

C³ main linac beam dynamics

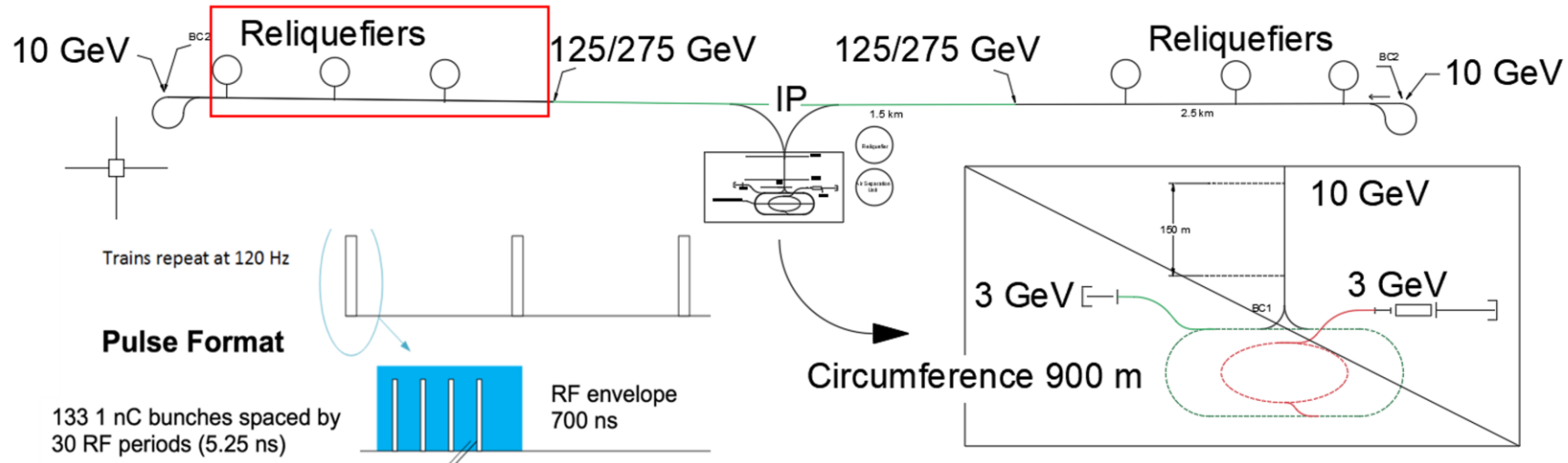
250 GeV beam dynamics

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The Cool Copper Collider (C³)



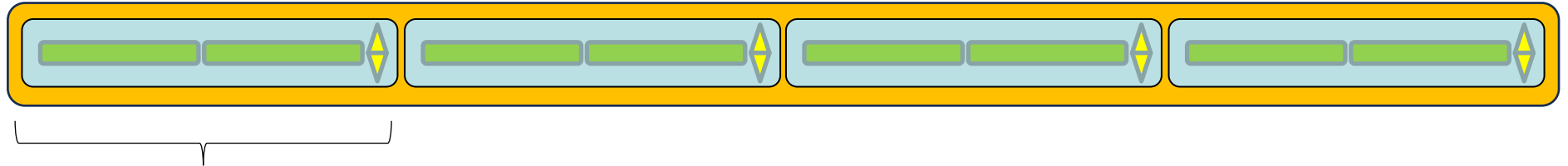
Parameter	Value
Cryocooled temperature	77 K
Length	8 km
Center of mass energy	250 GeV
Number of bunches	133
Charge per bunch	1 nC
Bunch spacing	5.25 ns (30 RF cycles)
Field gradient	70 MV/m

C³ main linac

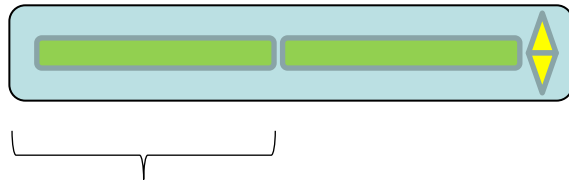
2.3 km main linac
253 cryomodules



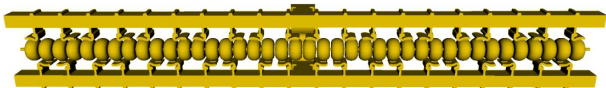
9.2 m
Cryomodule



2.3 m raft



1 m 40 cells RF structure



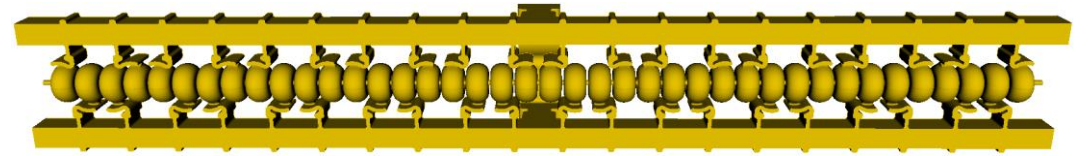
- Total length: 2.3-kilometer
- C³ main linac consists of
 - 253 cryomodules
 - 4 rafts in each cryomodule, 2.3-meter each
 - 2 RF structures in each raft, 1-meter each
 - 1 quad in each raft, 0.15-meter each

C³ main linac

Parameter	Initial value	Target value
Beam energy	10 GeV	125 GeV
Emittance x, y	775, 10 nm	900, 20 nm
Energy spread	1.5%	0.36%
Bunch length	100 μm	100 μm
Charge, # of bunches	1 nC, 133	1 nC, 133
Bunch spacing	5.25 ns (30 RF cycles)	N/A
Field gradient	70 MV/m	N/A
RF frequency	5.712 GHz, C-band	N/A
Quad length	15 cm	N/A

C³ accelerating structure

- Based on distributed coupling structure
- Aperture radius = 3.55mm
- The current design has 40 cells in a 1 meter structure
- Accelerating gradient of 70 MV/m
- Please check Zenghai Li's talk for details on designing the accelerating structure

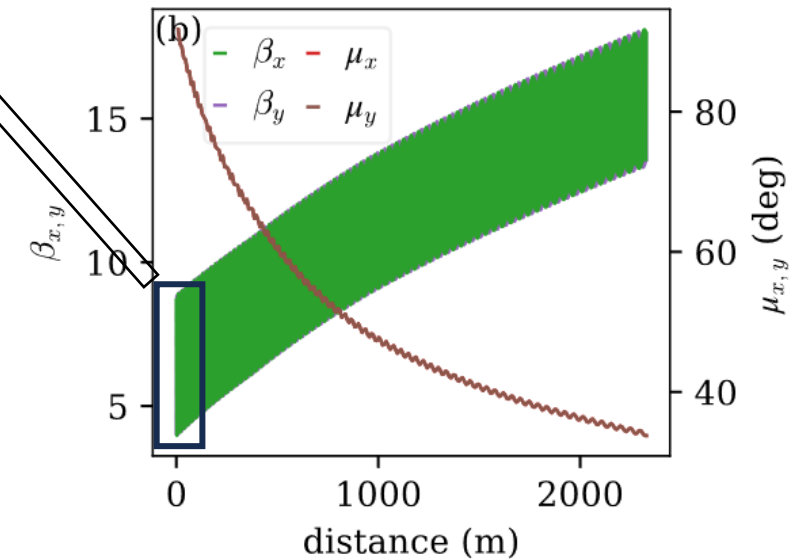
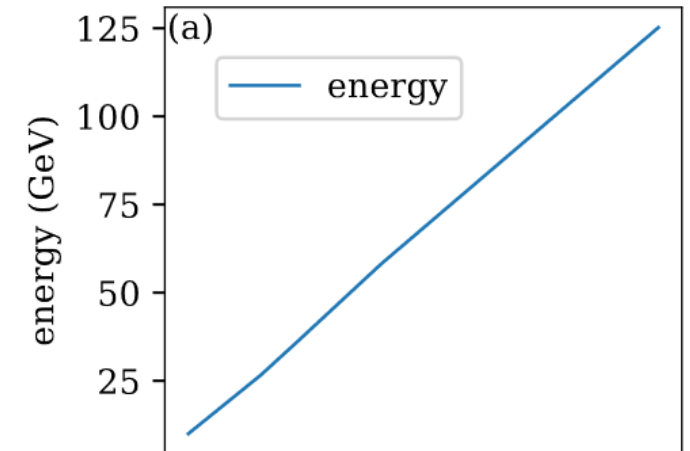
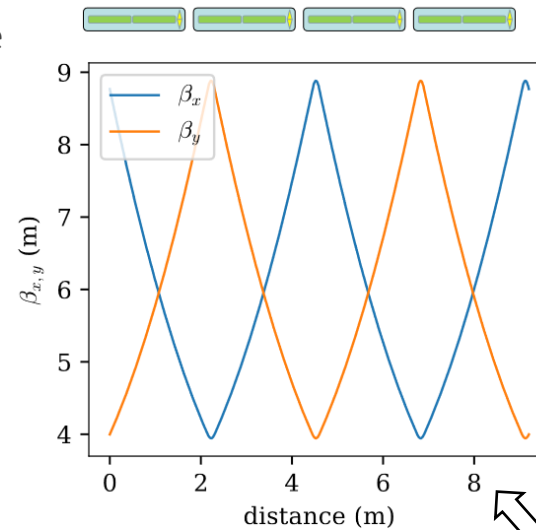


C³ main linac beam optics

- FODO lattice with logarithmic phase advance
- Keep L_n (length of quads) the same

$$\tan \frac{\mu_n}{2} = \tan \frac{\mu_1}{2} \left(\frac{\gamma_1}{\gamma_n} \right)^{0.5}$$

$$K_{1,n} L_n = K_{1,1} L_1 \left(\frac{\sin \mu_n / 2}{\sin \mu_1 / 2} \right)$$

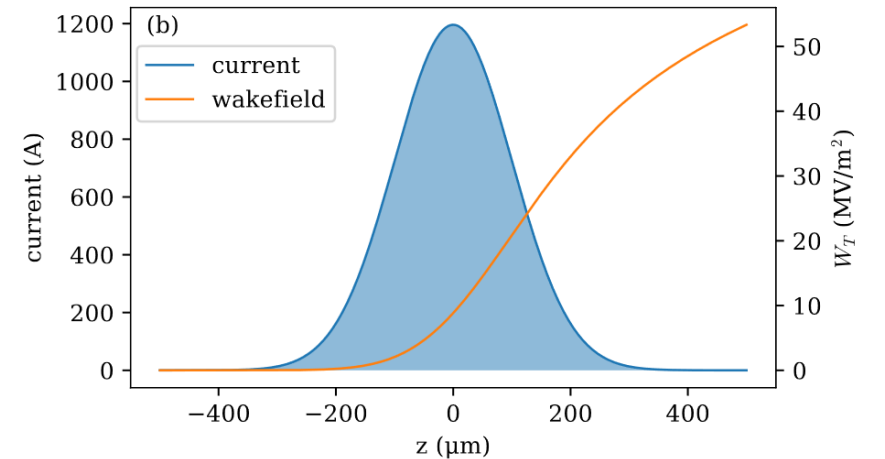
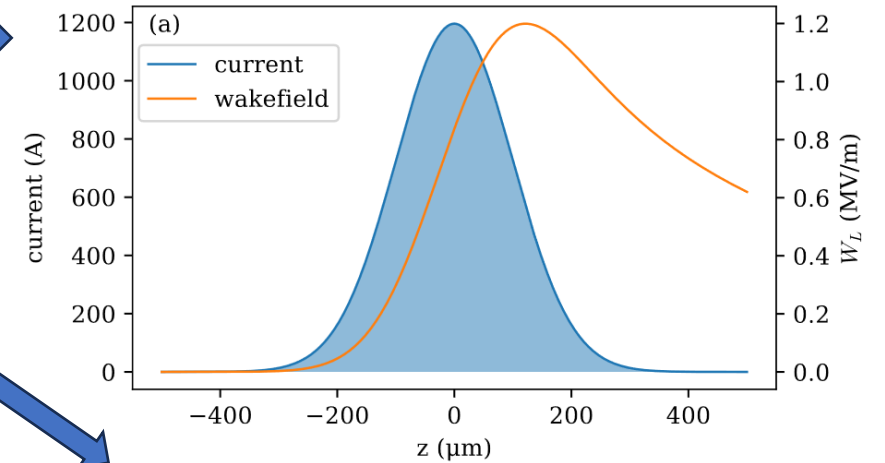
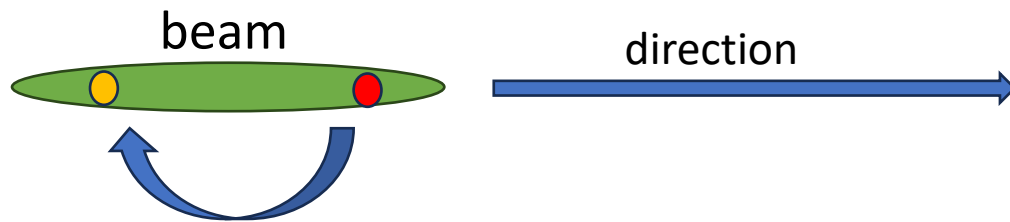


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Single-bunch beam dynamics

Short-range wakefields

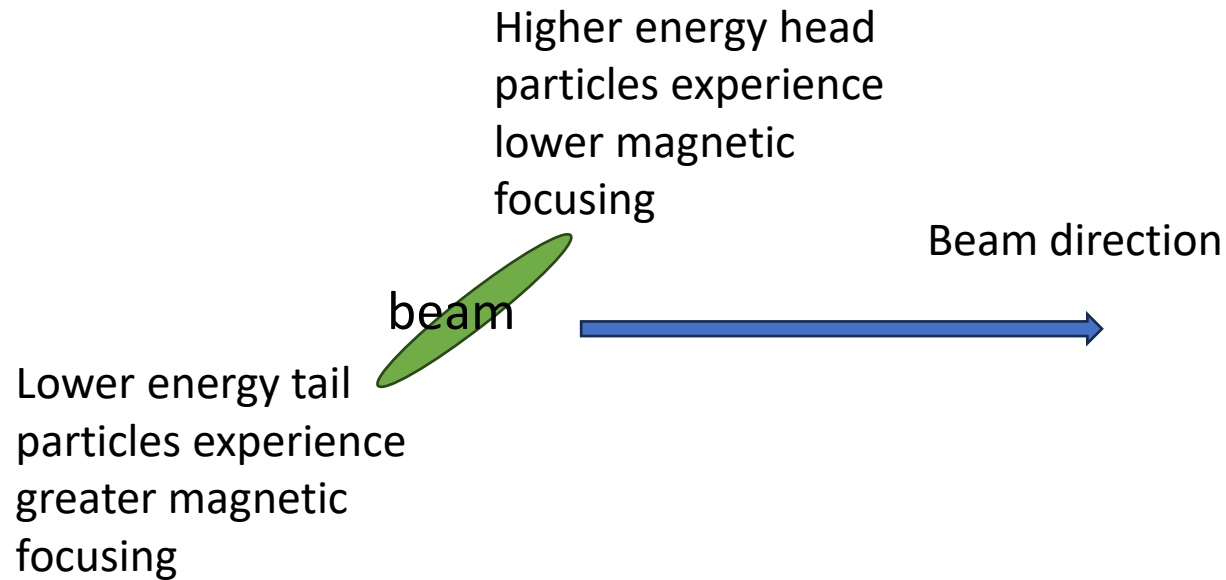
- Wakefields from head particles affect tail particles
- Longitudinal wakefield increases energy spread within the bunch
- Transverse wakefield kicks the beam away from the design trajectory and leads to instability



Wakefields affecting particles behind

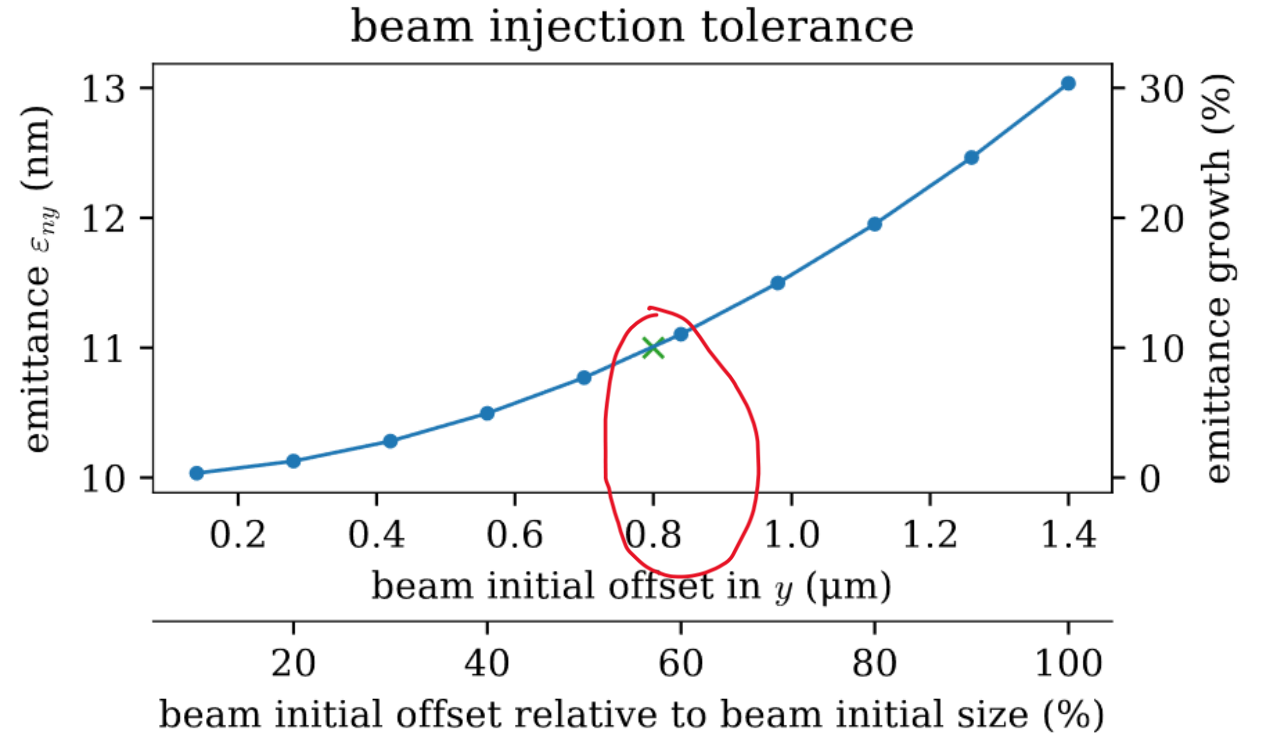
BNS damping

- BNS damping is a method to suppress transverse instability by adjusting RF phases to have differences in energy within the bunch
- Increase the energy spread -> suppress instability -> emittance growth



Beam injection tolerance

- Beam is assumed to have 10nm emittance
- Aim at 10% emittance growth, 11nm
- What is the beam injection offset that we can afford?
- Simulate the beam dynamics with different initial offset



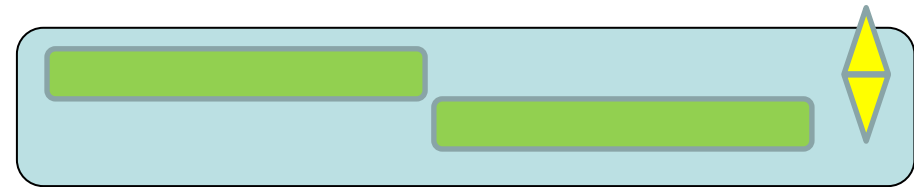
Vibration tolerance

- Beamline components (quads, accelerating structures) are subjected to vibration
- What is the vibration level that we can afford?
- Run 100 simulations with random offsets for quads and accelerating structures
- Use 90% confidence level as the tolerance

Perfectly aligned

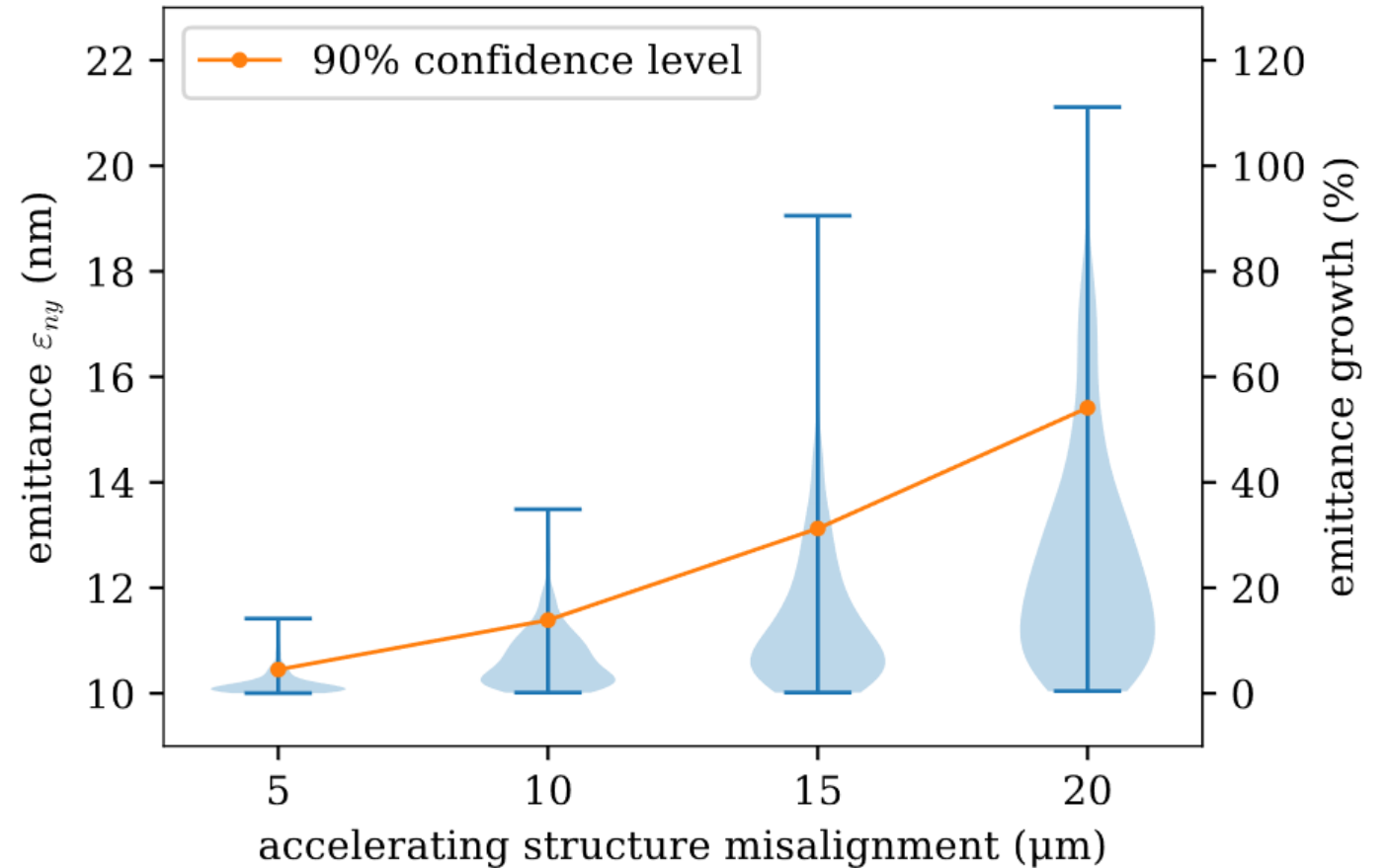


Misaligned due to vibrations



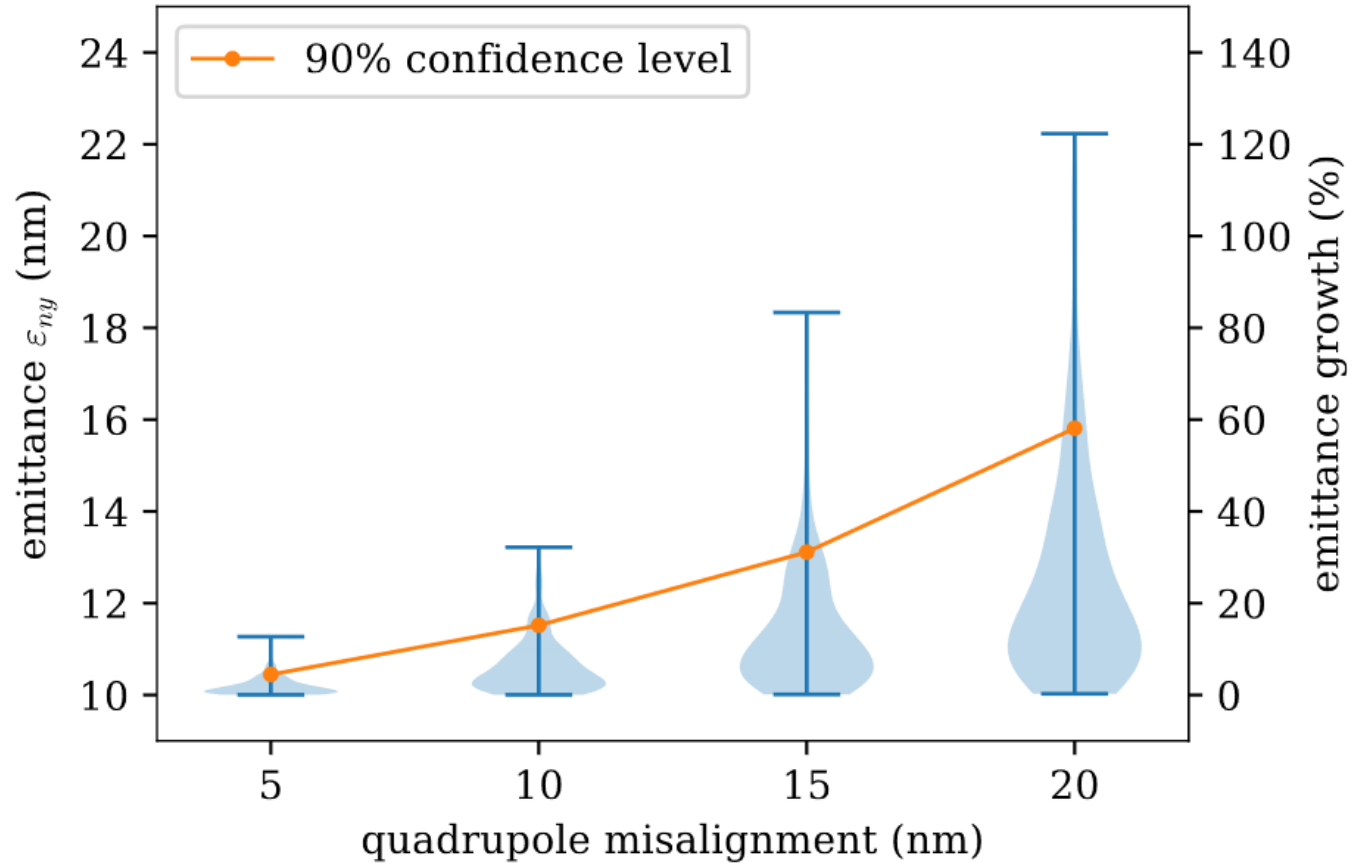
Vibration tolerance of accelerating structures

- 10 micron or less is required to have 90% confidence level for 11nm or lower emittance



Vibration tolerance of quads

- 10 nm or less is required to have 90% confidence level for 11nm or lower emittance

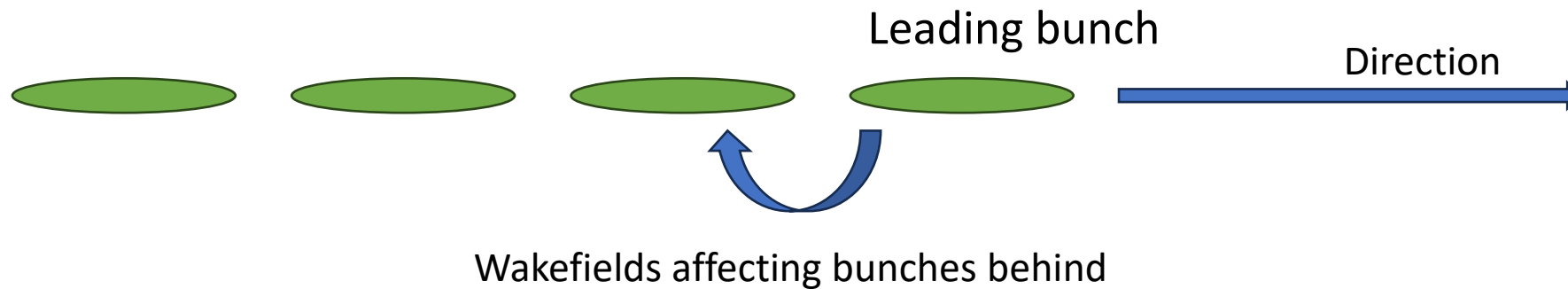


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Multi-bunch beam dynamics

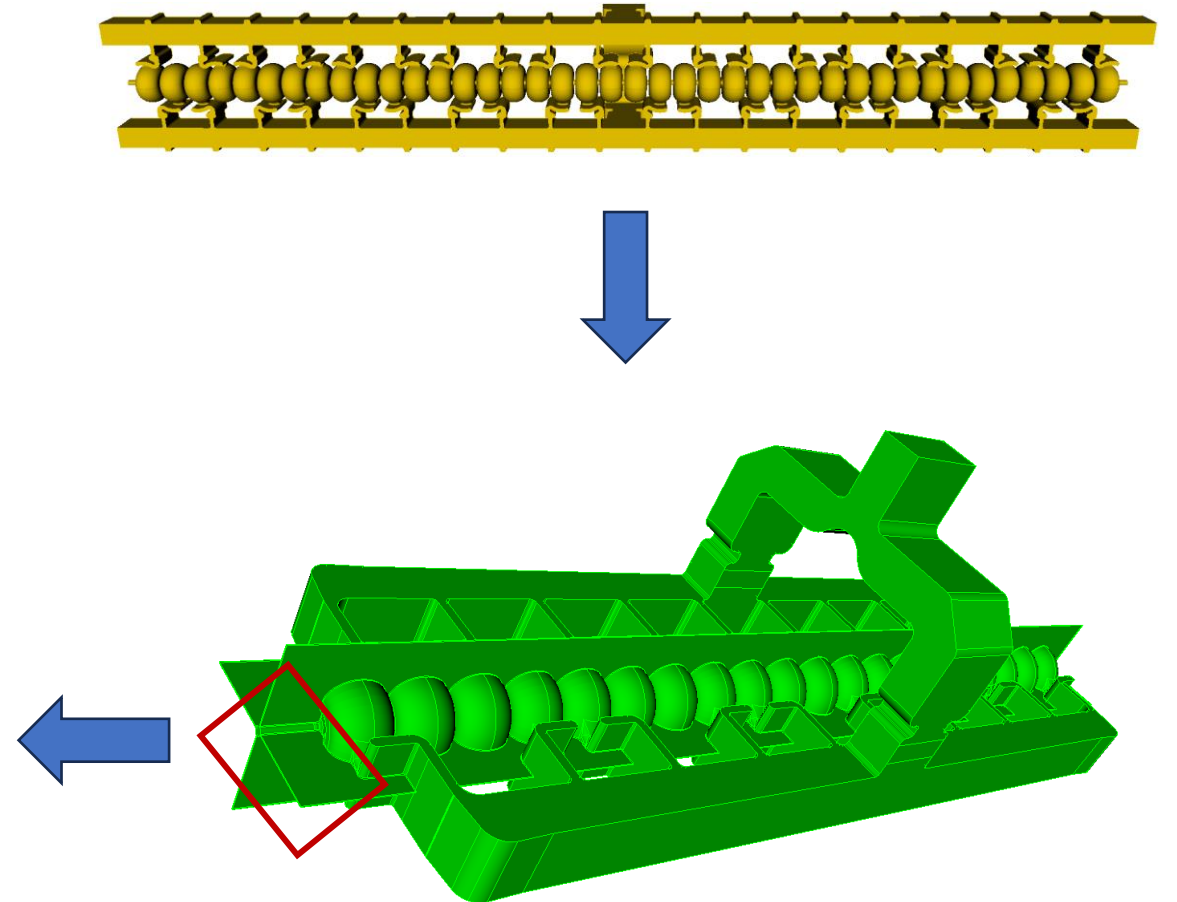
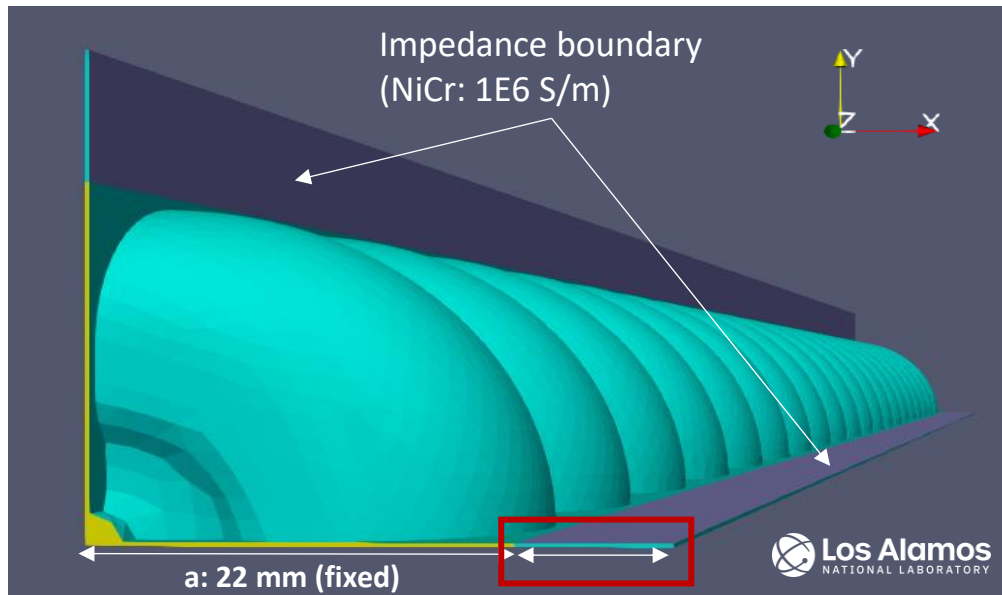
Long-range wakefields

- Long-range wakefields from leading bunches affect trailing bunches
- Longitudinal wakefields increase the energy spread
- Transverse wakefield kicks the beam away from the design trajectory and leads to instability



Long-range wakefields damping

- Waveguide slot with NiCr absorbers is used to provide damping
- Courtesy of Dongsung Kim, Haoran Xu, Evgenya Simakov from LANL
- Please check Evgenya Simakov's talk for details

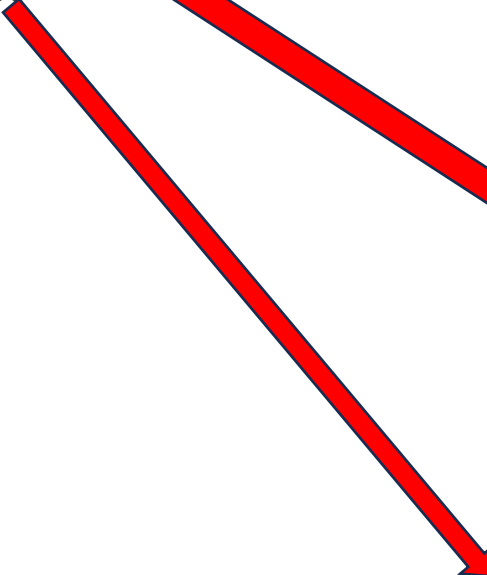


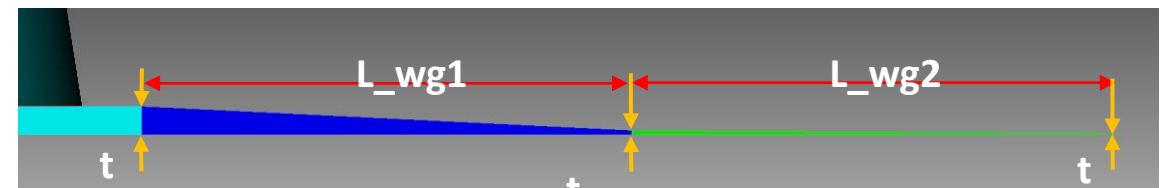
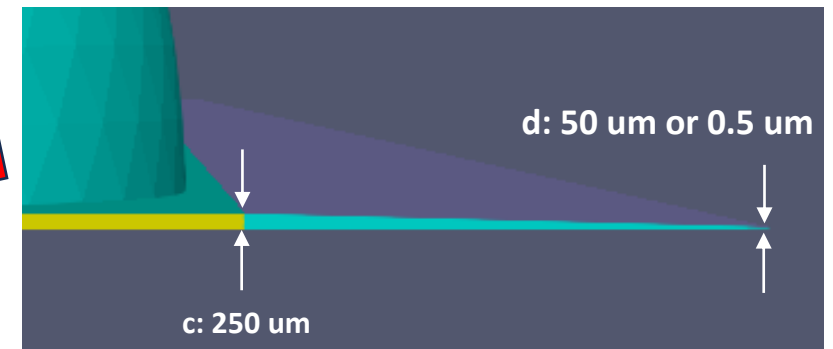
Long-range wakefields damping

- Three designs for damping slot were explored

1. Single waveguide slot 

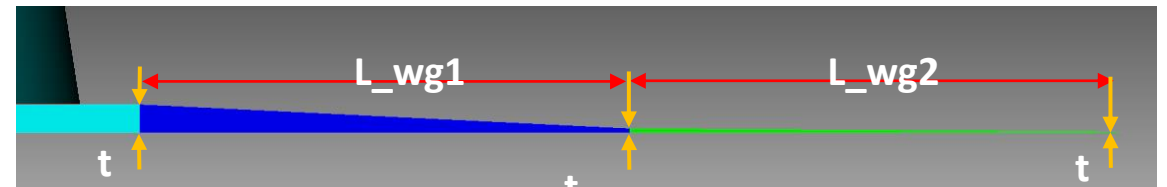
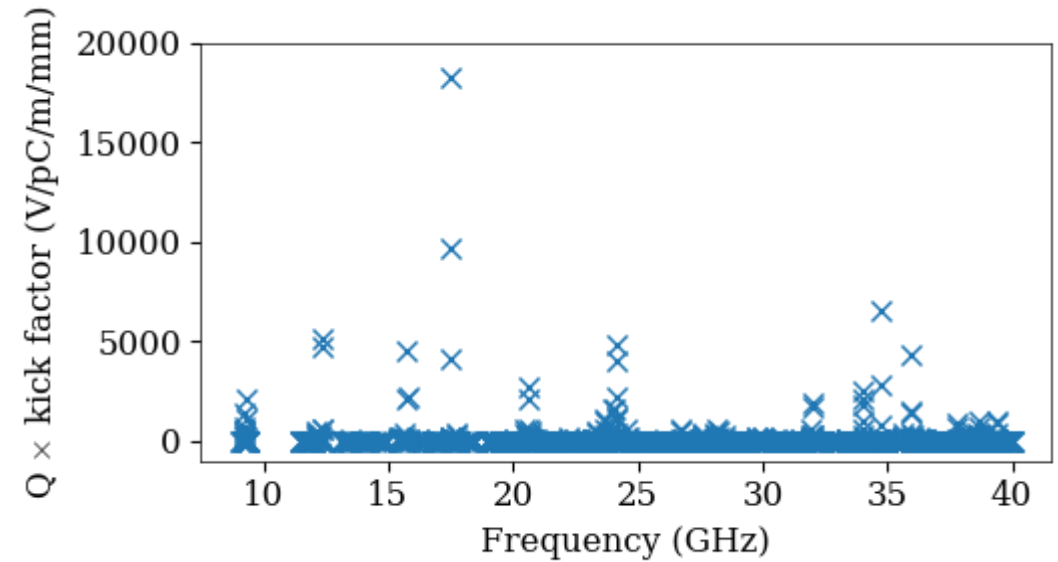
2. Single, tapered waveguide slot 

3. Two, tapered waveguide slot 



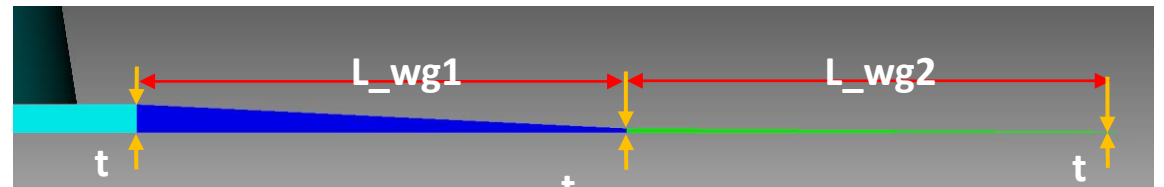
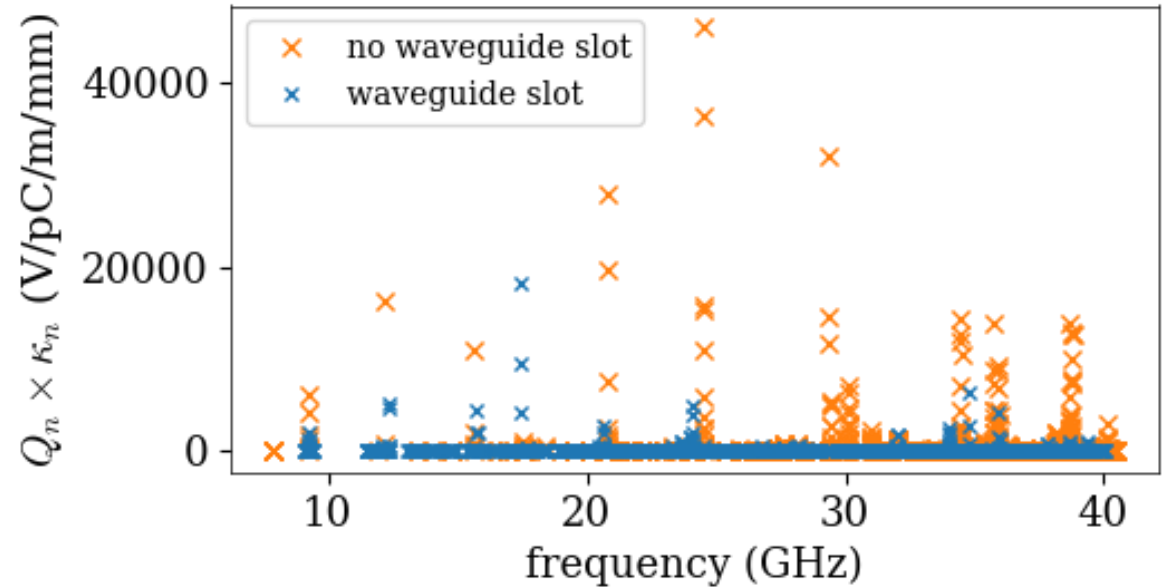
Long-range wakefields damping

- Two, tapered waveguide slot
- Reduced in kick factors for certain frequency bands



Long-range wakefields

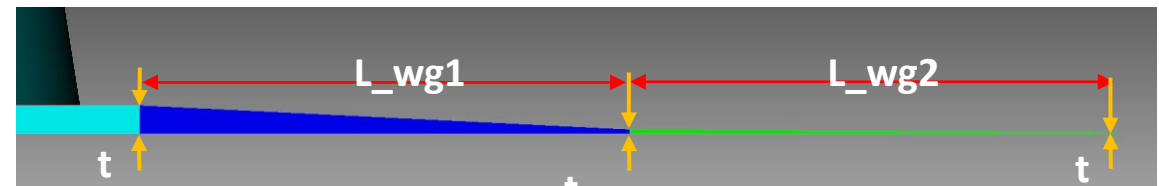
- Long-range higher-order modes (HOMs) wakefields are causing emittance growth along the bunch train
- Notably the transverse wakefields
- The current slot damping result is provided by Dongsung Kim from LANL



Multi bunches beam dynamics

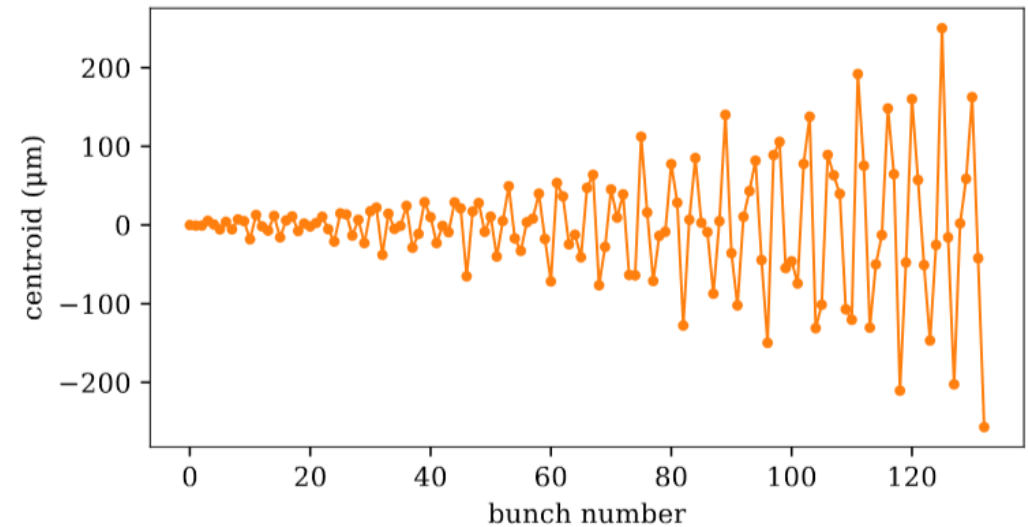
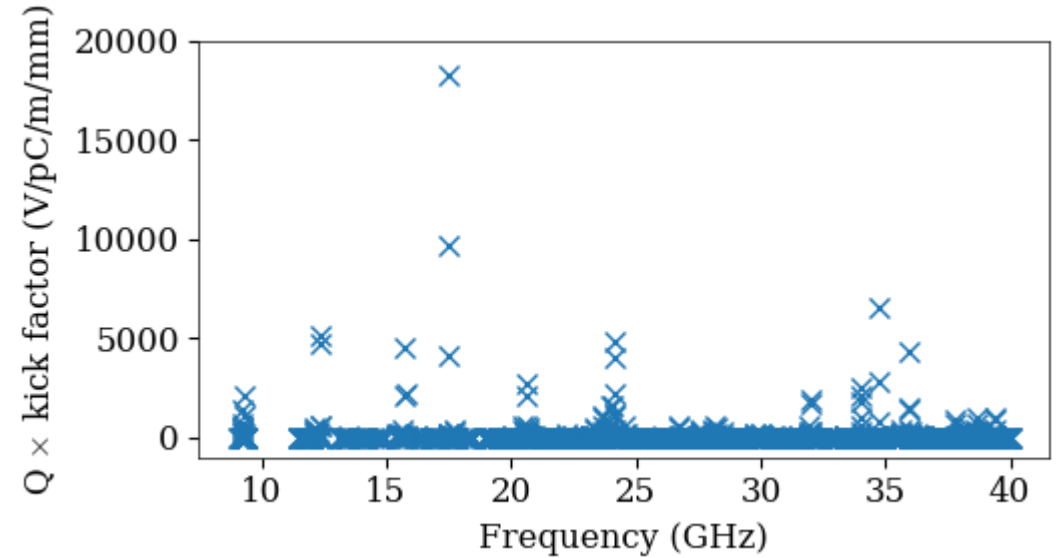
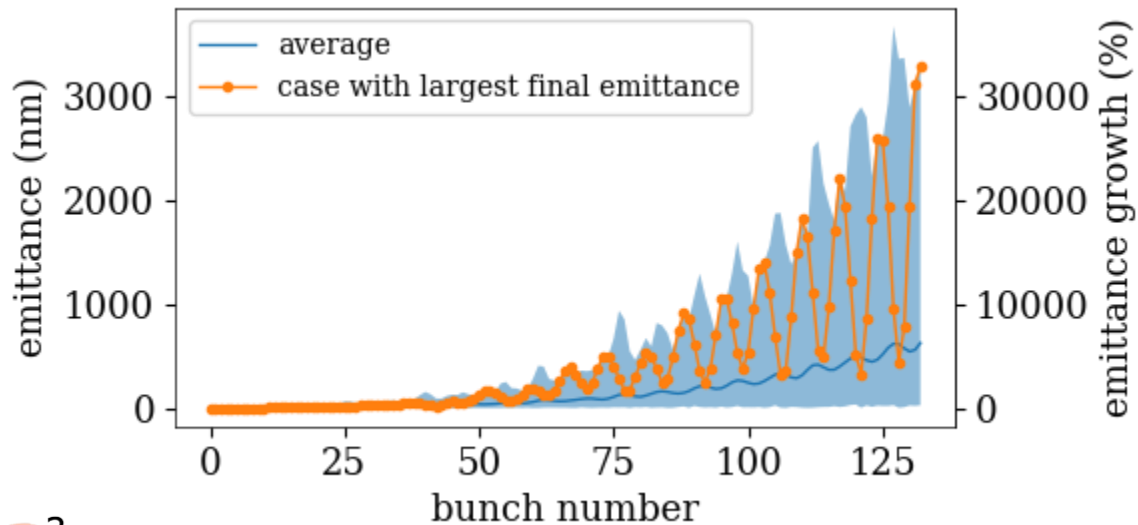
- Two, tapered waveguide slot
- Elegant simulations
- Only long-range transverse wakefields
- Assume perfectly aligned lattice
- Bunches are misaligned randomly with $0.8 \mu\text{m}$ RMS
- Identify frequency bands that need detuning or further damping
- Estimate the required detuning width

Parameter	Initial value	Target value
Beam energy	10 GeV	125 GeV
Emittance x, y	775, 10 nm	900, 20 nm
Bunch length	100 μm	100 μm
Charge, # of bunches	1 nC, 133	1 nC, 133
Bunch spacing	5.25 ns (30 RF cycles)	N/A
# of particles per bunch	1000	N/A



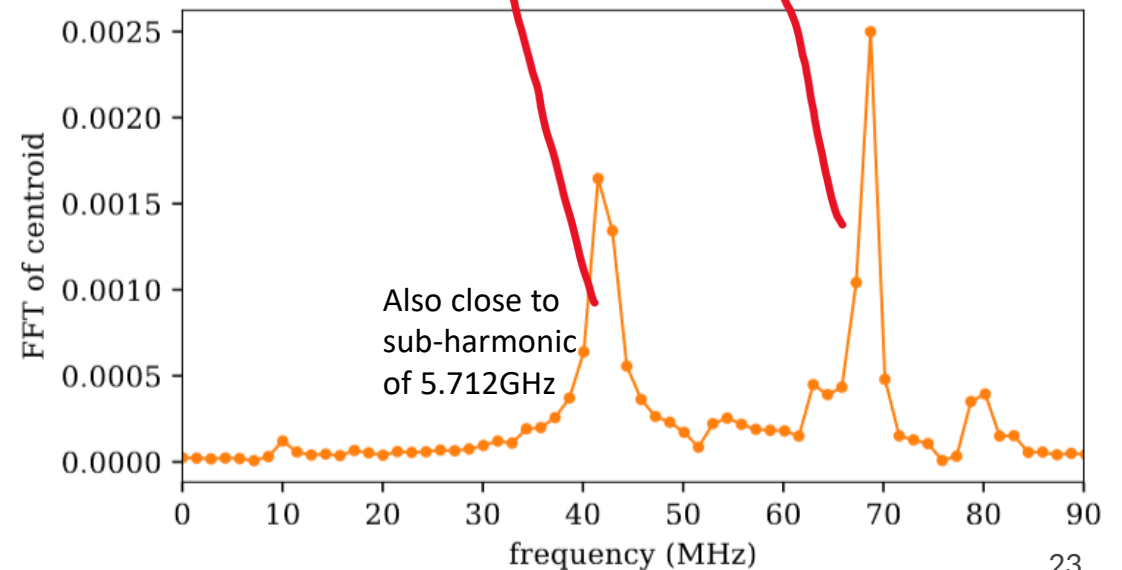
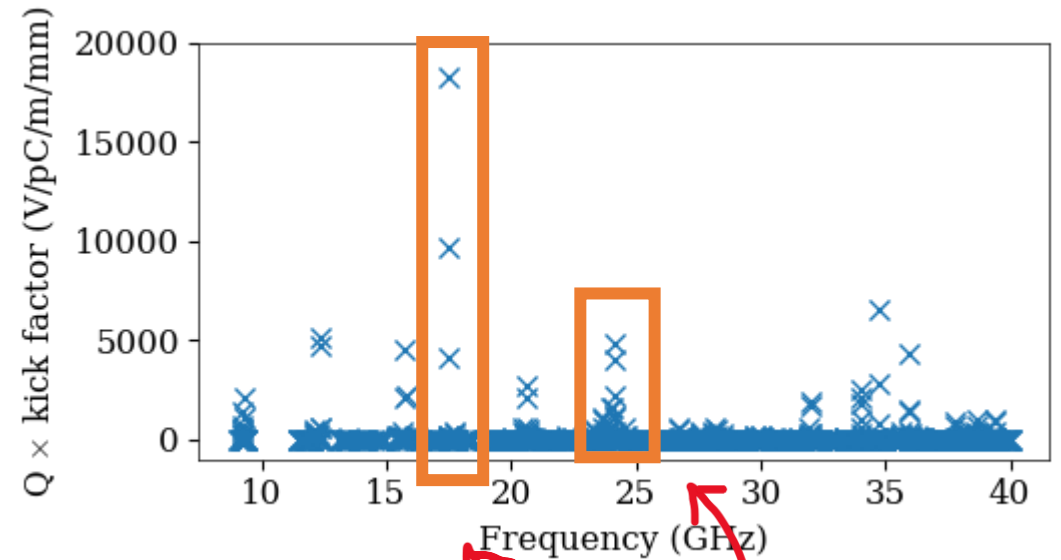
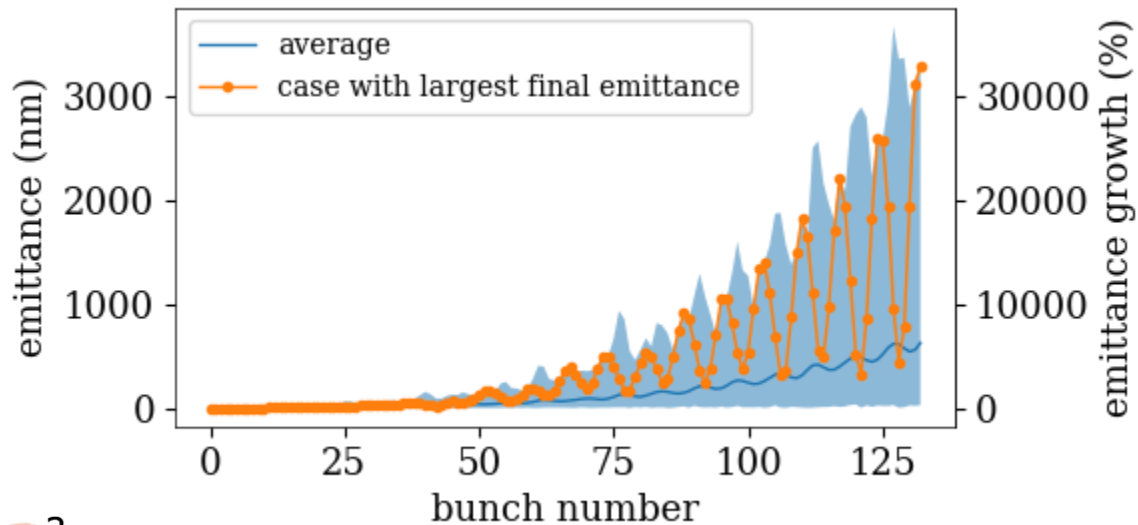
Identify frequency bands that need detuning

- Emittance growth along the bunch train
- Bunches oscillate at sub-harmonic of 17.4 GHz and 24.1 GHz bands



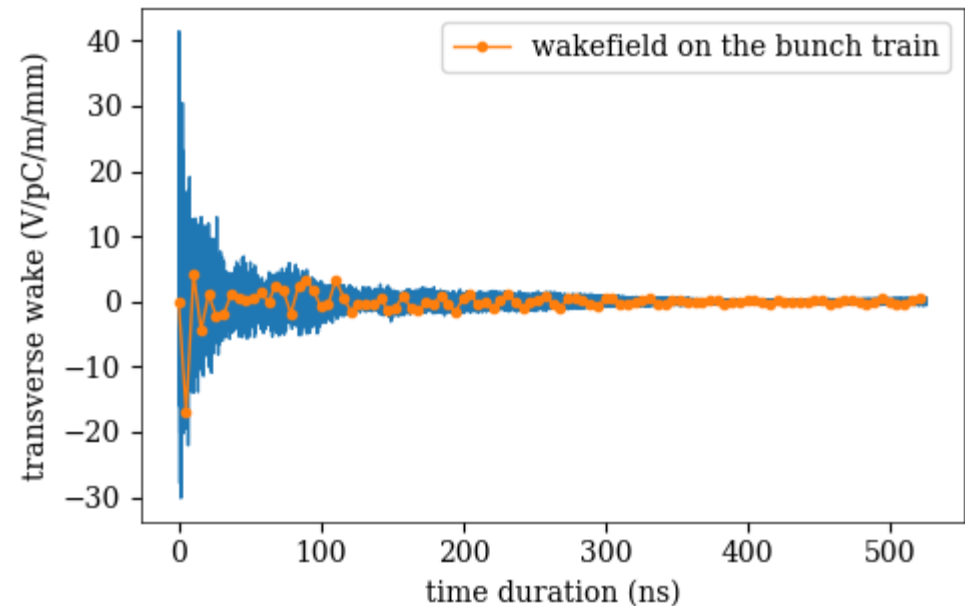
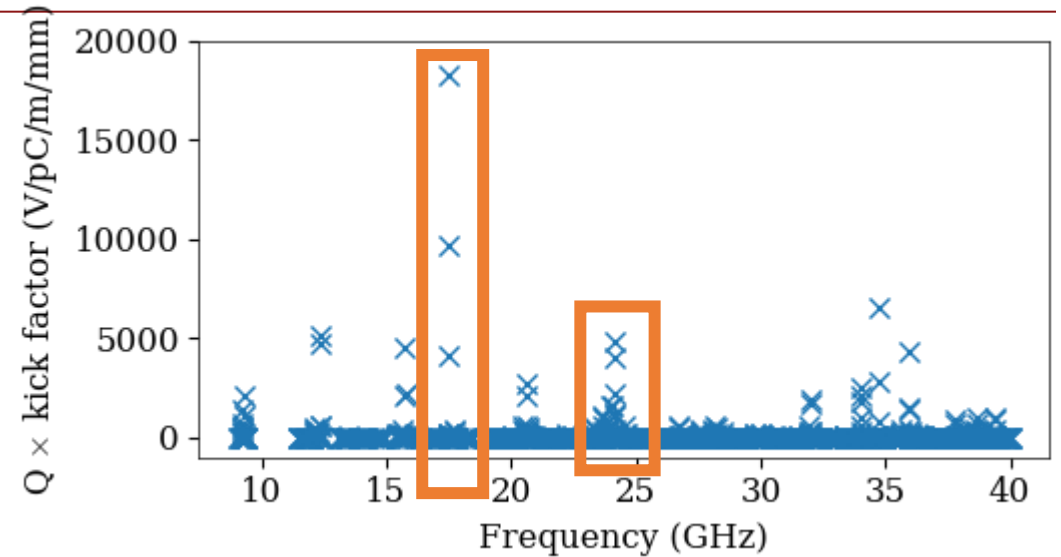
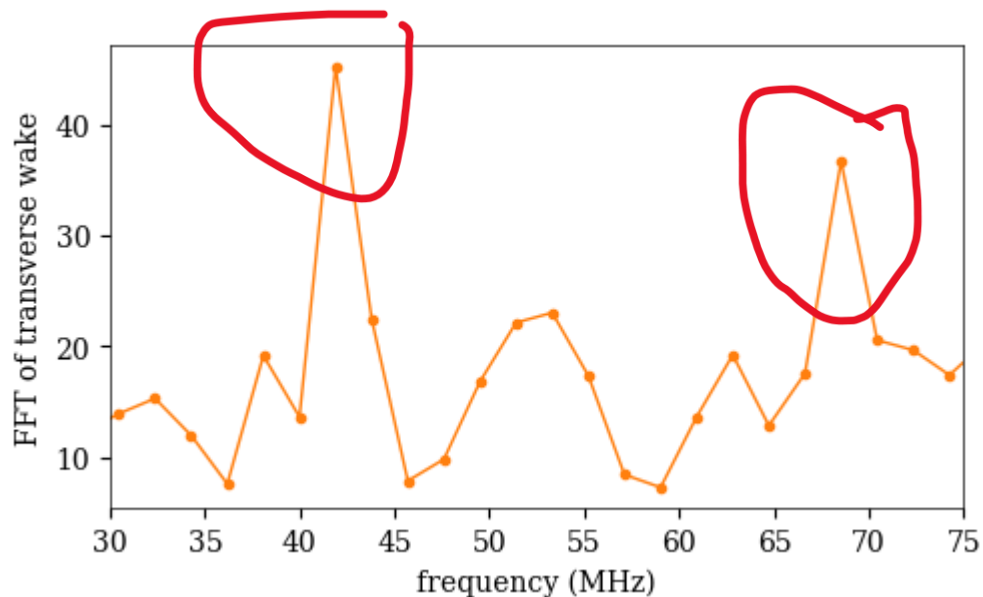
Identify frequency bands that need detuning

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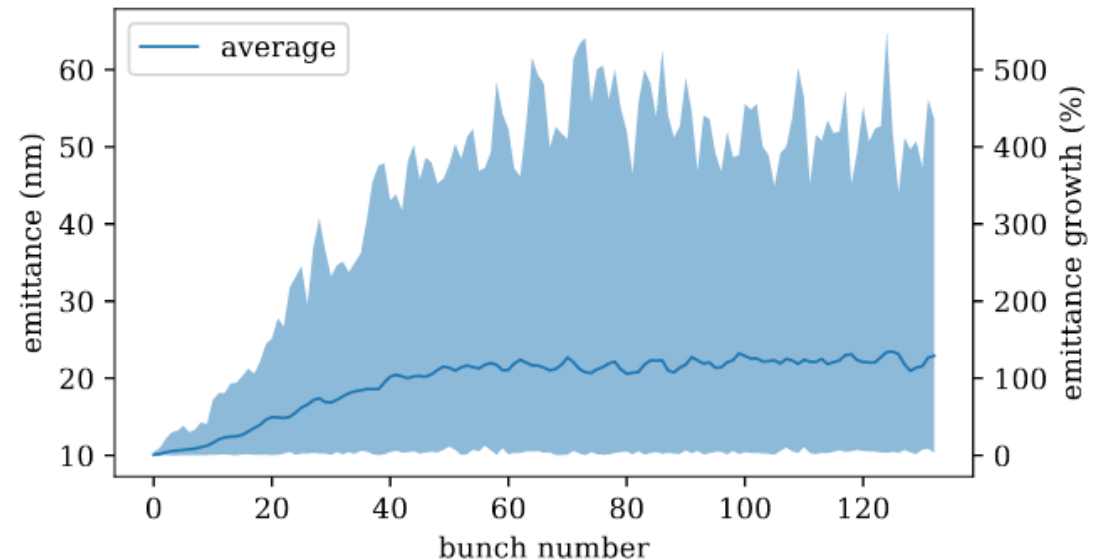
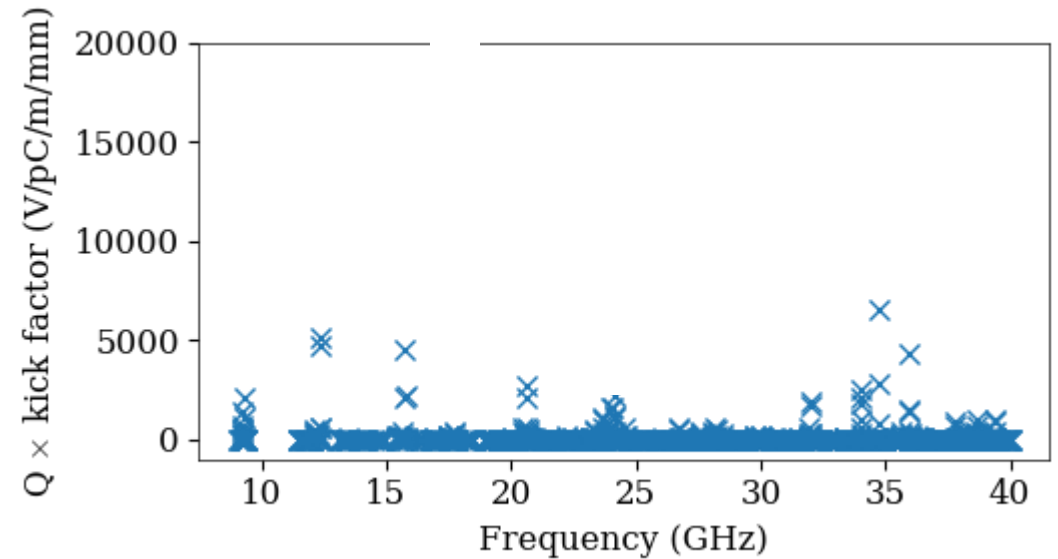
Identify frequency bands that need detuning

- Why do the bunches oscillate at these frequencies?



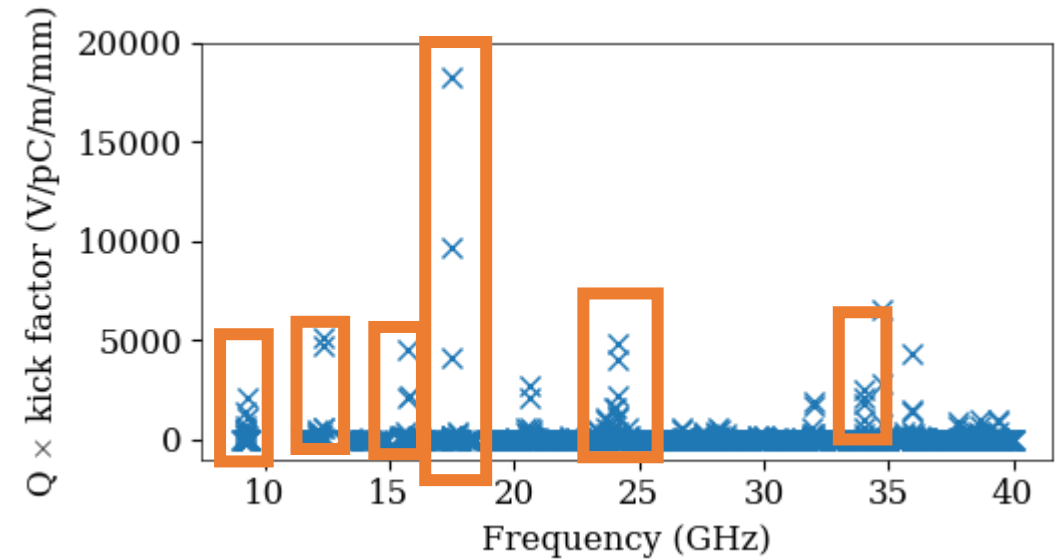
Identify frequency bands that need detuning

- What if we artificially remove these two bands?
- The emittance growth is significantly suppressed after removing these bands



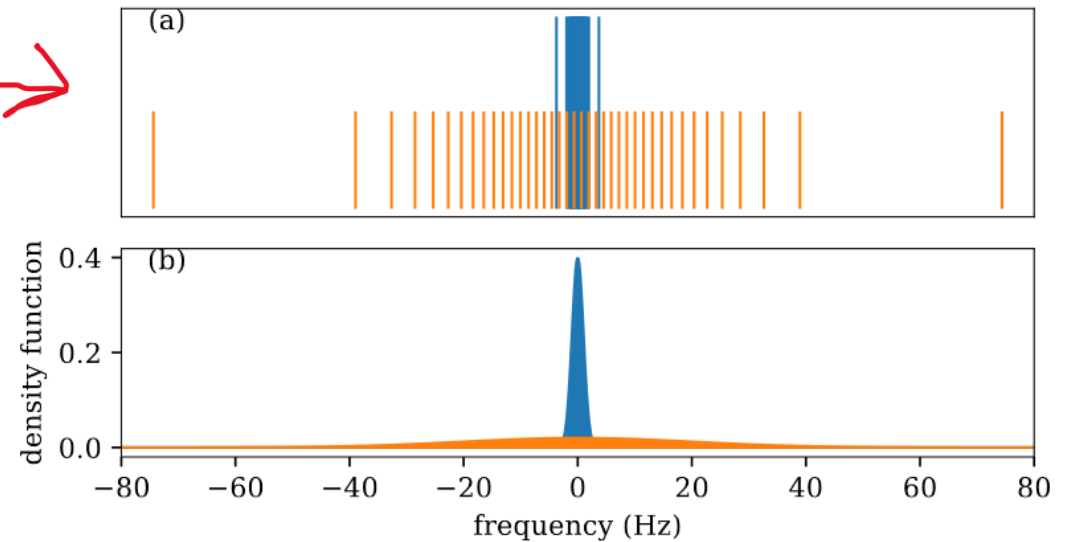
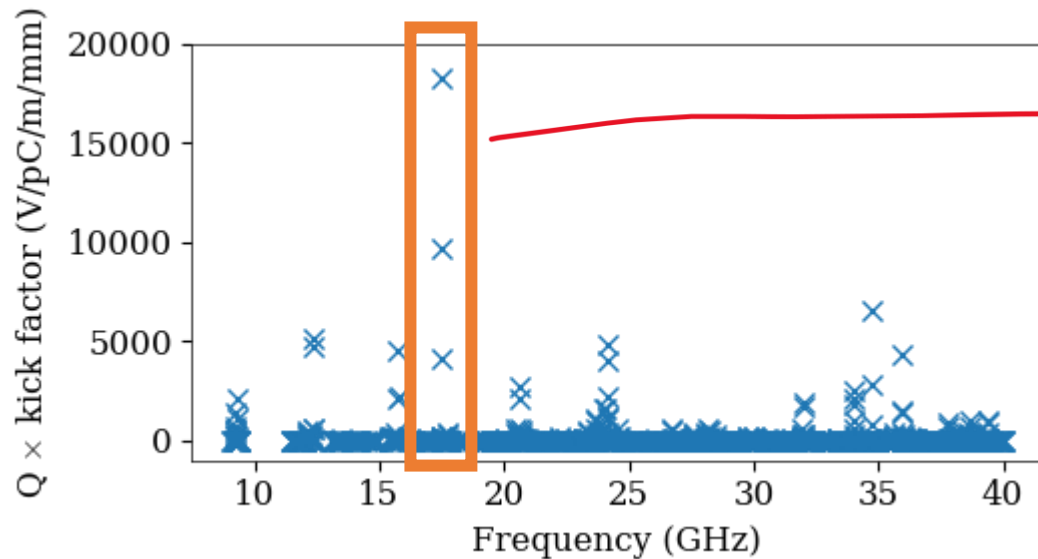
Identify frequency bands that need detuning

- Six frequency bands were identified
- Gaussian detuning were applied to investigate the required frequency width to suppress the emittance growth



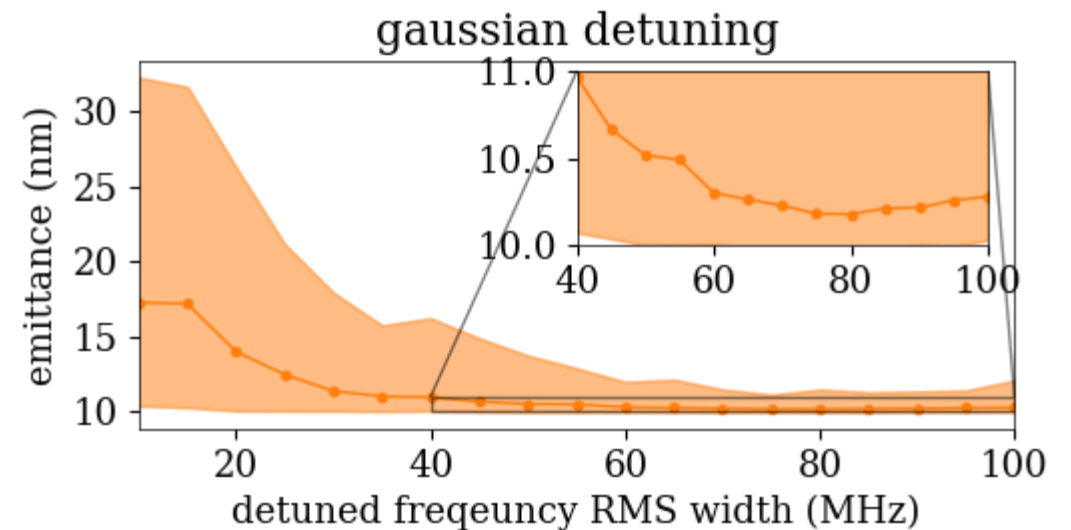
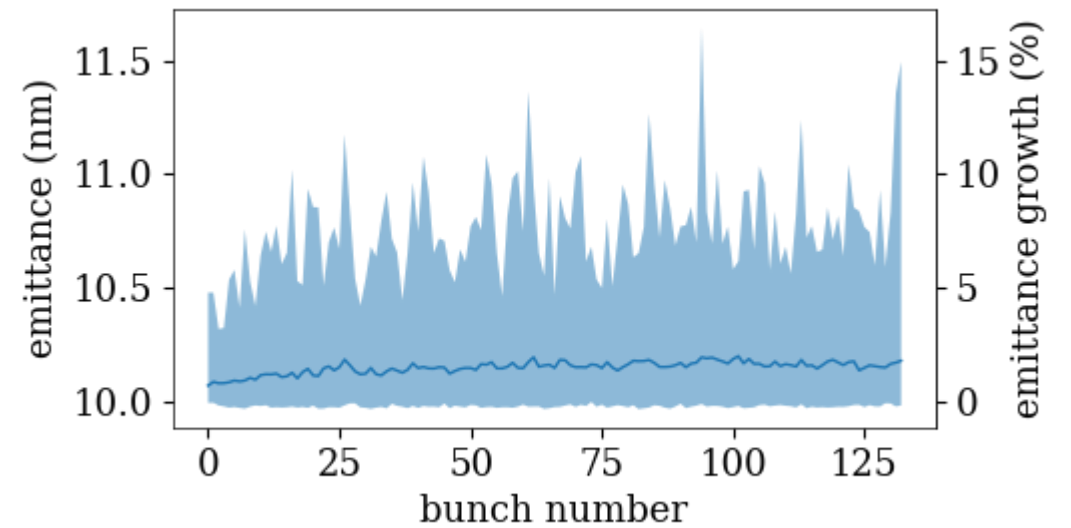
Gaussian detuning

- Gaussian detuning were applied to investigate the required frequency width to suppress the emittance growth



Multi bunches beam dynamics with detuning

- Emittance growth can be suppressed
- 40 to 80 MHz rms frequency width is needed for detuning



Summary

- Frequency bands that are detrimental to emittance are identified
- The amount of detuning were estimated using Gaussian detuning
- Results will be used to refine the design of the RF structure
- Please check these talks
 - Zenghai Li's talk on RF design
 - Evgenya Simakov's talk on detuning
 - Matt Andorf's talk on damping ring

Acknowledgement

- SLAC: Glen White, Zenghai Li, Ankur Dhar, Emilio Nanni
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- Simulations were performed at SLAC S3DF and NERSC computing facilities