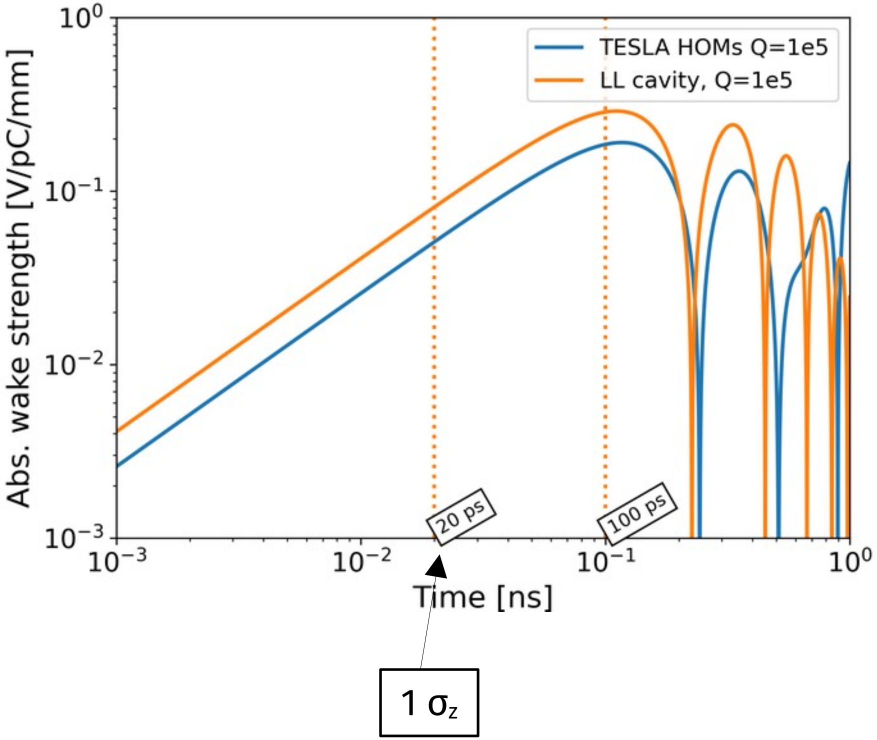
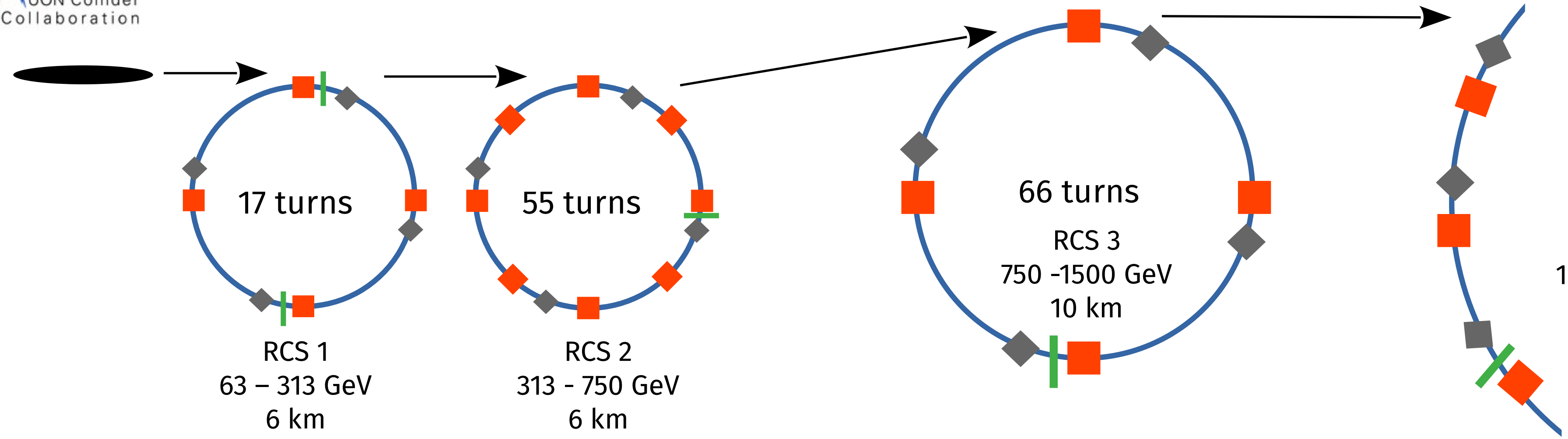
Classic TESLA cavities have lower HOMs compared to Low Loss cavity

- First cavity model that was used: **Low Loss SRF cavity**
  - HOM list from [J. Sekutowicz et al.]
  - Appear in orange on the plot
- Second cavity model used: "classic" **TESLA cavity**
  - HOM list reported in S.-A. Udongwo presentation
  - Appear in blue on the plot
- TESLA cavity has HOMs with lower R/Q, which has a visible impact on the short range wake (almost a factor 2 reduction)

Wake function for the two types of cavity studied



RCS chain parameters



- Main assumptions for the RCS are
  - 32 RF stations in each machine
  - One transverse damper unit, located at RF station 9 (~¼ of the ring)
- **Scan** several parameters
  - **Chromaticity** Q’ from Q’=-20 to Q’=+20
  - **Damper gain** from 4-turn to 100-turn + no damper
  - **Initial transverse offset** of the bunch (in each RCS), from 1 μm to 1 mm

Beam and machine parameters for the RCS

Beam parameters	Unit	Value
Bunch length 1σ	**mm**	**5.7**
Bunch intensity	**Particles per bunch**	**2.7e12**
ε_x / ε_y	**µm rad**	**25**
# of macropaticles		400k
# of turns wakefield		5
# of slices wakefield		2000

Machine parameters	Unit	RCS 1	RCS 2	RCS 3	RCS 4
Circumference	m	5990	5990	10700	35000
NC magnet length	m	3655	2539	4366	20376
Bunch intensity	10^{12}	2.7	2.7	2.7	2.7
Beam momentum	GeV/c	63	313.8	750	1500
Lorentz gamma (injection)		597	2971	7099	14198
Energy increase per turn	GeV	14.7	7.9	11.3	63.6
Rev. frequency	kHz	50	50	28	8.6
RF frequency	MHz	1300	1300	1300	1300
Harmonic number		25957	25957	46295	151433
RF voltage	GV	20.9	11.22	16.1	90.0
α_p		0.0024	0.0024	0.001	0.001
Avg. beta x/y	m	50 / 50	50 / 50	50 / 50	50 / 50
Chromaticity Q'_x/Q'_y		scan	scan	scan	scan
Detuning from octupoles x/y	m^{-1}	0 / 0	0 / 0	0 / 0	0 / 0

Parameters from F. Batsch RCS tables

List of HOMs, Low Loss cavity

HOM list from J. Sekutowicz et al. https://accelconf.web.cern.ch/p05/papers/tppt056.pdf and A. Grudiev presentation https://indico.cern.ch/event/1204745/

Mode name	f_{res} [GHz]	Q_{ext}	R/Q [kΩ/m]	Z [MΩ/m]
D:TE111-7	1.717	4.00E+04	0.695202139	27.8
D:TE111-8	1.738	6.00E+04	0.412081268	24.7
D:TM110-2	1.882	6.00E+03	0.431291291	2.6
D:TM110-4	1.912	9.00E+03	0.574356228	5.2
D:TM110-5	1.927	1.50E+04	1.932654732	29.0
D:TM110-6	1.94	2.00E+04	1.489001143	29.8
D:3rd-1	2.451	1.00E+05	3.077904652	307.8
D:3rd-2	2.457	5.00E+04	2.157045016	107.9
D:5th-7	3.057	3.00E+05	0.039046846	11.7
D:5th-8	3.06	8.00E+05	0.031206852	25.0

List of HOMs, TESLA cavity

HOM list from S.-A. Udongwo presentation
https://indico.cern.ch/event/1254437/contributions/5269860

Mode name	f_{res} [GHz]	Q_{ext}	R/Q [kΩ/m]	Z [MΩ/m]
1	1.659	3.14E+05	0.10384331	32.61
2	1.705	1.35E+04	1.0487417	14.16
3	1.706	1.34E+04	1.2142325	16.27
4	1.728	4.13E+02	0.96927264	0.40
5	1.729	3.81E+02	0.45211054	0.17
6	1.736	5.16E+02	1.2457026	0.64
7	1.737	5.74E+02	0.94678177	0.54
8	1.761	5.83E+03	0.34981612	2.04
9	1.762	6.21E+03	0.277156	1.72
10	1.788	8.67E+03	0.16479288	1.43
11	1.789	8.90E+03	0.18055962	1.61
12	1.798	1.23E+04	0.10527813	1.29
13	1.799	1.21E+04	0.10471937	1.27
14	1.865	3.91E+04	0.78949722	30.87
15	1.865	4.12E+04	0.82682261	34.07
16	1.874	3.88E+04	1.0908346	42.32
17	1.874	4.39E+04	1.0738693	47.14
18	1.880	4.23E+04	0.22164077	9.38
19	1.880	5.15E+04	0.23706297	12.21
20	2.561	6.20E+02	0.13473436	0.08
21	2.561	5.27E+02	0.12484995	0.07
22	2.577	3.64E+03	2.0500399	7.46
23	2.577	4.35E+03	2.0598681	8.96