# Z-Slicer Simulations for terahertz radiation experiments at FAST

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# Our purpose

Our goal is

to generate ~1 THz radiations with slits in chicane

Today's topics

1. Beam optics for THz radiations
2. Expected electron bunches and frequencies

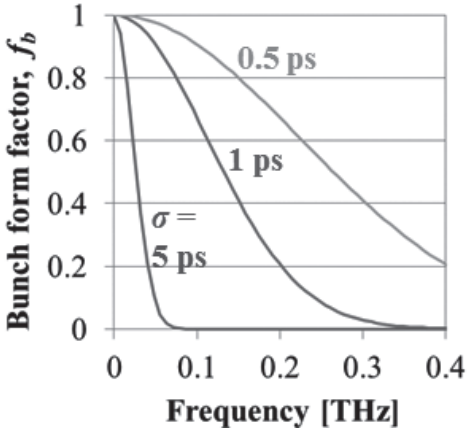
# THz radiations



Many THz sources using accelerated electron beams have been proposed and developed.

→ CSR, smith-purcell radiation and transition radiation…

To generate THz waves, longitudinal bunch length should be compressed to be < 0.3 mm.
(→ broadband)

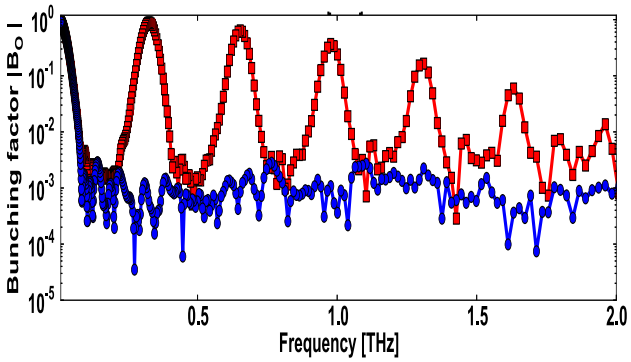



Narrow band THz waves require a short period bunch structure.

→ we use a micro-bunch beam.

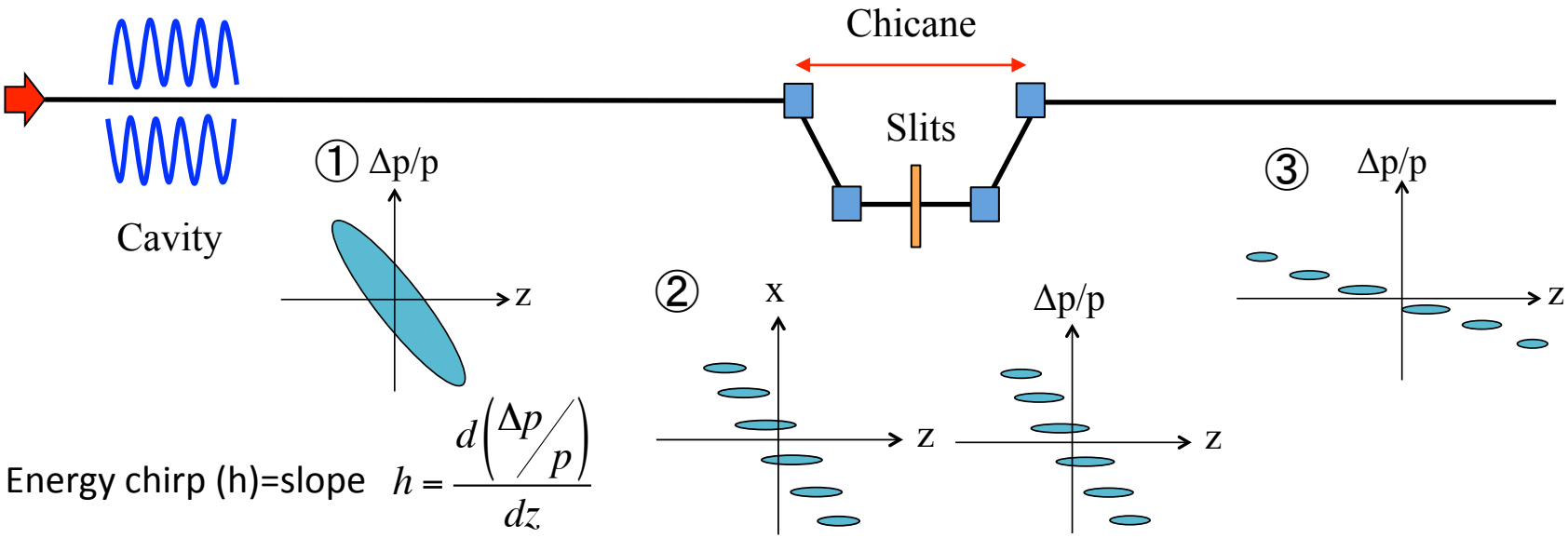
- slits
- chicane

＋ energy chirped beam



# How to make micro-bunch beams






Energy chirp (h)=slope $h = \dfrac{d\left(\Delta p / p\right)}{dz}$

① Energy chirped electron beam after a cavity.
② Separated in x (energy) plane using slits in chicane.
③ De and over compression to reduce overlaps between micro-bunches.

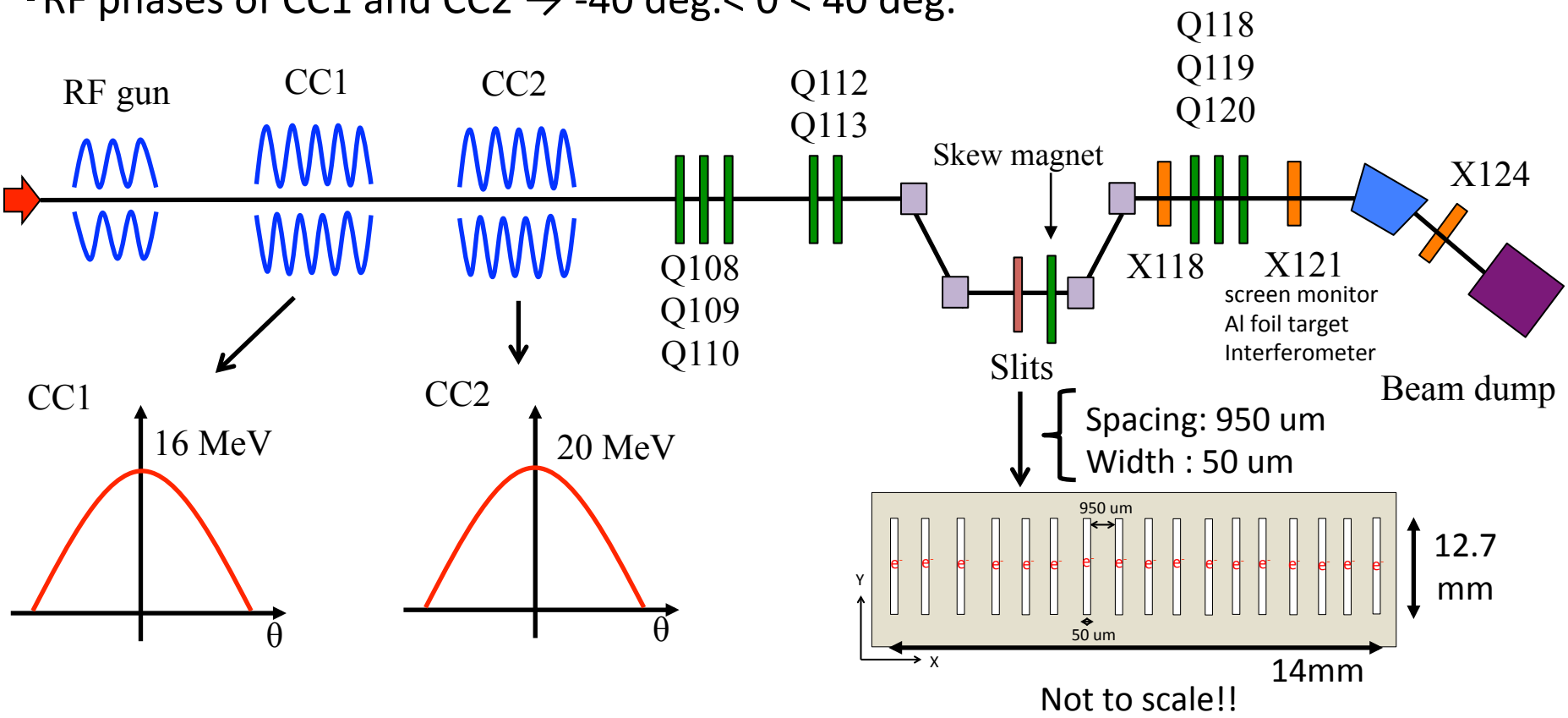
## Key points for a micro-bunch beam (longitudinal separation)

- Low uncorrelated and high correlated energy spreads for large chirped beam with no overlaps between micro-bunches.
- Low emittance beam.

# Simulation parameters



- Normalized emittance → 5x10$^{-6}$ m▪rad (for 50 pC last summer)
- Beam energy after RF gun → 5 MeV
- Rms uncorrelated energy spread after RF gun→ 0.1 % (5 keV) (comes from measurements at FLASH.
- Max. accelerating gradients of CC1 and CC2 → 16 and 20 MeV/m
- RF phases of CC1 and CC2 → -40 deg.< θ < 40 deg.



# RF phases for energy chirped beams



-40 deg.< RF phase < 40 deg.

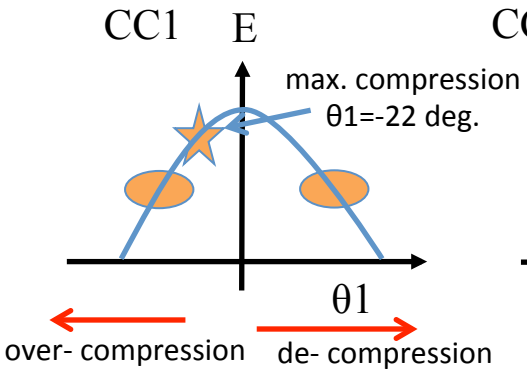
(Assumed no chirp from RF gun cavity)

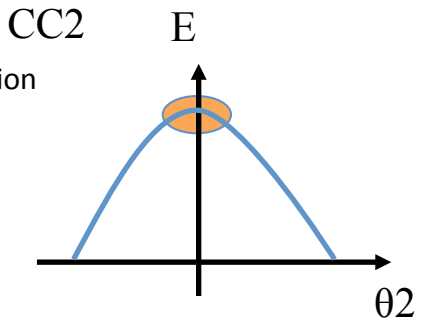
## 1. CC1 off-crest and CC2 on-crest

θ1=−,+ 35.4 deg. and θ2=0 deg.

→ Energy chirp =±7

Final energy: 38 MeV



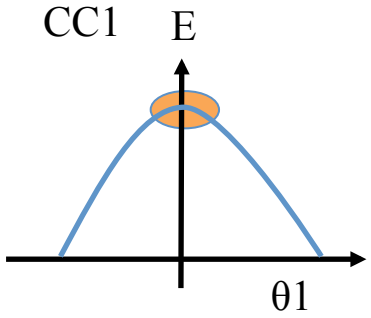



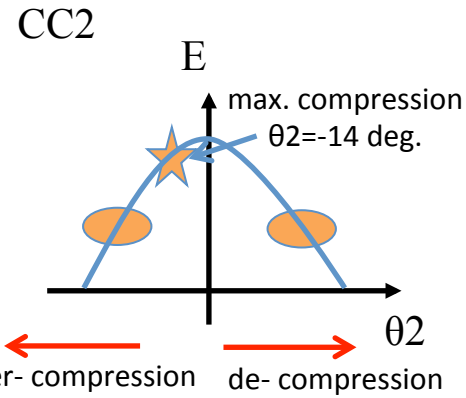

## 2. CC1 on-crest and CC2 off-crest

θ1=0 deg. and θ2=−,+34 deg.

→ Energy chirp =±9

Final energy: 32 MeV



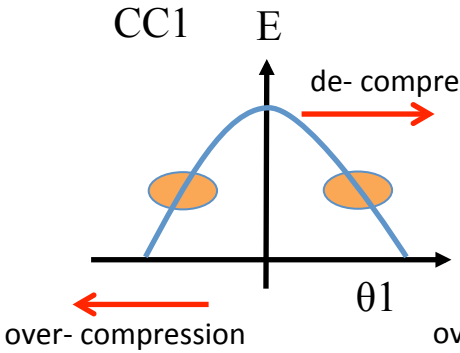



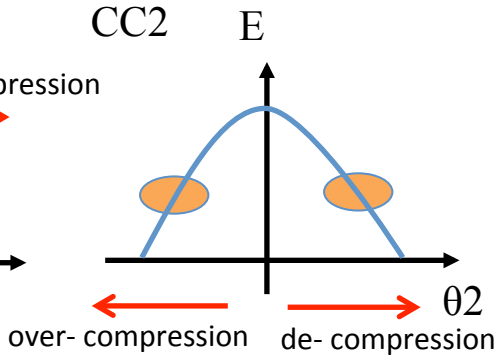

## 3. CC1 off-crest and CC2 off-crest

θ1=−,+35 deg. and θ2=−,+35 deg.

→ Energy chirp =±16

Final energy: 32 MeV

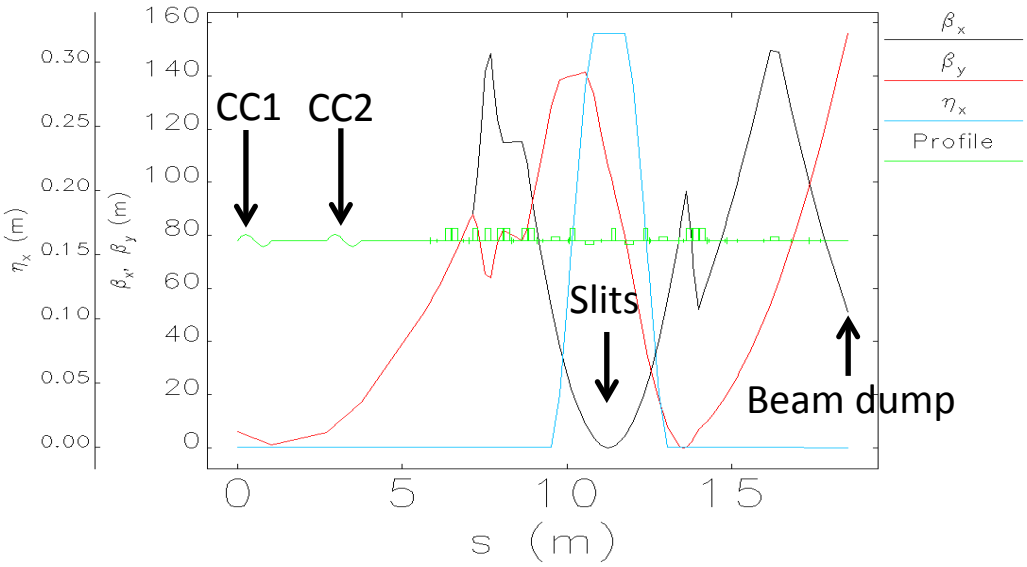


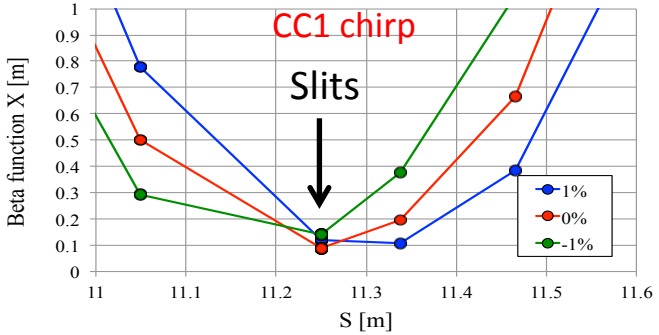
# Optical functions from CC1 to beam dump

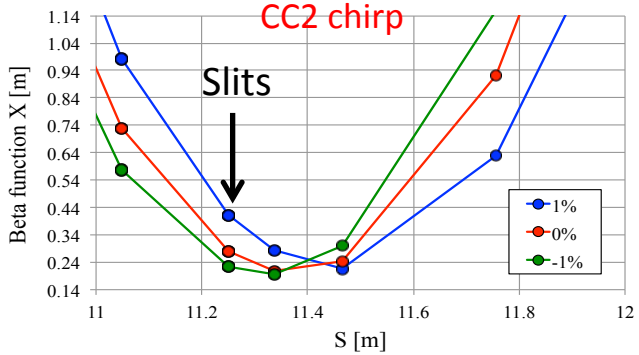


## Optical functions (on-momentum)

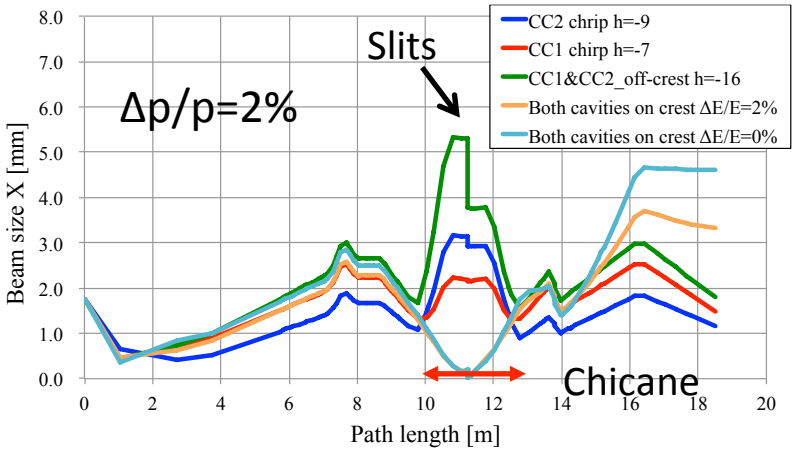



## Off-momentum (ΔE/E=-1%, 0%, 1%)




## Beam sizes X along beam line



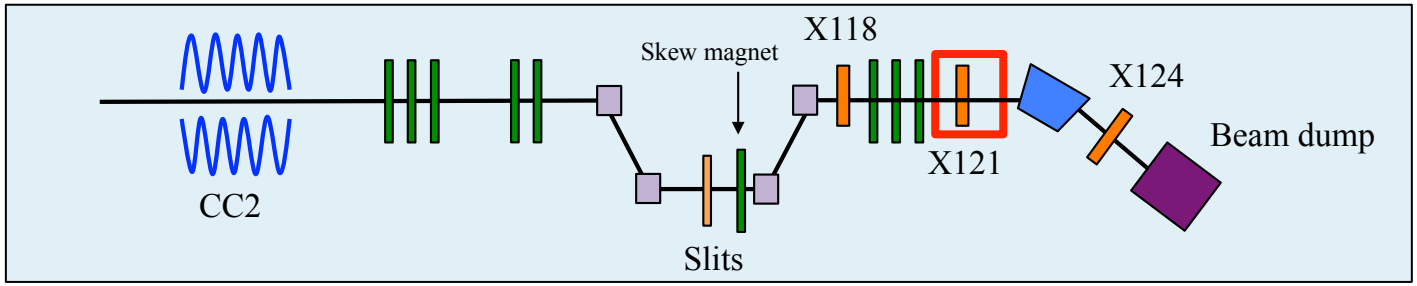

K values < 1.7 T/m (<< Max. K value: 7 T/m)

- For CC2 chirp, effect of energy deviation is large.
- For CC2 chirp, βx at slits : 0.44 m, 0.3 m, 0.24 m for ΔE/E=1%, 0%, -1%
- $\sigma_x=[\varepsilon\beta_x+(\delta_o+h\sigma_z)^2\eta^2]^{1/2}$; in chicane, beam size strongly depends on energy chirp
- Max. rms beam size: ~5.3 mm (beam pipe radius= 25 mm)

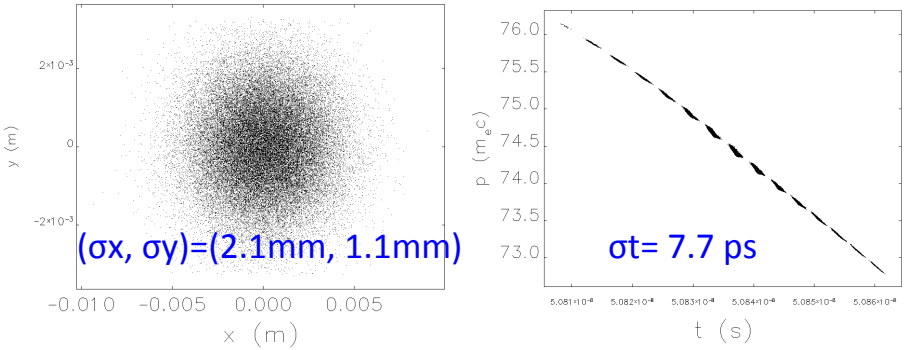
# Beam profiles at X121



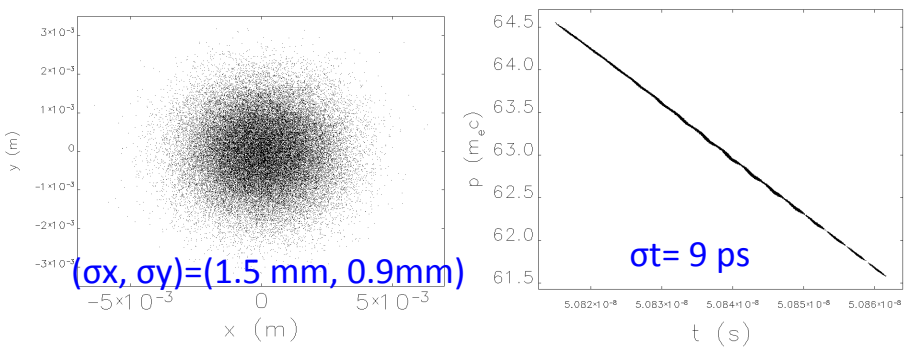
THz waves are emitted by hitting Al foil target at X121 with micro-bunch beam.



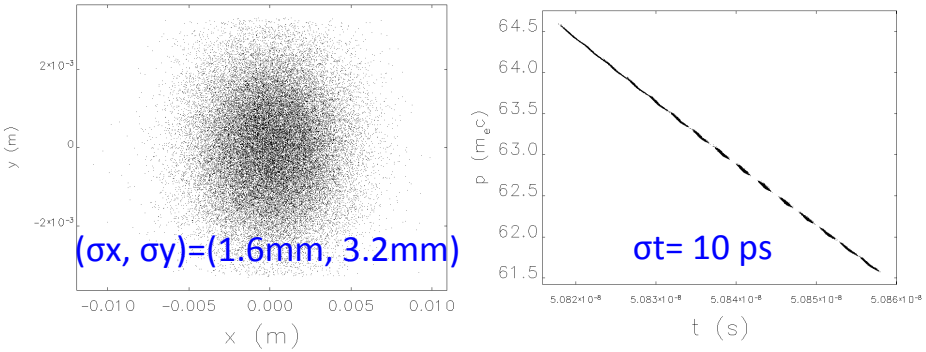

CC1=35.4°, CC2=0° (h=-7)




CC1=0°, CC2=34° (h=-9)




CC1=35°, CC2=35° (h=-16)

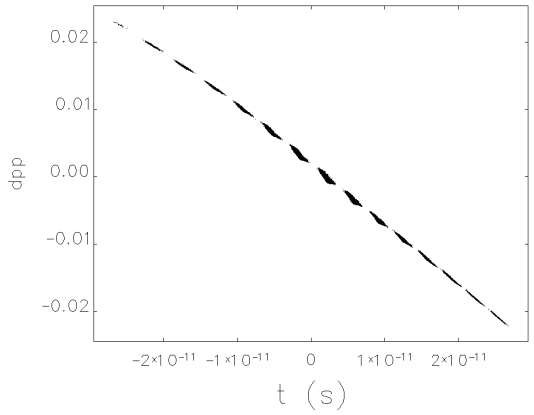


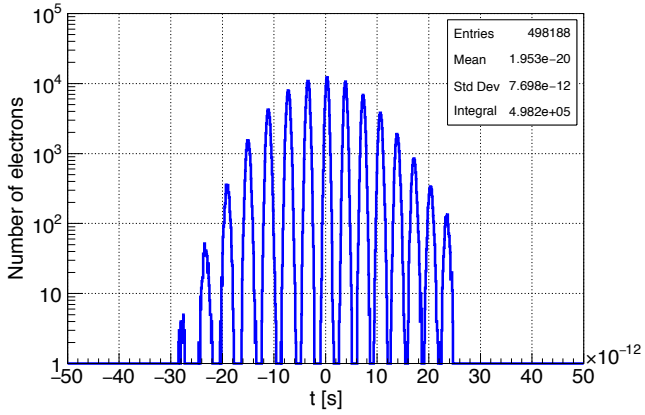

- Rms beam sizes at X121
  - σx <= 2.1 mm
  - σy <= 3.2 mm
  - (Al target size : ~ 25 mm)
- Rms bunch length at X121
  - σt < 10 ps (3 mm)

# Comparisons of micro-bunch after chicane (@X121) De-compression

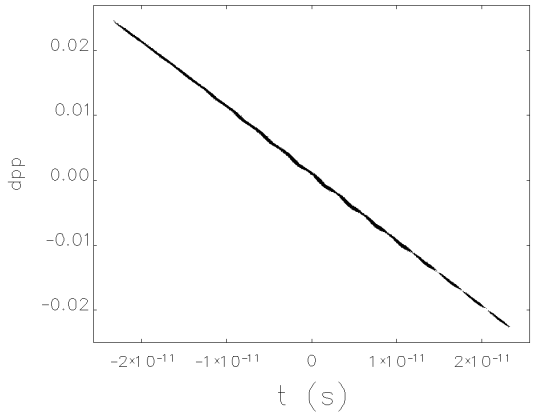


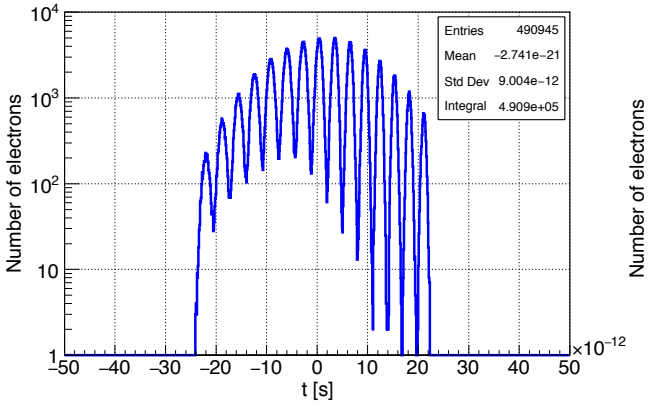
CC1=35.4°, CC2=0° (h=-7)



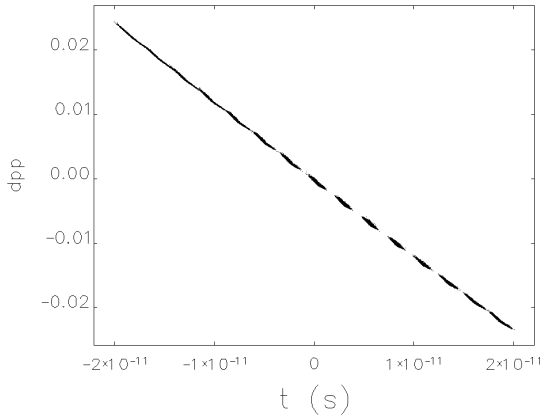



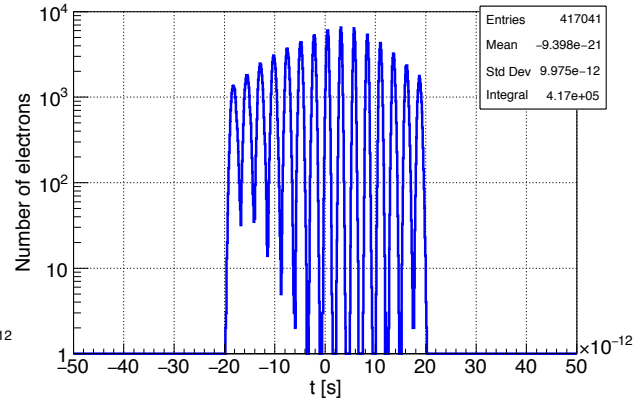

CC1=0°, CC2=34° (h=-9)




CC1=35°, CC2=35° (h=-16)



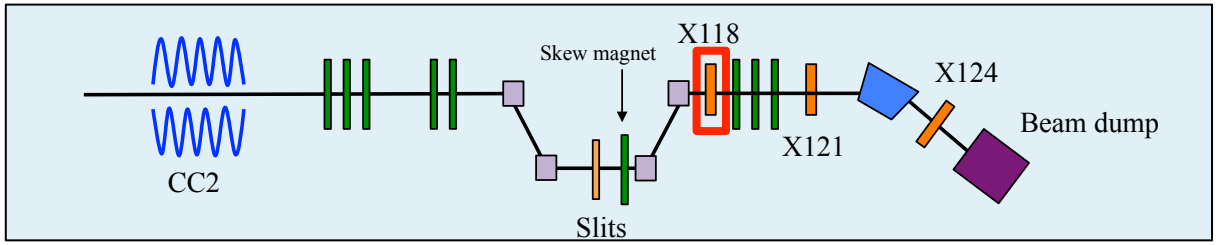



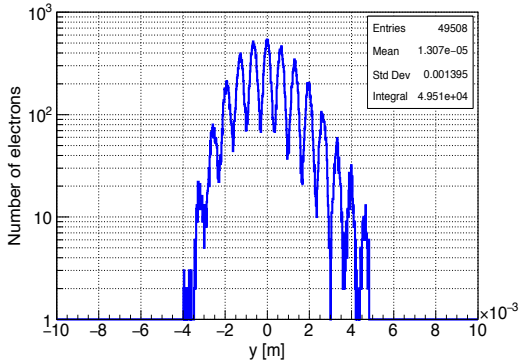

- For CC1 chirp and both CC1 & CC2 off-crest, distributions are separated.
- For CC2 chirp, distribution has large overlap at +Δp/p due to chromatic aberration from cavity.

# Micro-bunch beam on screen monitor X118

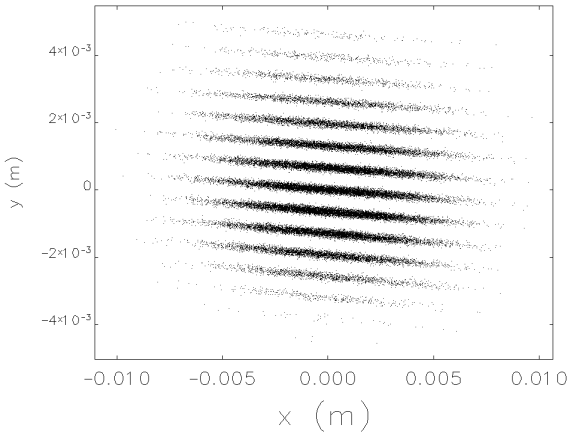


- To measure micro-bunch beam ($\sigma_t$~0.3 ps) using streak camera is difficult.
  → By turning on skew magnet after the slits, beam size Y after chicane can have information of z axis in the chicane. (Charles tried to do at A0)

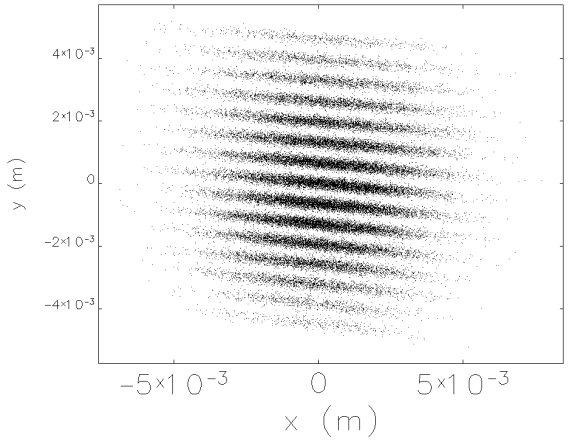


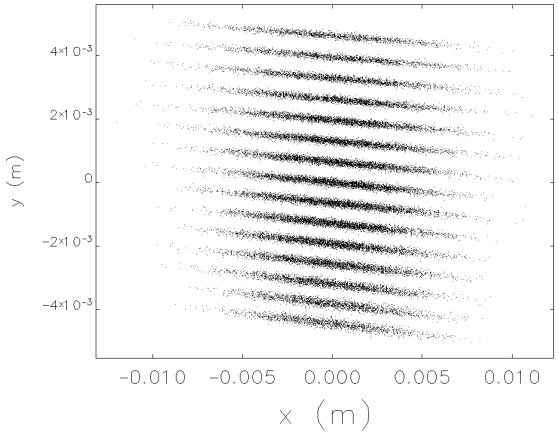

CC1=35.4°, CC2=0° (h=-7)




CC1=0°, CC2=26° (h=-9)




CC1=35°, CC2=35° (h=-16)

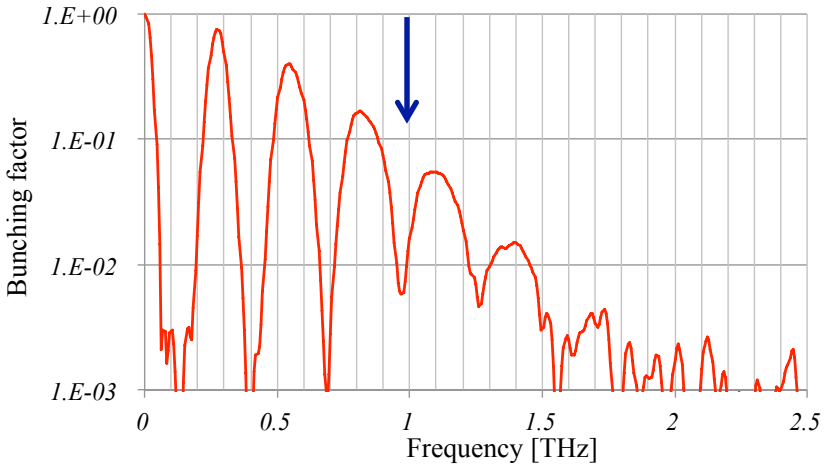



- Using skew magnet in chicane, distributions separated in y-plane can be obtained.
- K value of skew magnet should be ~0.4 [T/m] for clear separations.

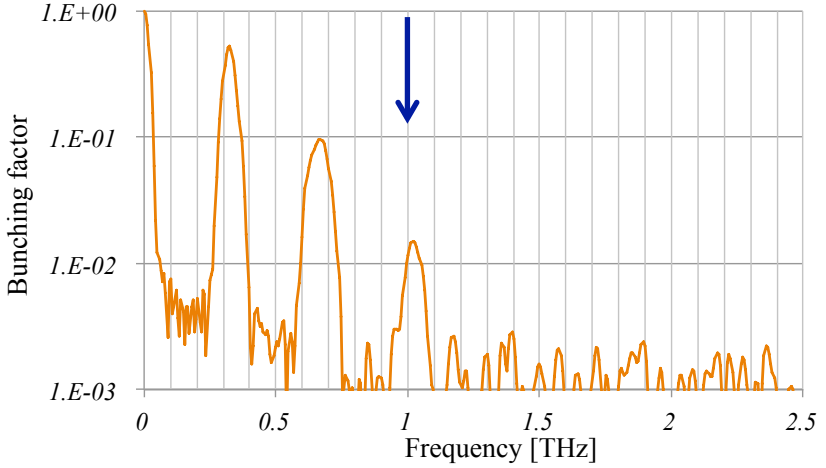
# Comparisons of bunching factor at X121 De-compression



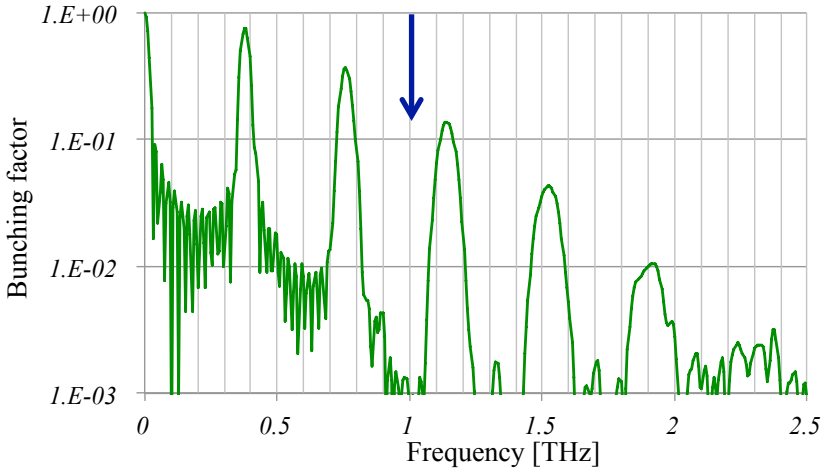
CC1=35.4°, CC2=0° (h=-7)




CC1=0°, CC2=34° (h=-8)




CC1=35°, CC2=35° (h=-16)



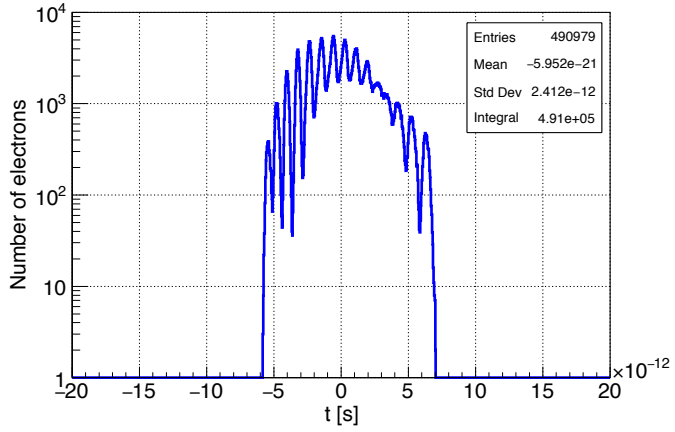

- Frequencies of over 1 THz are obtained.
- To detect over ~1 THz wave using interferometer may be difficult.
- For both CC1 and CC2 off-crest, max. frequency is around 1.9 THz.

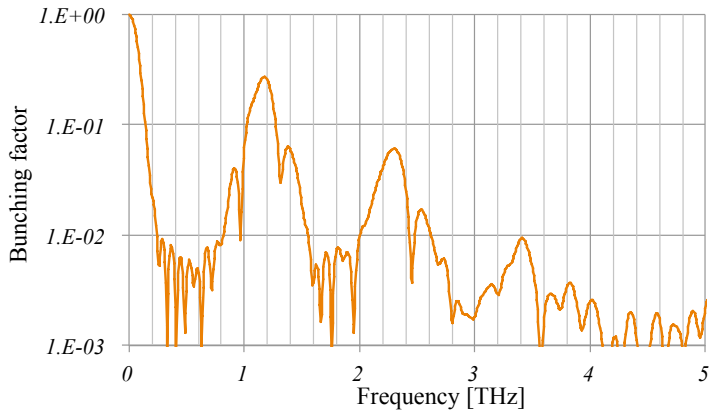
# Generation of higher frequency waves at X121 over-compression



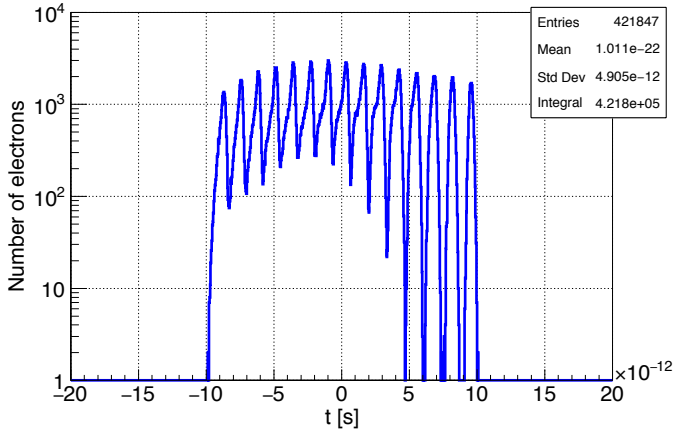
Higher frequency waves → Short spacing between bunches → Over-compression

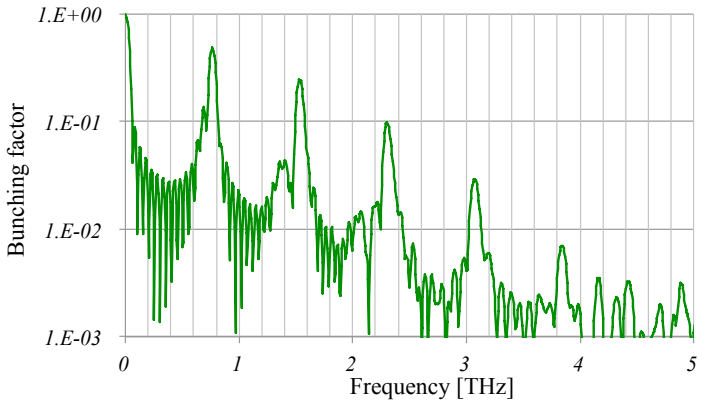
CC1=0°, CC2=-34° (h=8)




CC1=-35°, CC2=-35° (h=16)



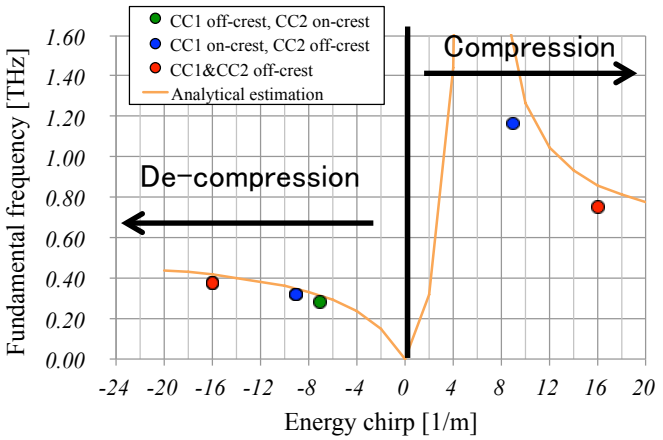




- Max. frequency is around 3 THz (higher than those for de-compression).
- Longitudinal distributions may become worse, maybe because of space charge effect (short bunch length).

# Comparisons of frequency spectra



## Fundamental frequency vs. Energy chirp

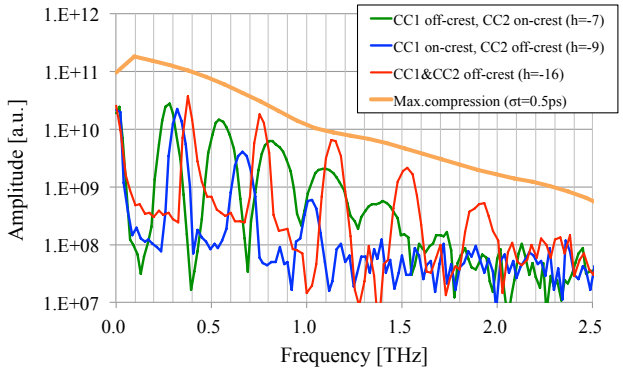



$$f_0 = \frac{\eta c|h|}{D|1+R_{56}h|}$$

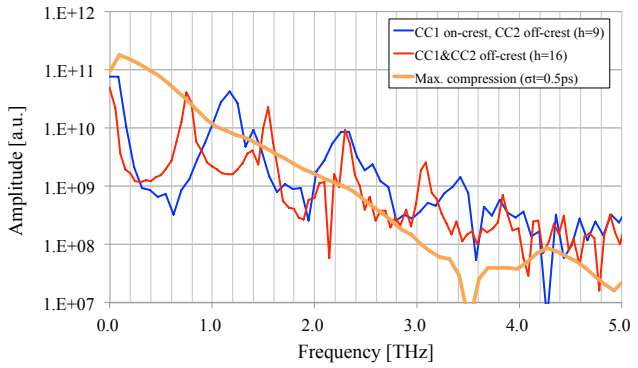
$D$: slit's spacing 950um, $\eta$: dispersion 0.32m
$h$: energy chirp, $c$: speed of light, $R56$: -0.18

- Fundamental frequencies for de-compression mode agree with the analytical estimation.
- For over-compression, simulation frequencies are low compared with analytical calculation due to bad longitudinal distributions.

## De-compression mode




## Over-compression mode




- Ratios of signal to background are over 10 for below 1 THz.
- At 1THz, amplitude for both cavities off-crest is about 3-10 times higher than that for the others cases.
- Amplitudes for de-compression are 5-10 times lower than that for single bunch with max. compression.
- For over-compression, amplitudes for two cases are almost same.
- Compared with single bunch with max. compression, over-compression is effective at higher frequencies.

# Conclusions

## Required beam parameters

- Normalized emittance → <5x10$^{-6}$ m・rad
- Beam energy after RF gun → ~5 MeV
- RF phases of CC1 and CC2 → -40 deg.< θ < 40 deg.
- Max. accelerating gradients of CC1 and CC2 → 16 and 20 MeV/m

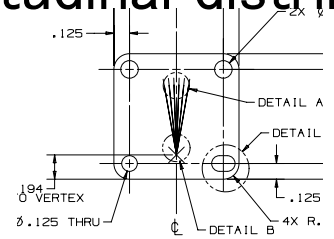
- Reveal micro-bunch at X118 with skew magnet in the chicane
- Varying energy chirp, fundamental frequency can be changed.

## Expected frequencies

- Over 1 THz for de-compression
- Max. 3 THz for over-compression but bandwidths of frequencies are wide due to bad longitudinal distributions

## Next study

- "V" slits



# Thank you for your attention