# SRF system for the muon collider acceleration chain

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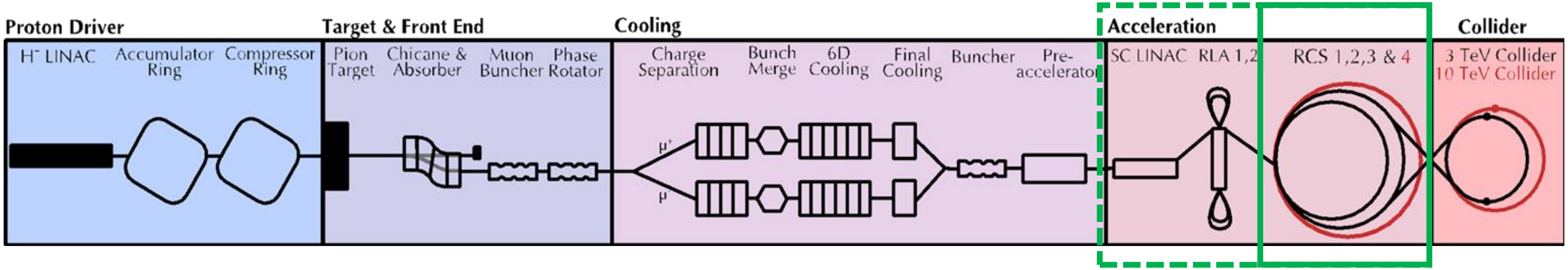
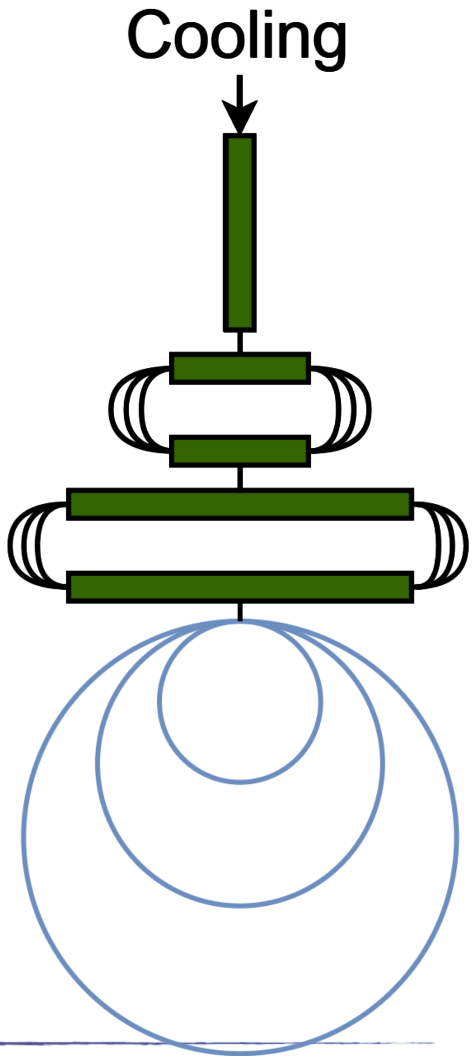


# Introduction

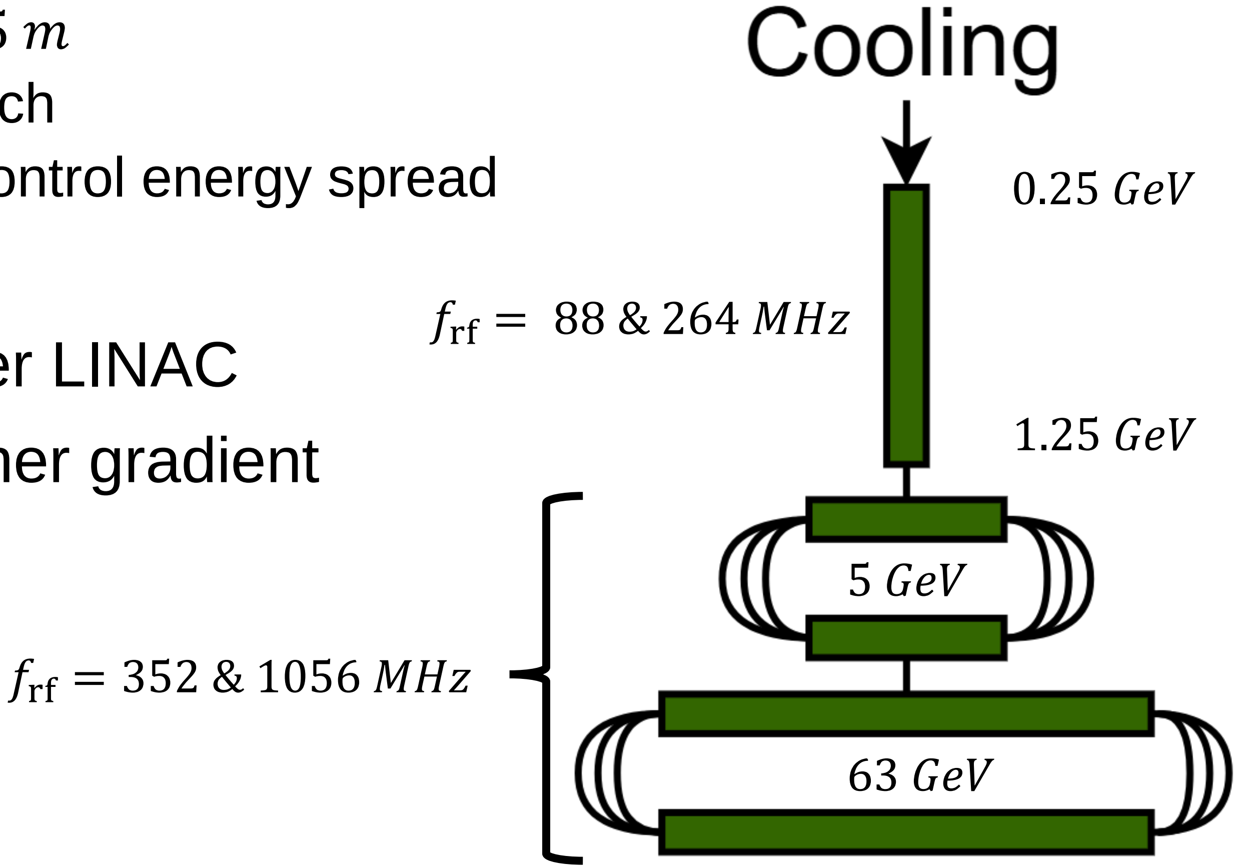
- Main Goal: Ensure high muon survival rate
  - Fast acceleration is key
  - Maximise average gradient
  - Most critical at lower energies → LINAC
- Increased RF efficiency with circular machines
  - Recirculating LINAC (RLA)
  - Rapid Cycling Synchrotron (RCS)
- Emittance preservation → luminosity
- Two high-intensity bunches (one $\mu^+$ and one $\mu^-$)
- Repetition rate of $5\ Hz$ combined with a few ms of acceleration

➢ Pulsed RF system



# Introduction
# Low-energy and Medium-energy

- Large energy spread & long bunch from cooling channel
  - $\approx 5\ \%$ energy spread with $\sigma_z \approx 0.5\ m$
  - Low RF frequency, $f_{\mathrm{rf}}$ → long bunch
  - 3rd harmonic system required to control energy spread
- Bunches are counter-rotating after LINAC
- RLAs: frequency increase → higher gradient
- More details in talk by [A. Aksoy]()



Cooling

$0.25\ GeV$

$f_{\mathrm{rf}} = 88\ \&\ 264\ MHz$

$1.25\ GeV$

$5\ GeV$

$f_{\mathrm{rf}} = 352\ \&\ 1056\ MHz$

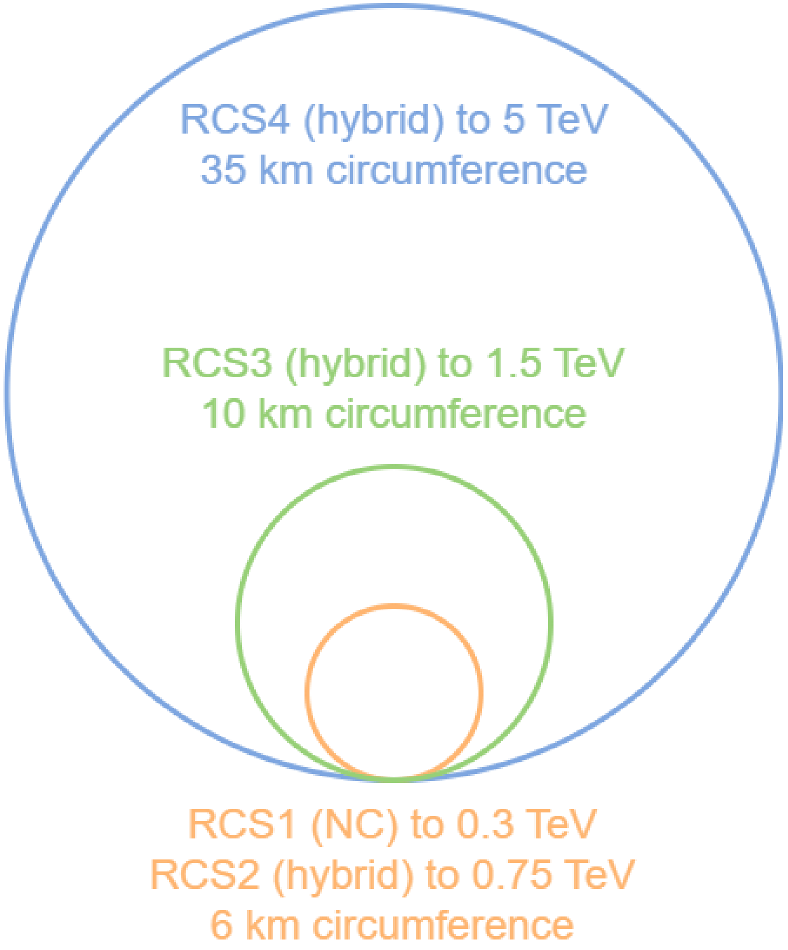
$63\ GeV$

# Introduction
# High-energy

- Chain of four RCS
- Shared RF system for both bunches

- Fast acceleration
  - ➢ Large voltage per turn: tens of gigavolt
  - ➢ Low number of turns
  - ➢ High-gradient RF structures necessary
  - ➢ Hundreds of cavities in each RCS

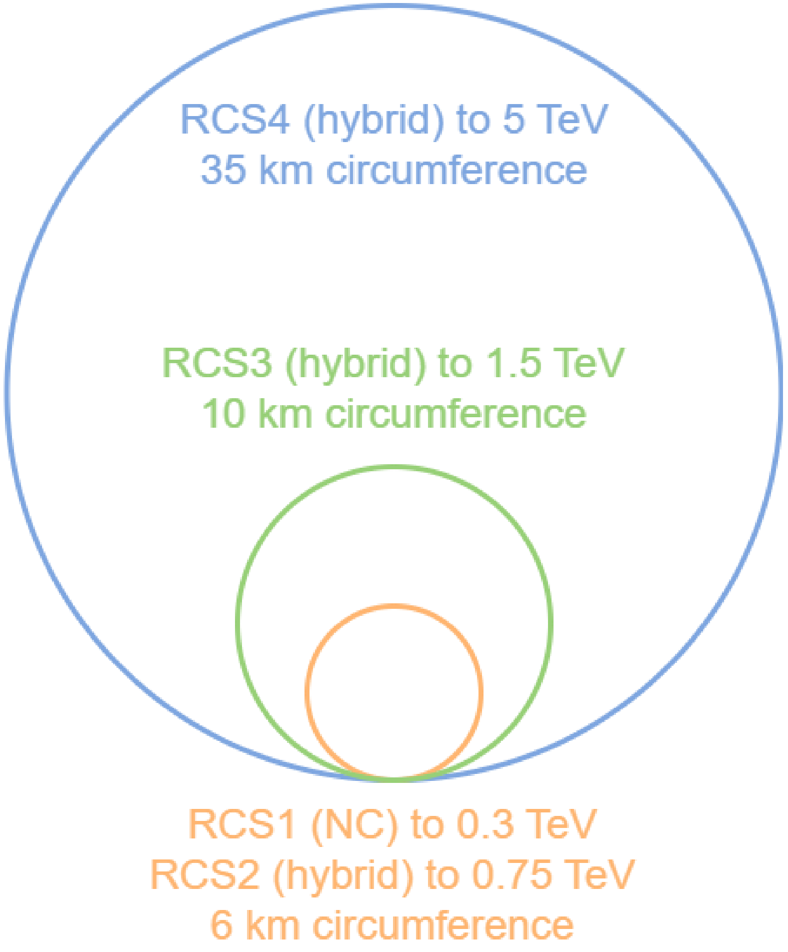
- Hybrid RCS
  - Combination of NC and SC magnets
  - NC → high ramp rate
  - SC → high average field (circumference reduction)



# Introduction
# High-energy

- Very different beam parameters in RCSs

| | **RCS1** | **RCS2** | **RCS3** | **RCS4** |
|---|---|---|---|---|
| Beam current [mA] | 43 | 39 | 20 | 5 |
| Acceleration time [ms] | 0.34 | 1.1 | 2.4 | 6.4 |
| Energy gain per turn [GeV] | 15 | 8 | 11 | 64 |
| Bunch length [mm] | 9 … 6 | 9 … 7 | 7 … 6 | 4 … 3 |



- Shorter bunches

➢Higher RF frequency usable

➢Assuming $1.3\ GHz$ TESLA as baseline

- Large frequency difference to RLA2
    - Matching at RCS1 injection challenging → E. Lamb

# Distribution of RF system

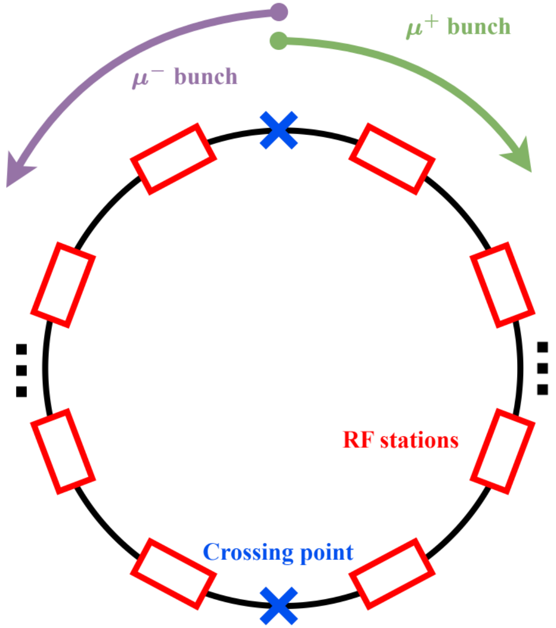
- Conventional acceleration in RCS unstable in long. plane
  - High synchrotron tune $Q_s = \frac{\omega_s}{\omega_{\mathrm{rev}}} = \sqrt{-\frac{h\eta e V_{\mathrm{rf}}\cos\phi_s}{2\pi E\beta^2}} \propto \frac{1}{n_{\mathrm{rf}}}$
  - For stability: $Q_s \ll 1/\pi$
  - In RCS1: $Q_s \approx 0.6$
- Separate RF system into multiple stations
  - ➢ Multiple, but smaller kicks and shorter drifts
  - ➢ Smoothens the synchrotron motion

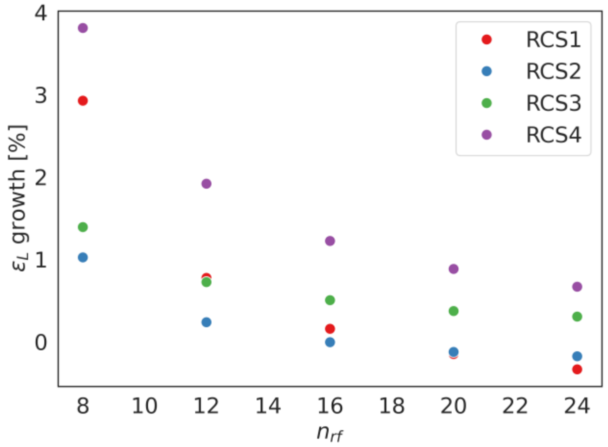
➢ Number of RF stations from beam dynamics simulation

- From RF & cost perspective:

➢ As few stations as possible (limit hardware distribution)

For details see presentation by [E. Lamb]()





# RF system powering

- Voltage only needs to be provided during short pulse
- Very different regimes throughout the chain
- First RCS:
  - High peak power
  - Low pulse duration
- Last RCS
  - Moderate peak power
  - Long pulses

| | MuCol RCS | ILC |
|---|---|---|
| Beam current [mA] | 43 … 5.5 | 5.8 |
| Pulse duration [ms] | 0.5 … 7 | 1.7 |
| Peak power per cavity [kW] | 1400 … 230 | 190 |
| CW power per cavity [kW] | 3.3 … 8.2 | 1.6 |

- Power coupler design
  - 1.4 MW peak power in TESLA-sized coupler → breakdown
  - High CW power in RCS4 → heat deposition

# Challenges of short bunches

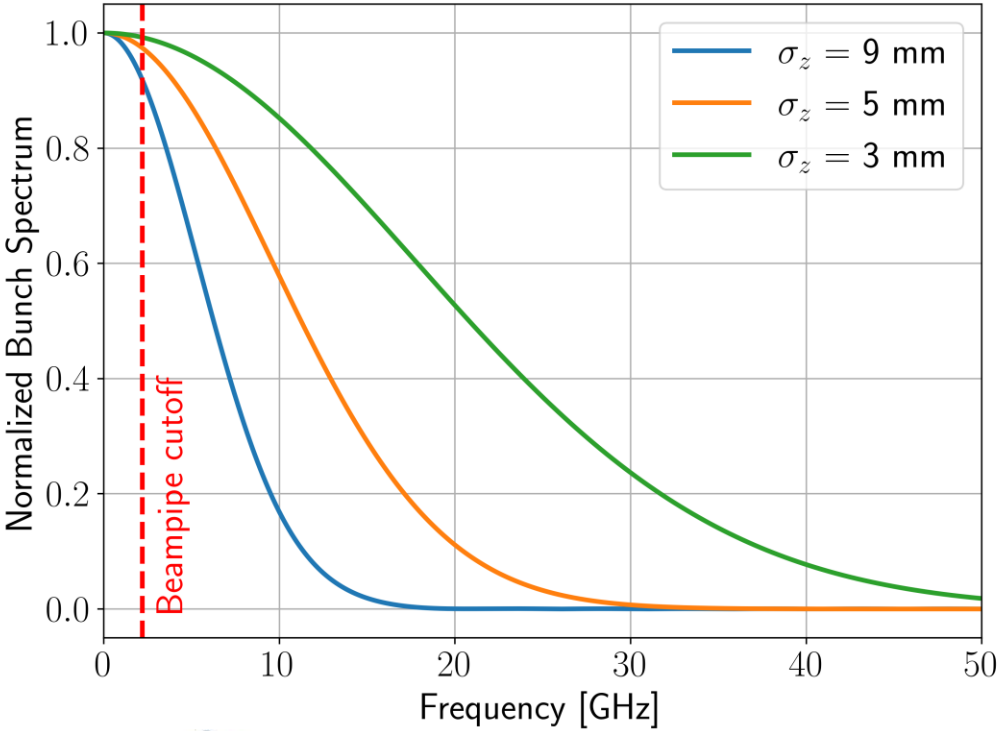
- Short bunch length ($\sigma_z = 9\,mm$ to $2.7\,mm$)

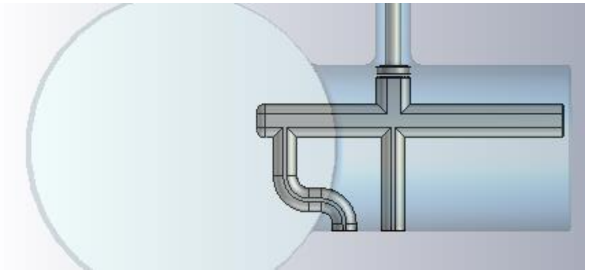
➢ High-frequency bunch spectrum

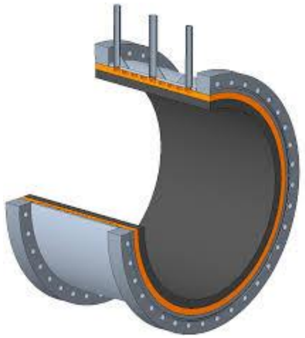
- Significant power above beampipe $f_c$ at $2.25\,GHz$
  - Beampipe absorbers between cavities
- High HOM power
  - In the order of tens of kW

  ➢ TESLA HOM coupler design was created for $\approx\ 5\,W$

  ➢ Design challenging within baseline cryomodule



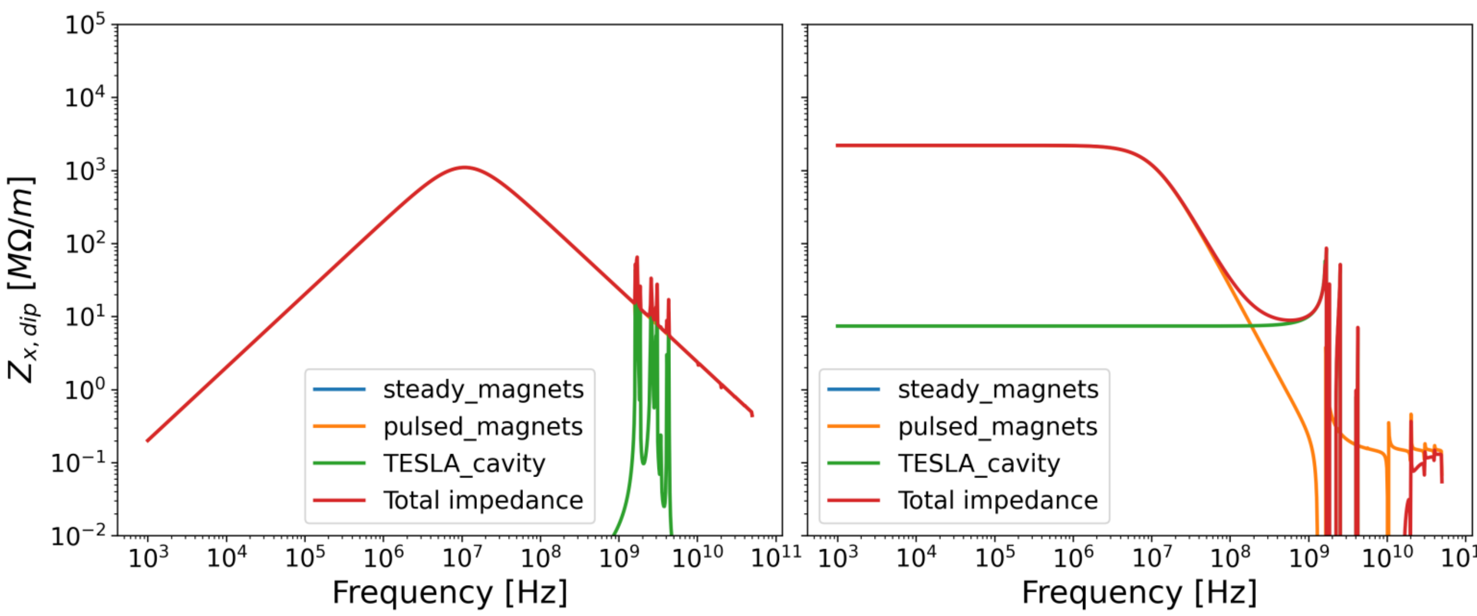




From [1]

# Higher order modes

- Small aperture of TESLA cavity combined with high bunch charge
  - ➢ Significant amount of induced voltage
  - Potential to cause beam instability or emittance growth
- Total cavity impedance is highest in RCS1 and 4
- Single turn instabilities
  - Beam break-up
  - Cavity design/frequency choice
- HOM damping requirement
  - Multiturn instabilities
  - HOM coupler / beam pipe absorber requirements


RCS1 dipolar impedance for the beam pipe and TESLA cavities

Talk by D. Amorim

# Orbit length change in hybrid RCS

- Each fixed-field superconducting magnet acts as spectrometer

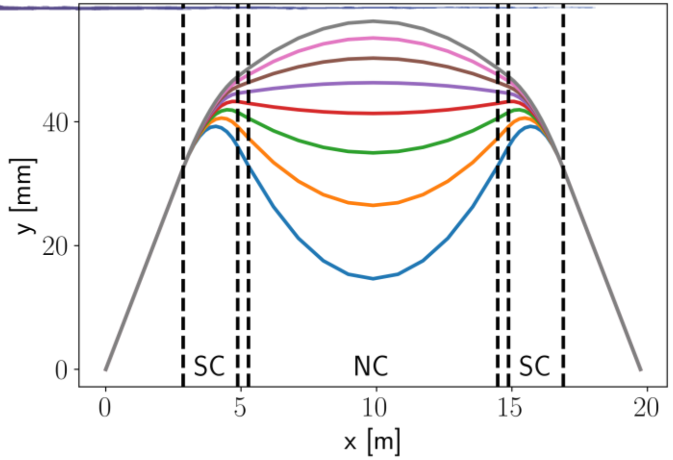
➢Path length change during acceleration

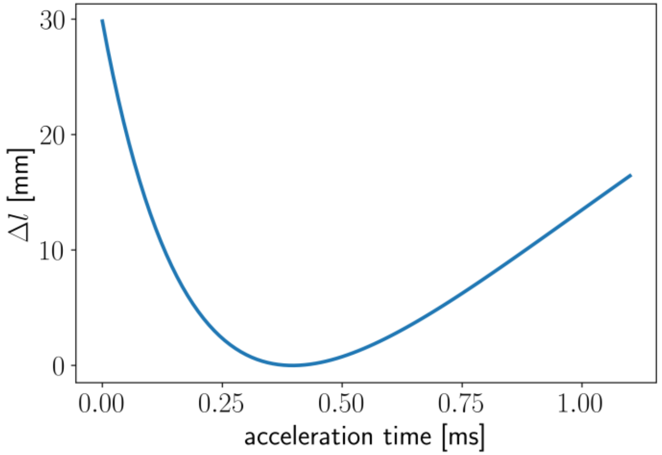
➢$f_{\mathrm{rf}}$ needs to be an integer harmonic of $f_{\mathrm{rev}}$ → cavity tuner

- Both magnitude and speed are high:
  - $\Delta f \approx 6.5\ \ldots 0.9\ kHz,\ \Delta\dot{f} \approx 20\ MHz/s$

Additional tuning requirements:

1. Lorentz force (LF) detuning
2. Change in $t_{\mathrm{rev}}$ (RCS1)
3. Static detuning for beam loading compensation





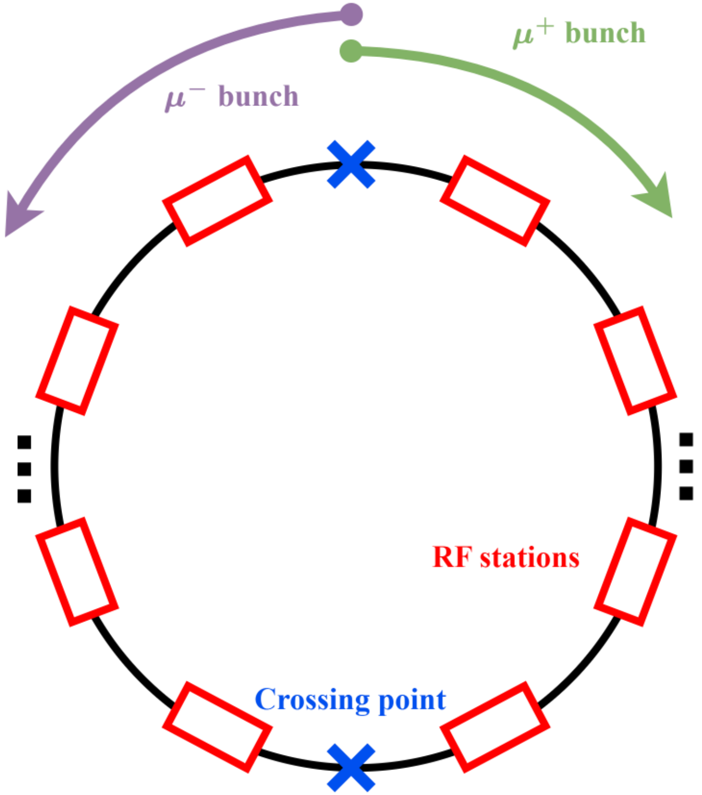
Plots from L. Soubirou

# Transient beam loading Introduction

- High bunch charge and unevenly filled ring
  - ➢Klystron compensates for average beam loading
  - ➢RF voltage changes within one turn and during acceleration

- Alteration of synchronous phase, $\phi_s$
  - ➢Affects dynamics of bunch and counterrotating bunch

- Different for each RF station
  - ➢Decay of induced voltage dependent on time



# Transient beam loading Simulation

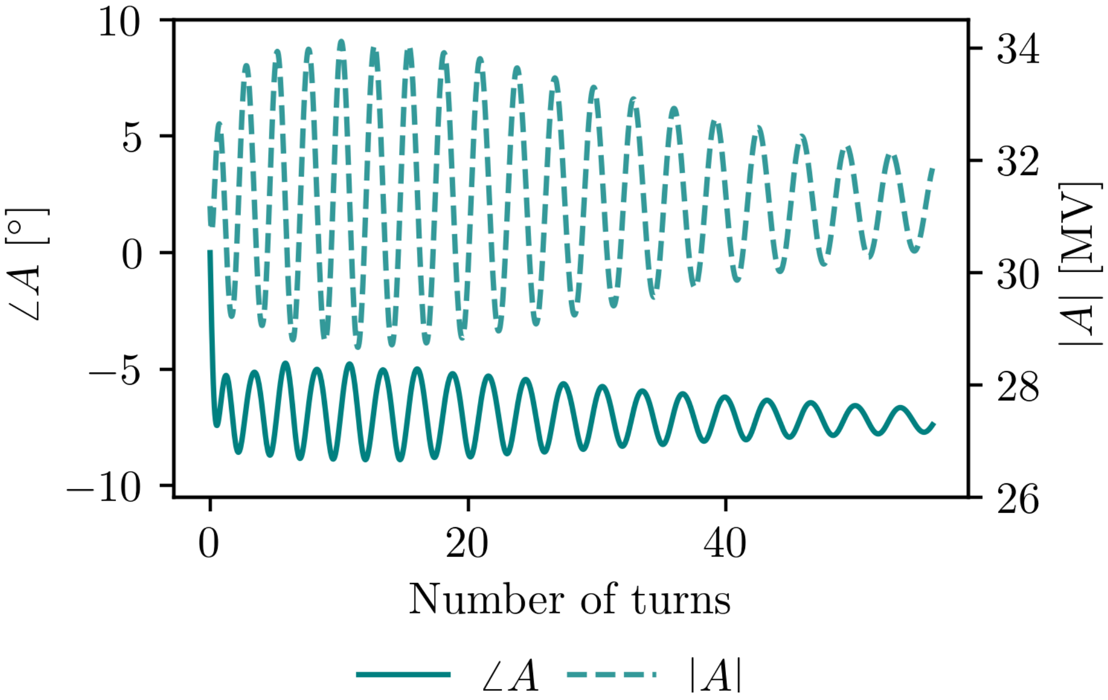
- Simulations of long. beam dynamics performed in BLonD [2]
- Module implemented to analyse beam-cavity interaction
  - Differential equation from equivalent circuit model [3]
  - Simplification: counter-rotating beam is modelled in same direction at fixed distance
  - Opposite charge and direction
  - ➢ Worst case-scenario

- Detuning, $\Delta\omega$ and loaded quality factor, $Q_L$, can be freely chosen

➢ $Q_L$ is chosen to minimise the required generator power at given $\Delta\omega$

# Transient beam loading

- Voltage transient at injection
  - Build-up of induced voltage

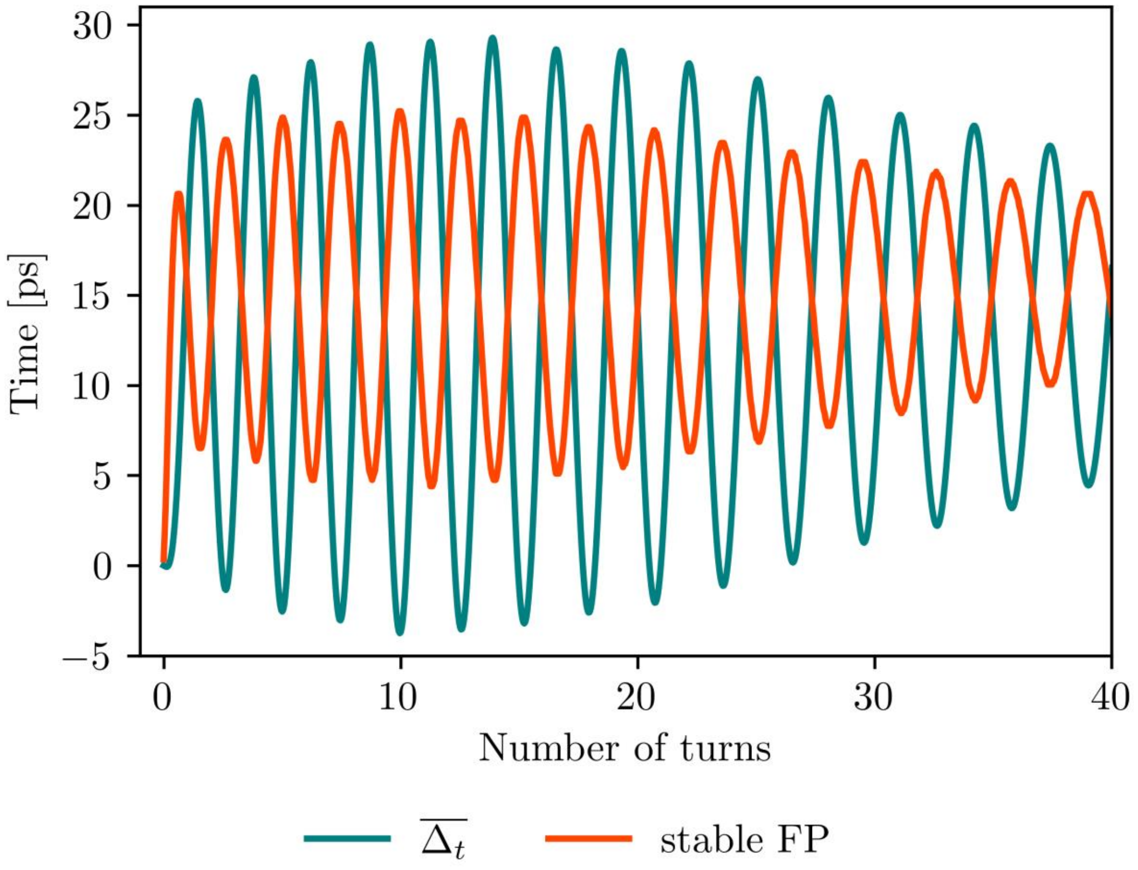


# Transient beam loading

- Voltage transient at injection
  - Build-up of induced voltage
  - Change of stable fixed-point (FP)
- Synchrotron motion causes bunch to converge towards stable FP

➢Too slow for bunch to follow initially

➢Bunch centroid oscillation around stable FP



# Transient beam loading

- Oscillation can have negative effect on emittance
- Depends on
  - Number of RF stations → effective $Q_s$
  - Cavity detuning $\Delta\omega$

- Requirement for number of stations increased compared to induced voltage only BLonD simulation

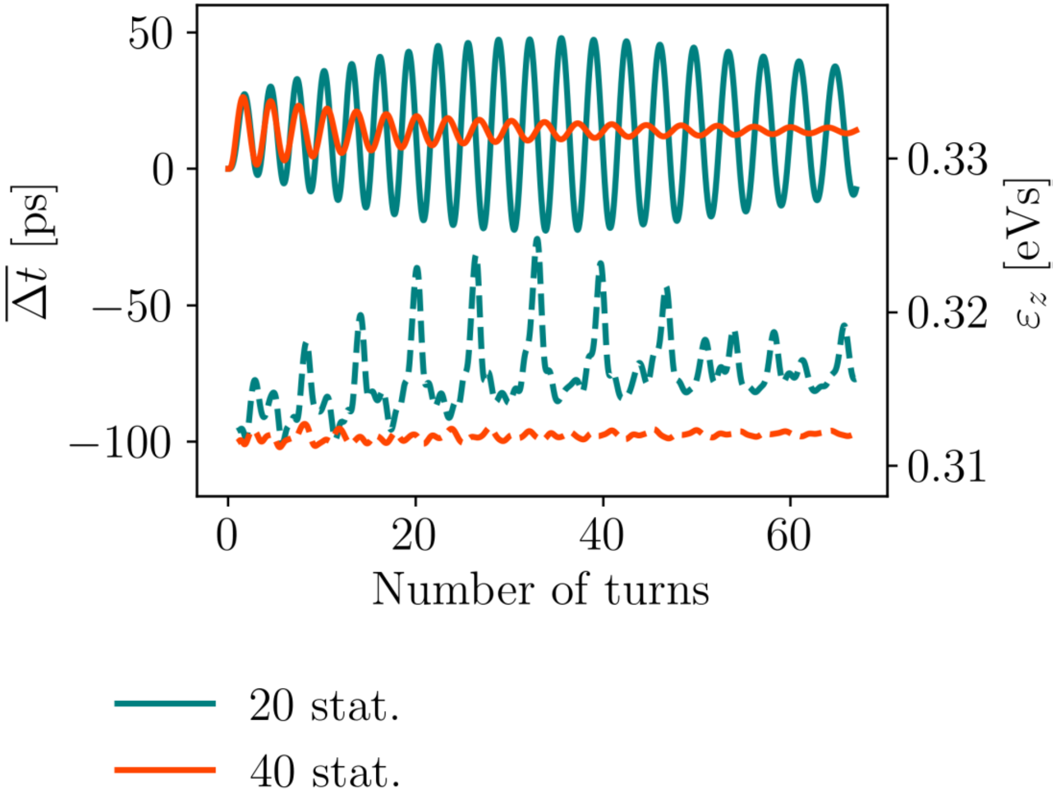
➢ ESPPU assumption: eight stations

➢ E. Lamb’s presentation: 16 stations

➢ With transient beam loading: 22 … 40

- Requires acceleration with $\Delta\omega_m = \Delta\omega_{\mathrm{opt}}/\sin\phi_s^2$

➢ Larger power consumption and reflected power



# Conclusion

- RF system is separated into multiple stations
  - Reduction of effective synchrotron tune
  - Challenging for installation → distribution of hardware
- RF parameters and requirements differ significantly in the RCS
  - First RCS: high current, large peak power requirement, lower CW power
  - Last RCS: lower current, lower peak power, larger CW power
- Beam stability under investigation with TESLA cavity HOMs (long. & transv.)
- Huge amount of HOM power above beam pipe cutoff frequency
- Challenging tuning required for different reasons:
  - Orbit length change in hybrid RCS, change of $f_{\mathrm{rev}}$ in RCS1, LF detuning, static detuning
  - Very different speeds and ranges required
- Strong transient beam loading: major challenge
- Next: Investigate damping of injection transient and different counter-rotation model

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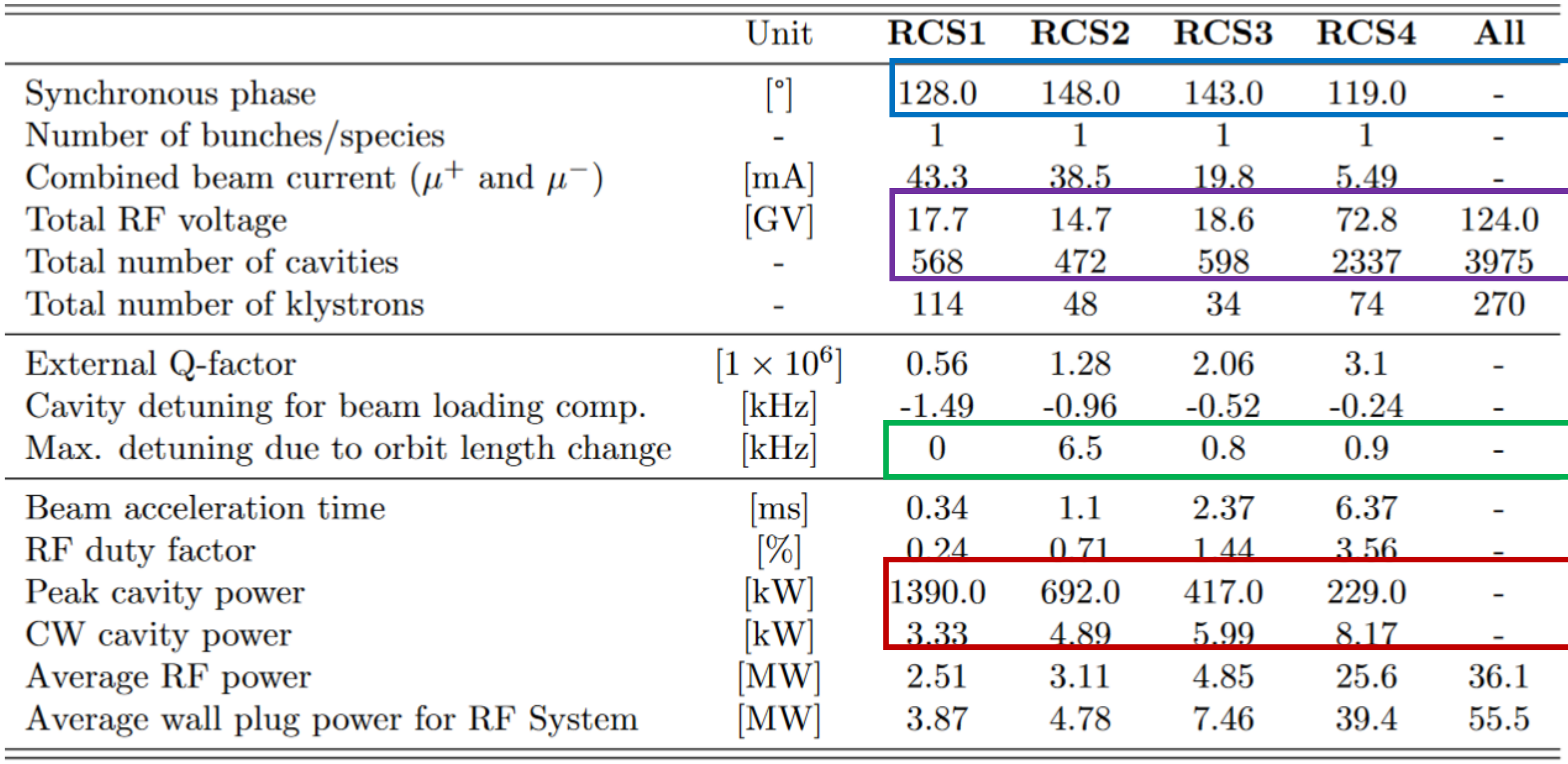
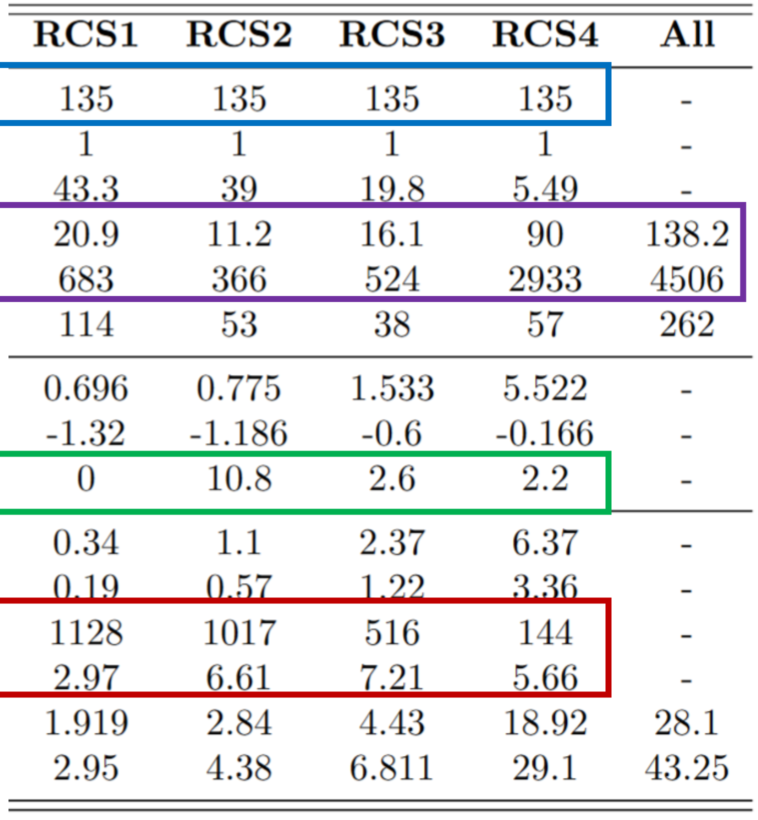
# Parameter overview

## Parameter set with new synchronous phases and optics



| | Unit | RCS1 | RCS2 | RCS3 | RCS4 | All |
|---|---|---|---|---|---|---|
| Synchronous phase | [°] | 128.0 | 148.0 | 143.0 | 119.0 | - |
| Number of bunches/species | - | 1 | 1 | 1 | 1 | - |
| Combined beam current ($\mu^+$ and $\mu^-$) | [mA] | 43.3 | 38.5 | 19.8 | 5.49 | - |
| Total RF voltage | [GV] | 17.7 | 14.7 | 18.6 | 72.8 | 124.0 |
| Total number of cavities | - | 568 | 472 | 598 | 2337 | 3975 |
| Total number of klystrons | - | 114 | 48 | 34 | 74 | 270 |
| External Q-factor | [$1 \times 10^6$] | 0.56 | 1.28 | 2.06 | 3.1 | - |
| Cavity detuning for beam loading comp. | [kHz] | -1.49 | -0.96 | -0.52 | -0.24 | - |
| Max. detuning due to orbit length change | [kHz] | 0 | 6.5 | 0.8 | 0.9 | - |
| Beam acceleration time | [ms] | 0.34 | 1.1 | 2.37 | 6.37 | - |
| RF duty factor | [%] | 0.24 | 0.71 | 1.44 | 3.56 | - |
| Peak cavity power | [kW] | 1390.0 | 692.0 | 417.0 | 229.0 | - |
| CW cavity power | [kW] | 3.33 | 4.89 | 5.99 | 8.17 | - |
| Average RF power | [MW] | 2.51 | 3.11 | 4.85 | 25.6 | 36.1 |
| Average wall plug power for RF System | [MW] | 3.87 | 4.78 | 7.46 | 39.4 | 55.5 |

## ESPPU parameter set



| RCS1 | RCS2 | RCS3 | RCS4 | All |
|---|---|---|---|---|
| 135 | 135 | 135 | 135 | - |
| 1 | 1 | 1 | 1 | - |
| 43.3 | 39 | 19.8 | 5.49 | - |
| 20.9 | 11.2 | 16.1 | 90 | 138.2 |
| 683 | 366 | 524 | 2933 | 4506 |
| 114 | 53 | 38 | 57 | 262 |
| 0.696 | 0.775 | 1.533 | 5.522 | - |
| -1.32 | -1.186 | -0.6 | -0.166 | - |
| 0 | 10.8 | 2.6 | 2.2 | - |
| 0.34 | 1.1 | 2.37 | 6.37 | - |
| 0.19 | 0.57 | 1.22 | 3.36 | - |
| 1128 | 1017 | 516 | 144 | - |
| 2.97 | 6.61 | 7.21 | 5.66 | - |
| 1.919 | 2.84 | 4.43 | 18.92 | 28.1 |
| 2.95 | 4.38 | 6.811 | 29.1 | 43.25 |

# Formula collection

- $P_{HOM} = k_{ll,HOM} e N_b I_{b,\,dc}$

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

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

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

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

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

https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.22.081002 ; electron machine convention of $\phi_s$

# Optimum cavity parameters

- From [2]

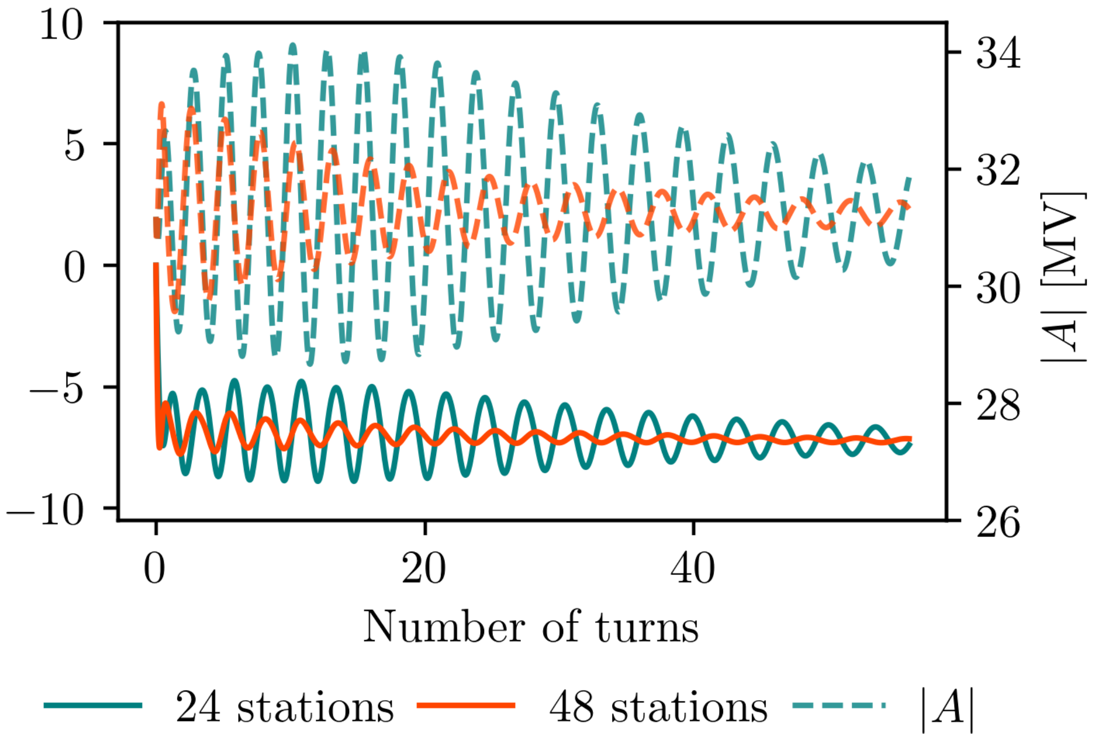
$$I_g = \left[\frac{V}{2(R/Q)Q_L} + I_{b,DC}F_b\cos(\phi_s)\right] + i\left[-I_{b,DC}F_b\sin(\phi_s) - \frac{V\Delta\omega}{\omega(R/Q)}\right]$$

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

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

$$Q_{L,opt} = \frac{V_{cav}}{2(R/Q)|F_b|I_{b,DC}\cos(\Phi_s)} \quad (13)$$

# Cavity voltage for different Number of RF stations



# References

- [1]: https://indico.cern.ch/event/817780/contributions/3715796/attachments/1979806/3296363/RD_Toward_High_Power_Warm_SiC_Beam_Line_HOM_Absorbers.pdf
- [2]: https://cds.cern.ch/record/1323893/files/CERN-ATS-Note-2011-002%20TECH.pdf
- [3]: https://blond.web.cern.ch/

# TESLA cavity

- High gradient → $30\ MV/m$
  - Ensure compactness of system
  - 39 mm aperture
- High R/Q
- $1.3\ GHz$ 9-cell structure
- Wide-spread and industrialized technology (XFEL, ILC)