Summary of Z-slicer studies

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Our goal

Final goal

- To generate narrow band ~1 THz waves with micro-bunch beams.

THz wave

- 0.1 THz – 10 THz (30 um – 3 mm)
- transmitted through clothes, paper and plastics
- non-ionizing

⬇

THz waves are expected to be used in a wide range of scientific fields.

Material science
Communication technology
Homeland security
Medical treatment

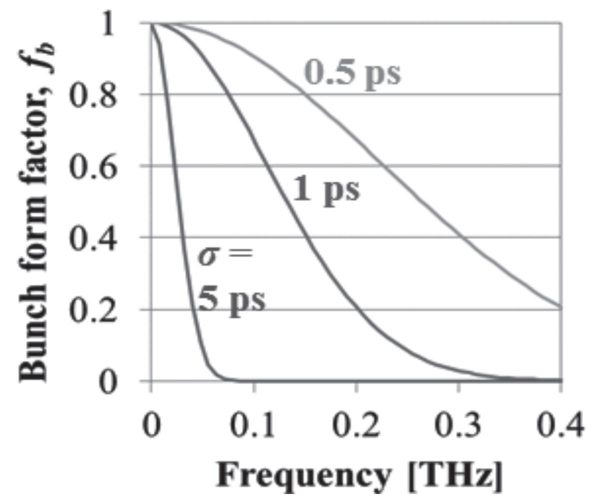
We would like to generate THz waves for applications.

THz radiation

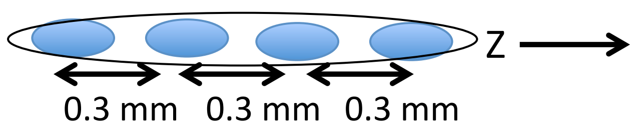
Many THz sources using high energy electron beams have been proposed and developed.

→ CSR, Smith-Purcell radiation and transition radiation…

To generate THz waves, longitudinal bunch length should be compressed to be < 0.3 mm (1 ps)
(→ broadband)



Narrow band THz waves require a short period bunch structure.
→ We use a micro-bunch beam with each spacing of 0.3 mm.

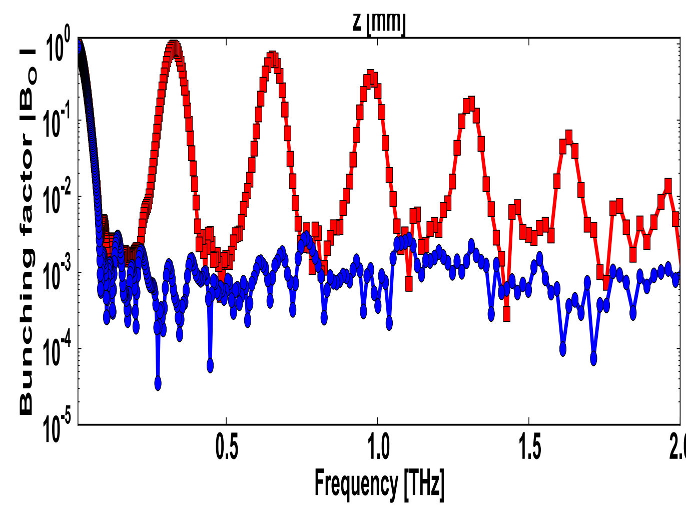


- slits
- chicane

＋ Energy chirped beam

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

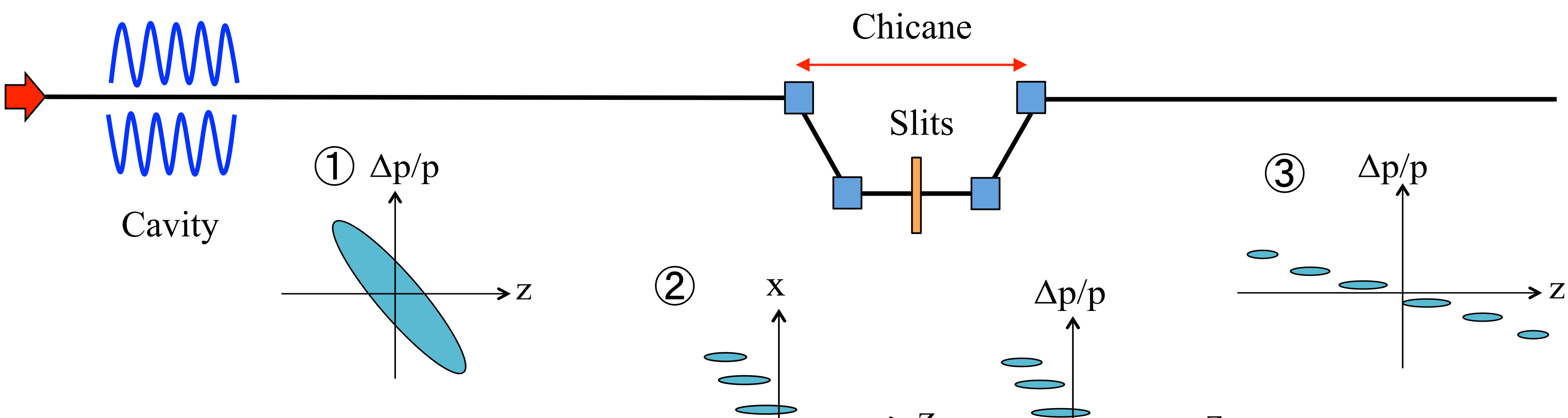
D: slit's spacing 950um, η: dispersion 0.32m
h: energy chirp, *c*: speed of light, *R56*: -0.18



Frequency can be tunable by changing energy chirp.

arXive:1310.5389v1, J. Thangaraj and P.Piot

How to make micro-bunch beams



Energy chirp (h)=slope $h \approx \frac{\sigma_\delta}{\sigma_z}$ (Energy spread) / (Bunch length)

① Beam acceleration with off-crest RF phase in a cavity.
② Beam separation in x (energy) plane using slits in chicane.
③ De-compression to reduce overlaps between micro-bunches.

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

- A large energy chirped beam
- Small beam size $\sigma_x = \sqrt{\varepsilon\beta}$ without dispersion at slits.

→ Flat beam is the optimal beam in this method.

Energy chirped beams at FAST

-35 deg. < RF phase < 35 deg.

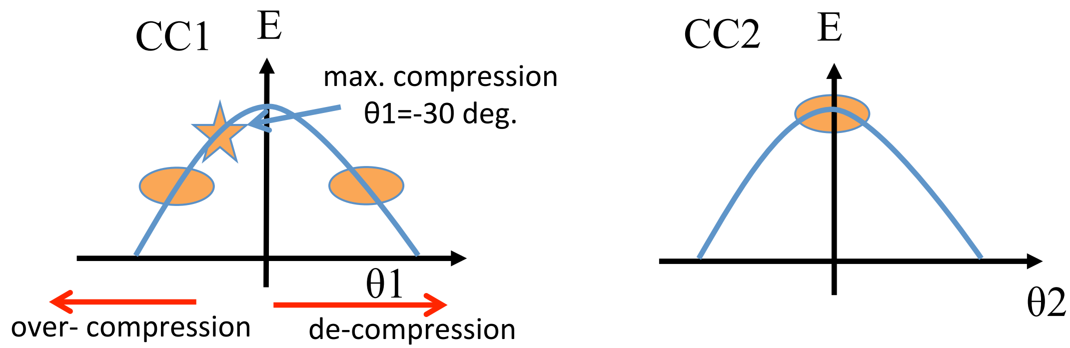
(Assumed no chirp from a RF gun cavity)

1. CC1 off-crest and CC2 on-crest

θ1=±30 deg. and θ2=0 deg.

→ Energy chirp =-,+5.5 m^{-1}

Final energy: ~30 MeV

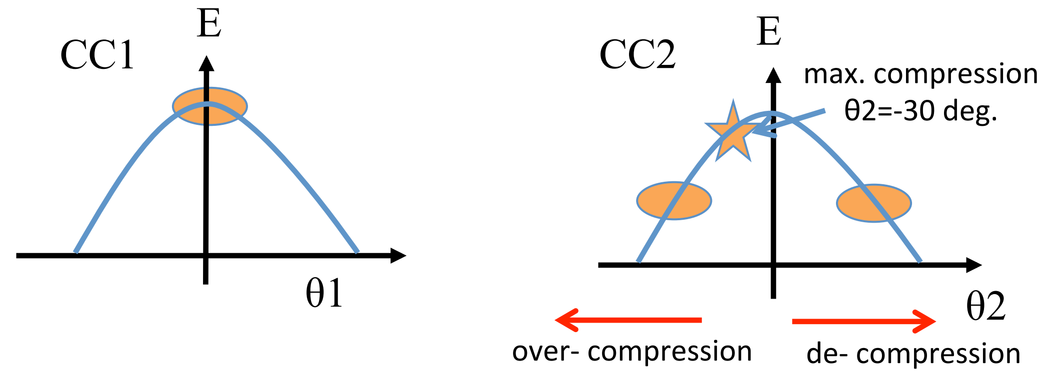


2. CC1 on-crest and CC2 off-crest

θ1=0 deg. and θ2=±30 deg.

→ Energy chirp =-,+5.5 m^{-1}

Final energy: ~30 MeV

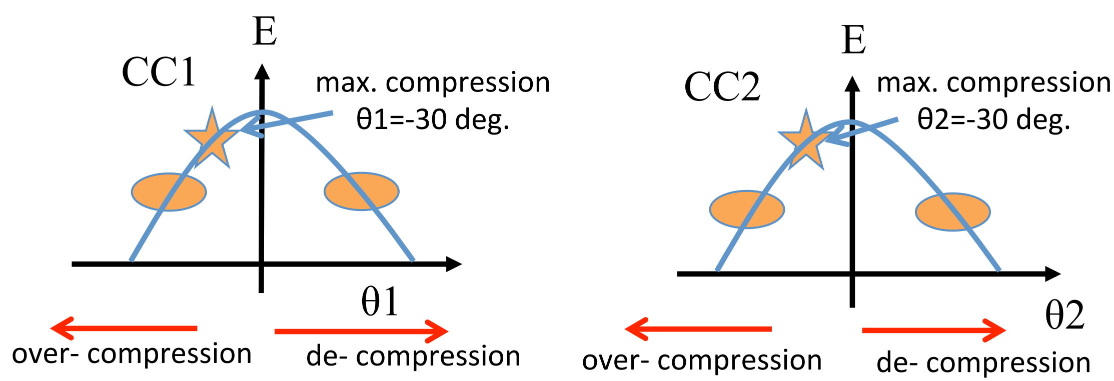


3. CC1 off-crest and CC2 off-crest

θ1=±30 deg. and θ2=±30 deg.

→ Energy chirp =-,+12.6 m^{-1}

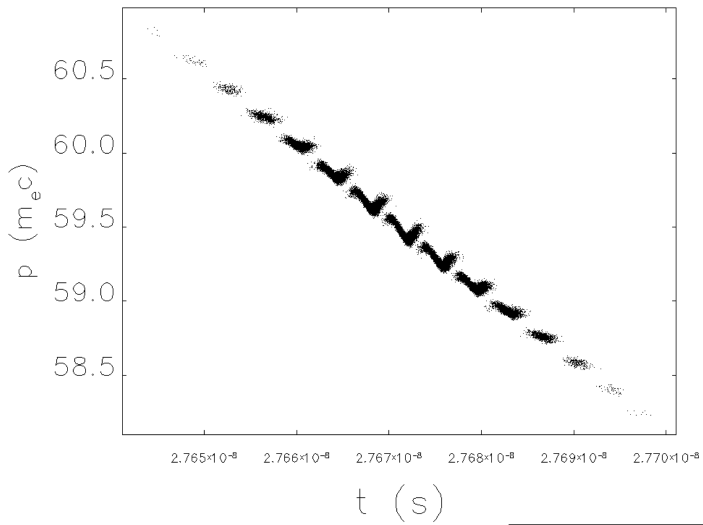
Final energy: ~30 MeV



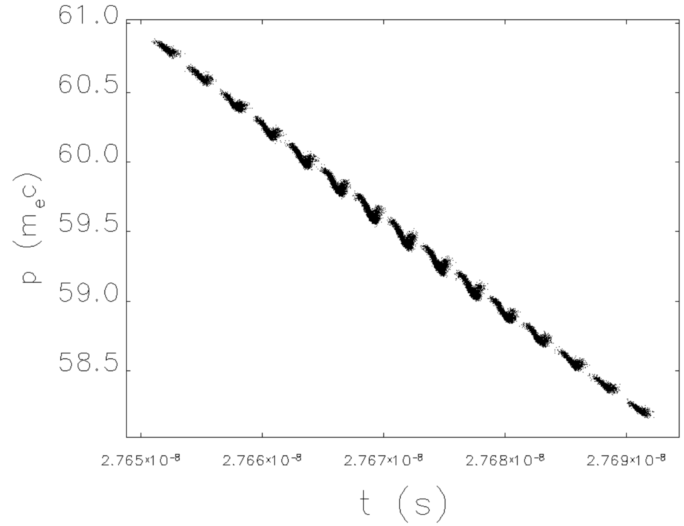
Expected micro-bunch beams and frequencies at FAST

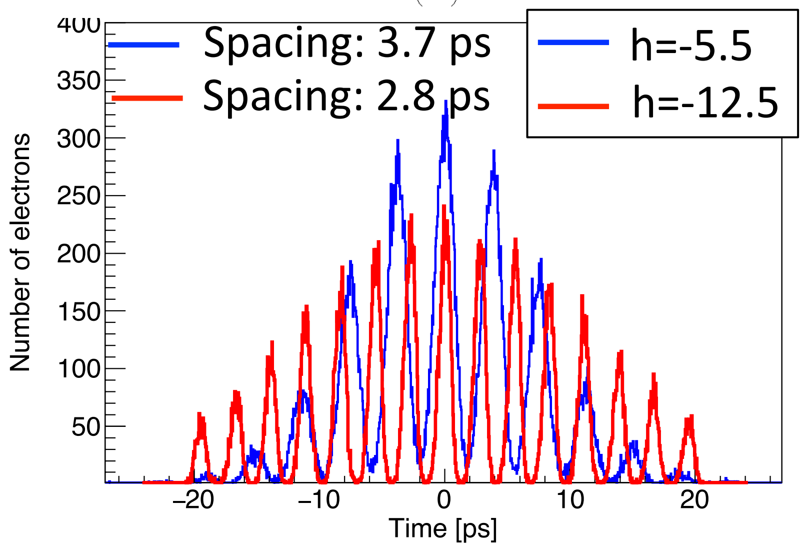
Energy chirp= -5.5 (30 degs.), -12.5 (both off-crest phases :30 degs.)

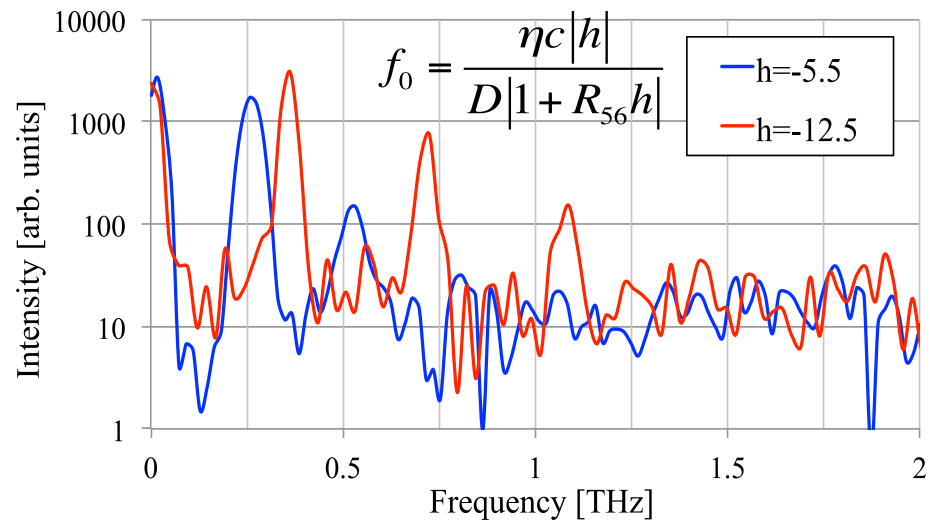
Energy chirp =-5.5 (-30 degs. CC1 or CC2)



Energy chirp =-12.5 (both RF phases: -30 degs.)

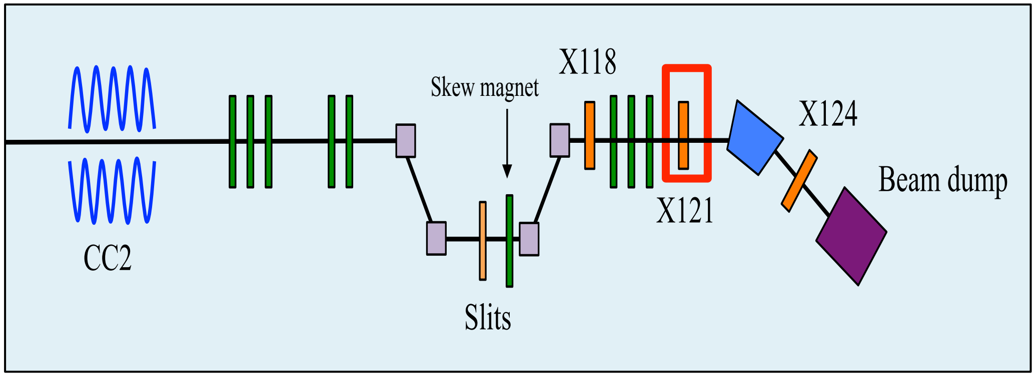


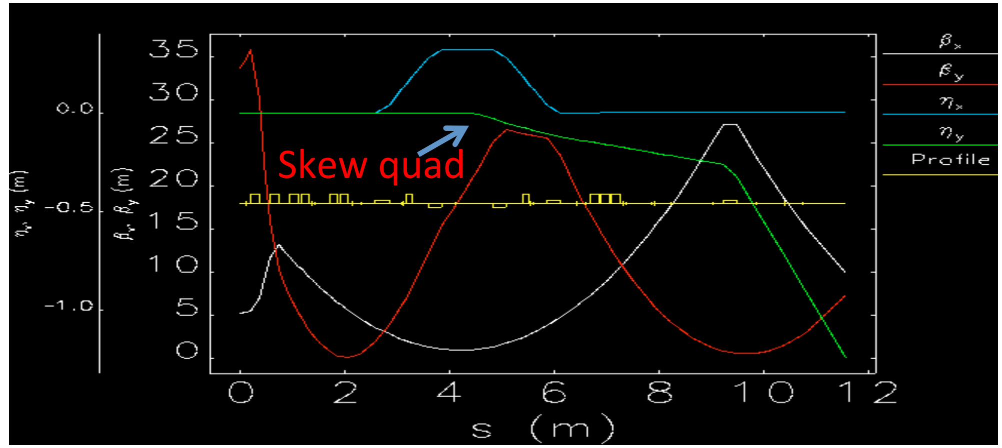




Indirectly micro-bunch beam measurements

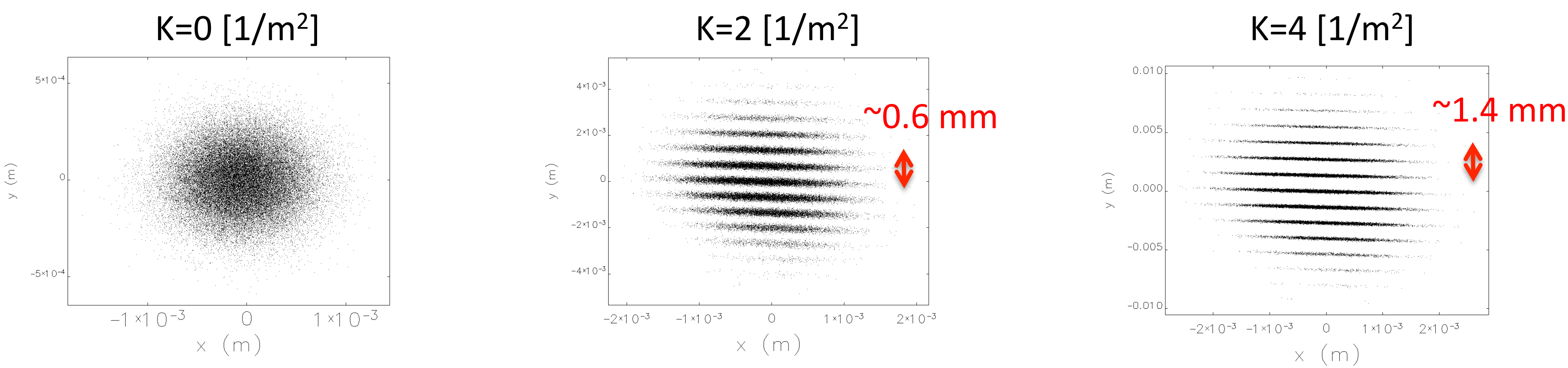
By turning on a skew quad magnet after slits, a dispersion Y after chicane shows energy modulations at the skew quad. → Vertical separated beam





Vertical spacing: $y = (KL)R_{34}D$

K: K-value, D: slit's spacing 950um
L: magnet length, R34: transfer matrix



- Using a skew magnet in chicane, a vertical separated beam can be obtained.

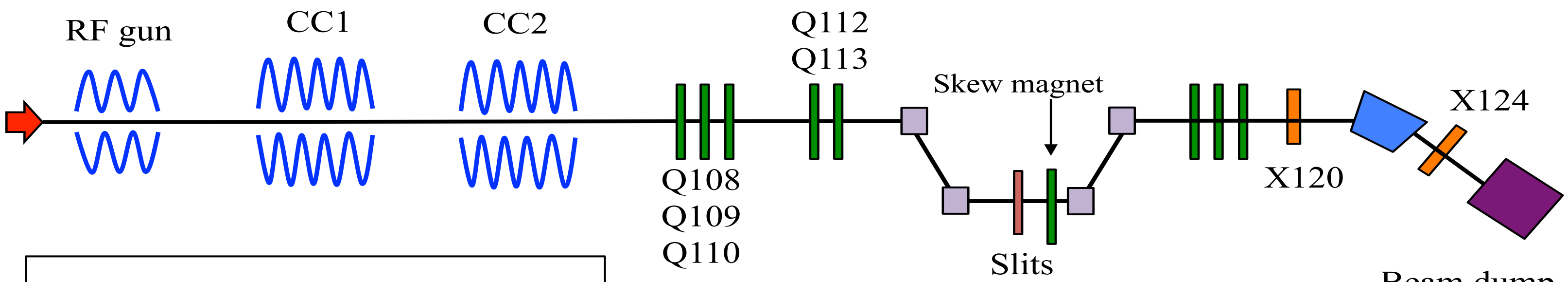
Z-slicer studies

Total shifts

- 9 shifts during 10/20 – 12/1

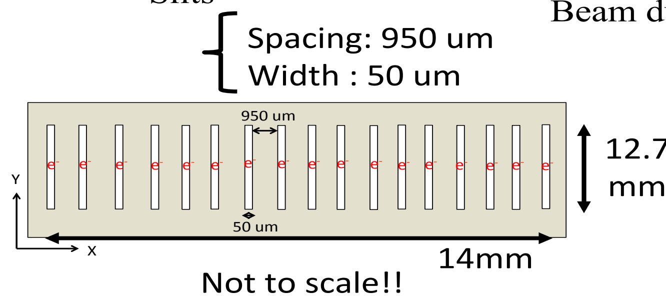
# of Studies	Objectives
1 (10/20)	To pass through electron beams into Chicane ⟶ Achieved
2 (10/28)	To produce micro-bunch beams with CC2 RF phase ⟶ Achieved
3 (10/31)	To produce micro-bunch beams with CC1 RF phase ⟶ Achieved To measure bunch length ⟶ Achieved
4 (11/08)	To measure micro-bunch beams scanning a skew quad using CC1 RF phase ⟶ Achieved
5 (11/10)	To measure micro-bunch beams at X124 because of Y dispersion ⟶ Achieved To measure bunch length ⟶ Achieved
6 (11/16)	To measure micro-bunch beams with a streak camera ⟶ Just preparation To measure bunch length ⟶ Achieved
7 (11/20)	To measure micro-bunch beams with a streak camera ⟶ ???
8 (11/28)	To measure micro-bunch beams with a pyrometer ⟶ ???
9 (12/01)	To measure micro-bunch beams with a pyrometer ⟶ ???

Study procedure for micro-bunch beams



～Beam parameters～

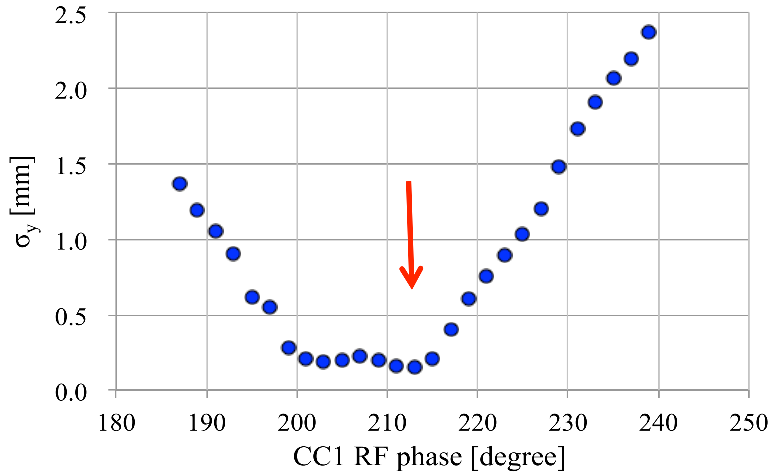
- Final beam Energy: ~30 MeV
- Bunch charge range: 200-260 pC/bunch
- Energy chirp range: from -5.5 to 5.5 m^{-1}
- Normalized emittance X: ~0.6 um



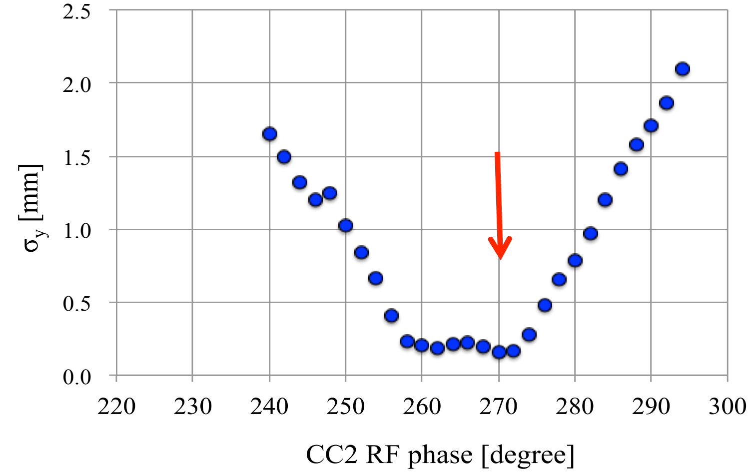
1. Transmitted electron beams to the chicane (beam dump) without particle loss.
2. Made a small beam size in y-plane at X120 (after the chicane) due to an increase of beam size Y when a skew quad is turned on. (By turning on skew magnet in the chicane, we can extract information of energy modulation.)
3. Inserted the slits at the middle of the chicane.
4. Scanned RF phases of CC1 or CC2.
5. Measured micro-bunch beams with either a skew quad, a pyrometer or a streak camera.

Minimum energy spread

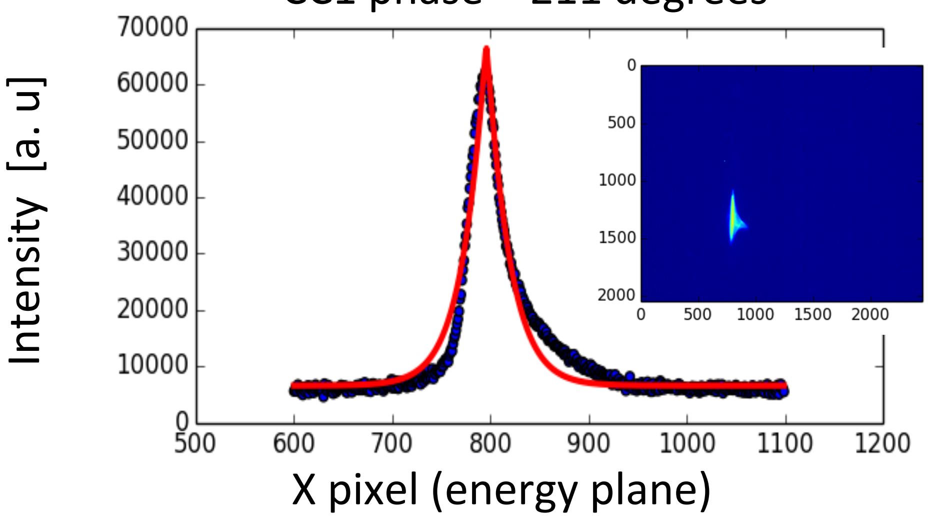
CC1 phase vs beam size



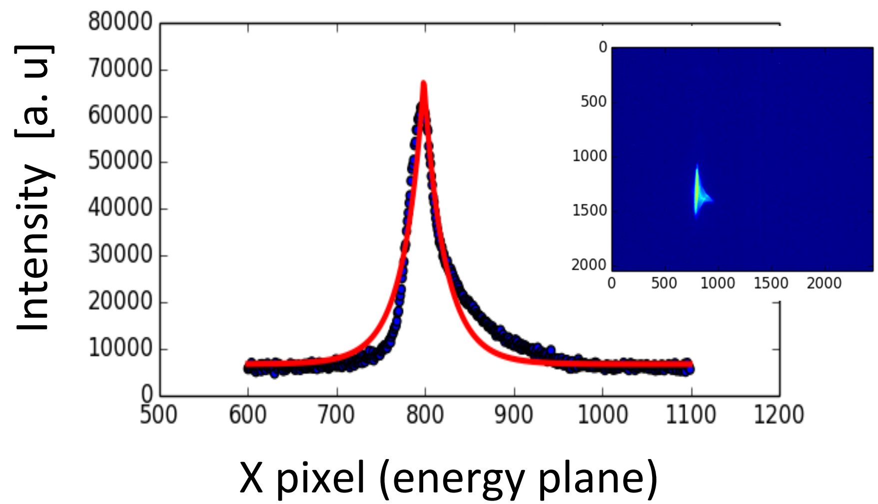
CC2 phase vs beam size



CC1 phase = 211 degrees



CC2 phase = 270 degrees



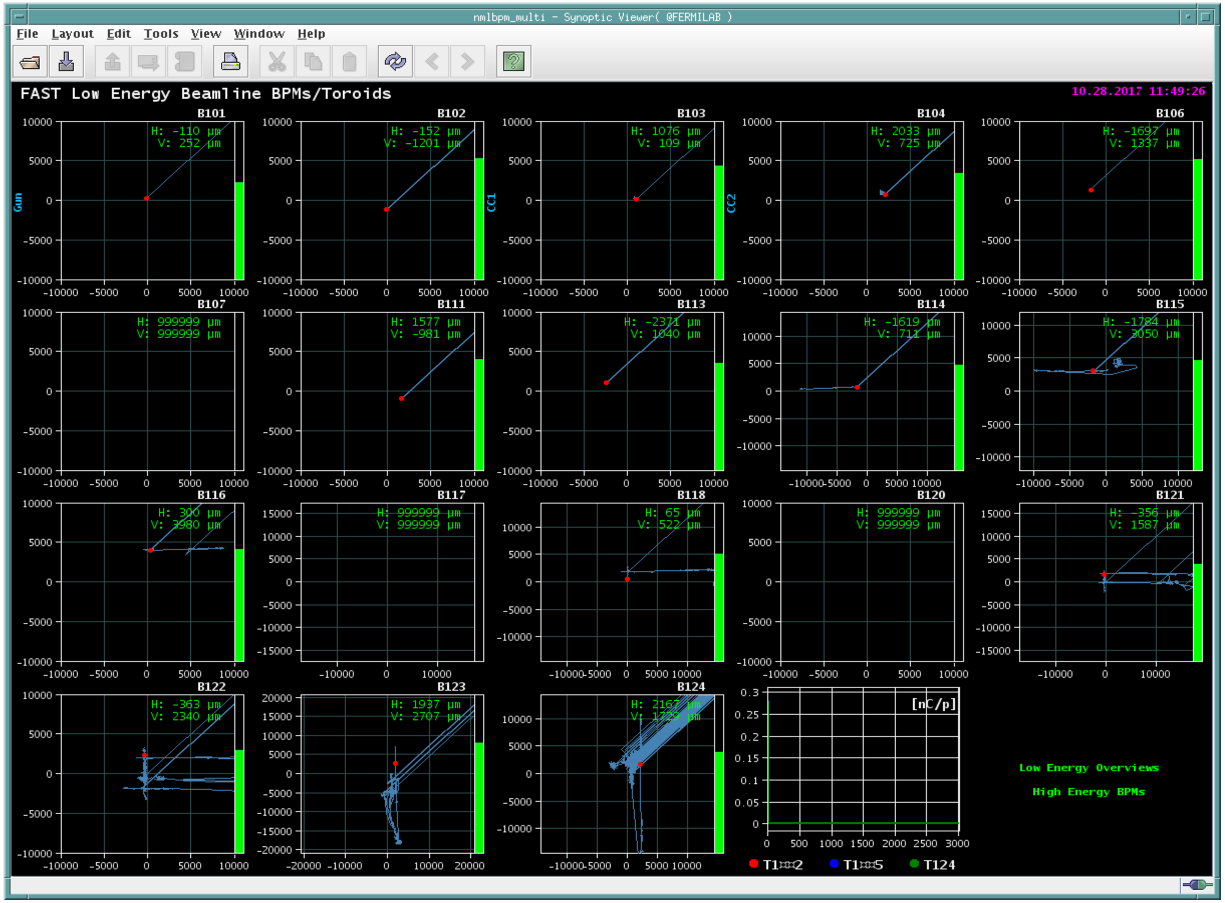
Minimum Energy spread: ~5.5×10^{-4}.

Minimum Energy spread: ~5.4×10^{-4}.

Electron beam passing through the chicane (Study 1)

We transmitted electron beams to the low energy beam dump

Chicane currents for 30 MeV beams at 200 pC
(dipole 1, dipole 2, dipole 3, dipole 4) = (-3.734 A, 3.677 A, 3.684 A, -3.734 A)



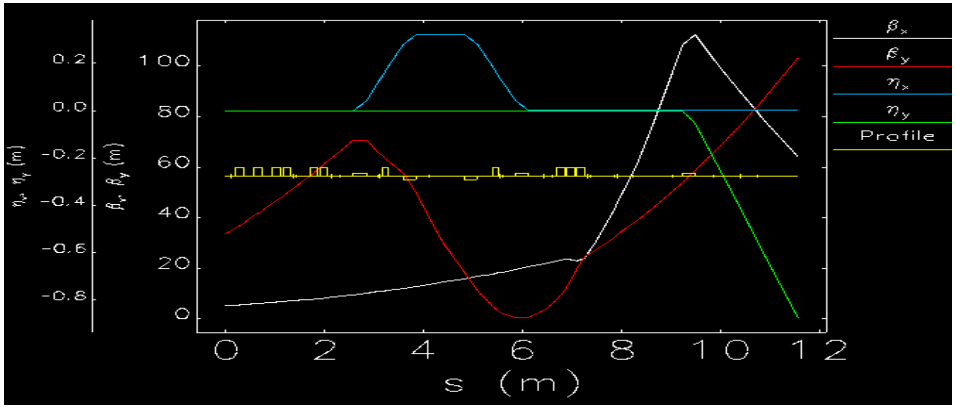
Electron beams are centered in the beamline.

→ ~100 % transmission to the beam dump (we checked beam currents)

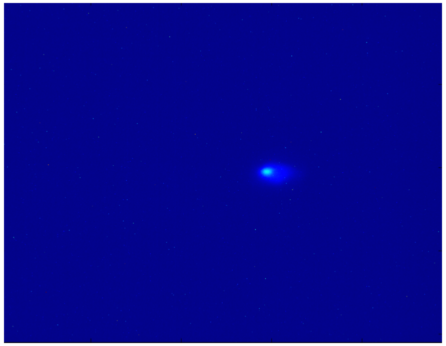
A small beam size in y-plane at X120 (Study 2, 3)

Quads turned OFF before chicane

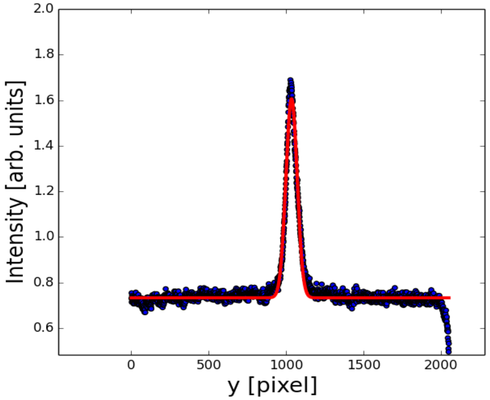
Beam optics from 107 to beam dump



Beam distribution at X120

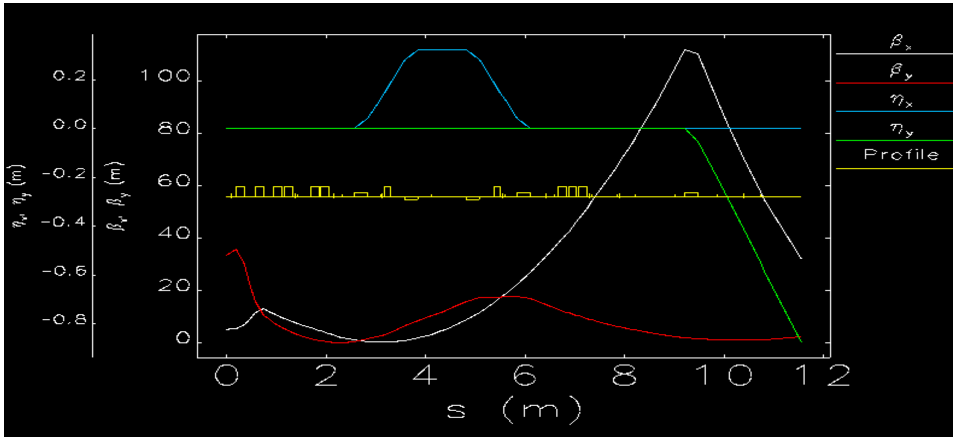


σy= 0.34 mm

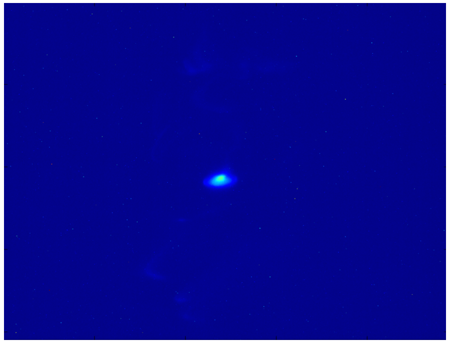


Quads turned ON before chicane : Q108 (-1.115 A), Q109 (1.115 A), Q113 (0.179 A)

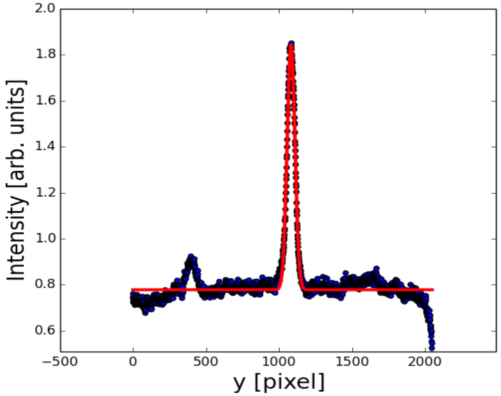
Beam optics from 107 to beam dump



Beam distribution at X120



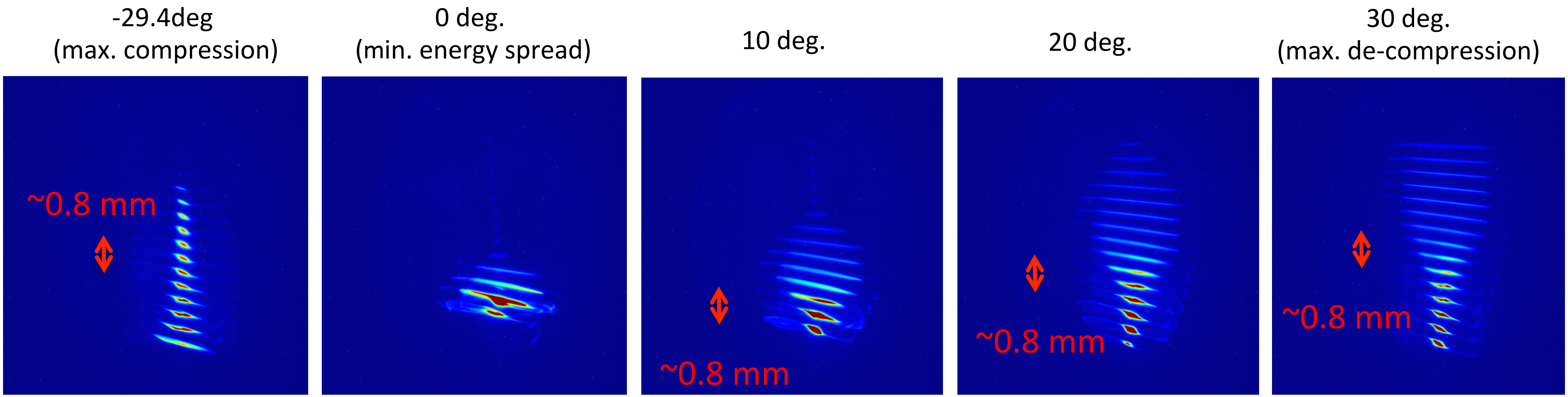
σy= 0.25 mm



→ A small beam size in y-plane was made at X120 (after the chicane)

Micro-bunch beams (slits IN and RF phase scan) (Study 4)

・RF phase scan (-29.4, 0, 10, 20, 30 deg.)
・Skew quad Q115 ON (0.905 A) to check micro-bunch beams



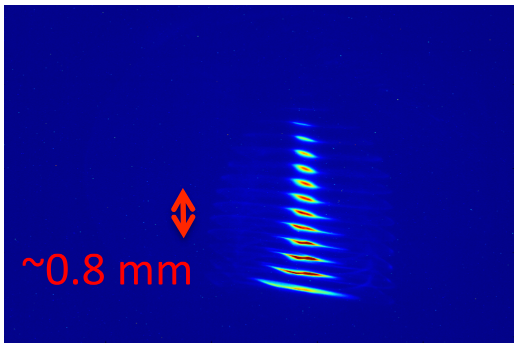
Separations in y-direction in turning on skew quad → Micro-bunch beams
Spacing is ~0.8 mm at each phase (almost independent of RF phases)

Spacing in y-plane: $y = (KL)R_{34}D$

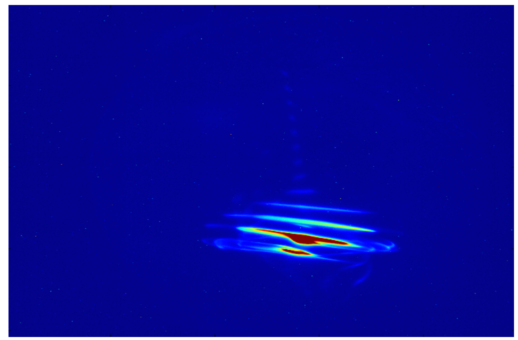
Comparisons of measurements and simulations (Study 4)

Measurements (upper) and Simulations (lower)

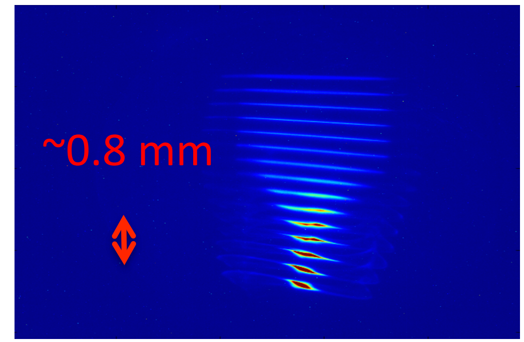
-29.4 deg. (max. compression)



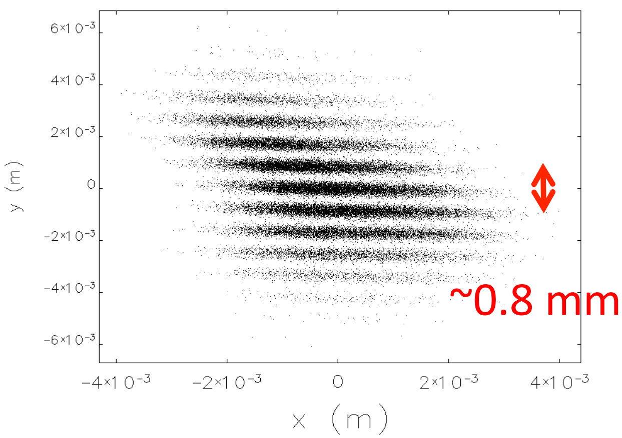
0 deg. (min. energy spread)



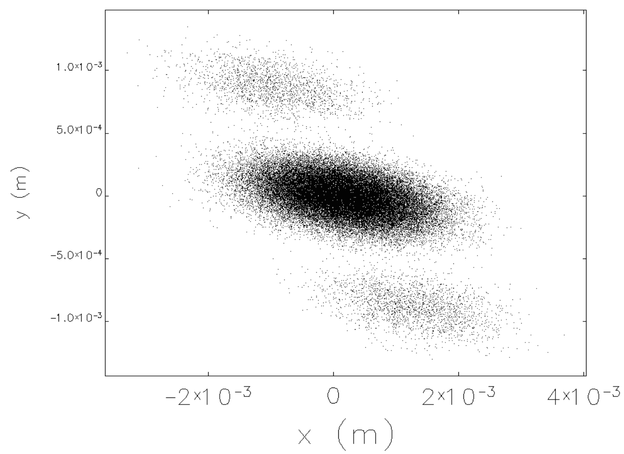
30 deg. (max. de-compression)



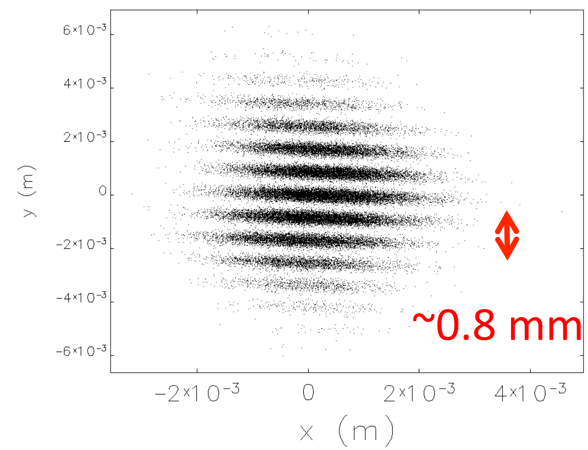
-29.4deg



0 deg. (on-crest)



30 deg.



Simulations were done with Elegant code.

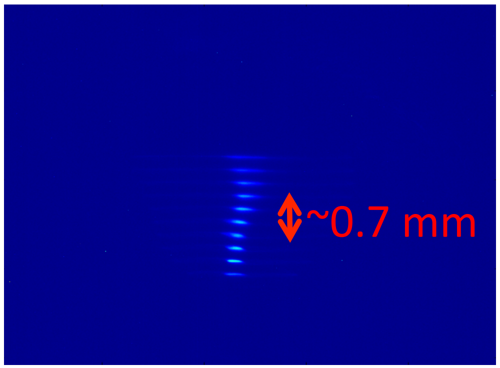
Measured distributions are in reasonable agreement with simulations by Elegant.

Beam distributions for different skew quad currents (Study 4)

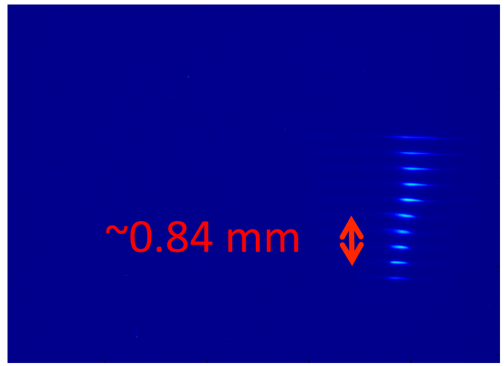
- Scanned skew quad current

<u>CC1 phase: 30degs.</u> (CC2 phase: min. energy spread)

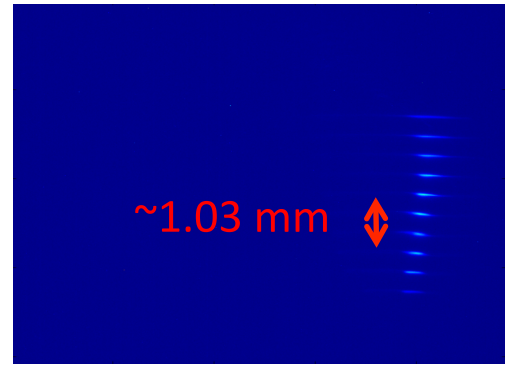
Q115: 0.75 A



Q115: 1.0 A

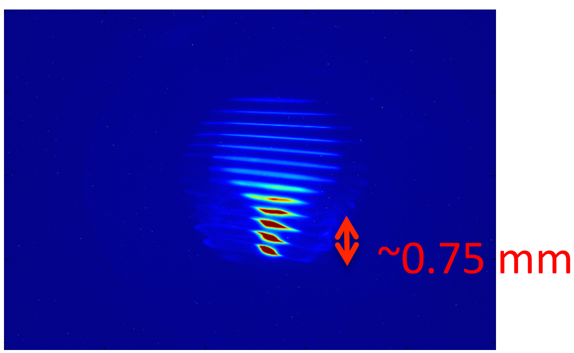


Q115: 1.25 A

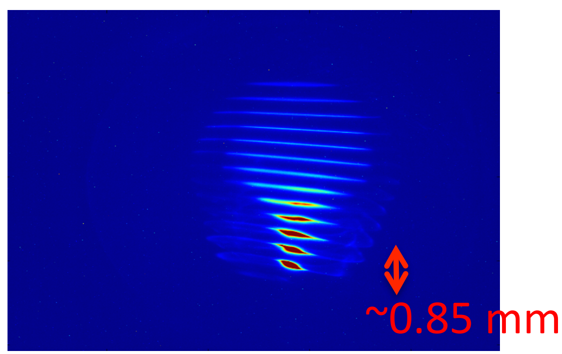


<u>CC2 phase: 30degs.</u> (CC1 phase: min. energy spread)

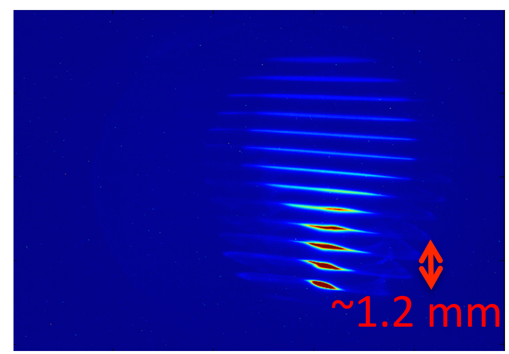
Q115: 0.8 A



Q115: 1.0 A



Q115: 1.2 A

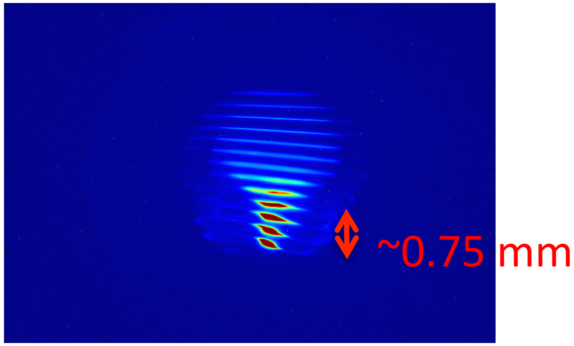


Greater separations with an increase of skew quad current.

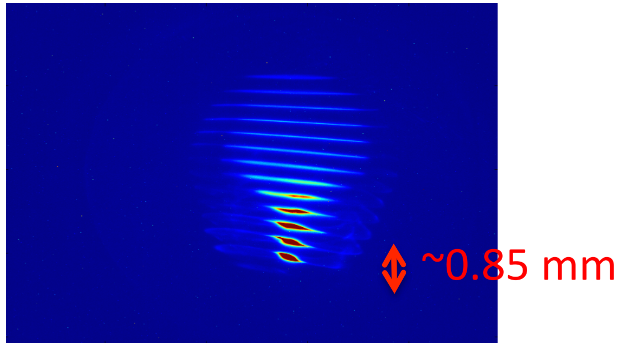
Comparisons of measurements and simulations (Study 4)

- Beam distributions measured at X120

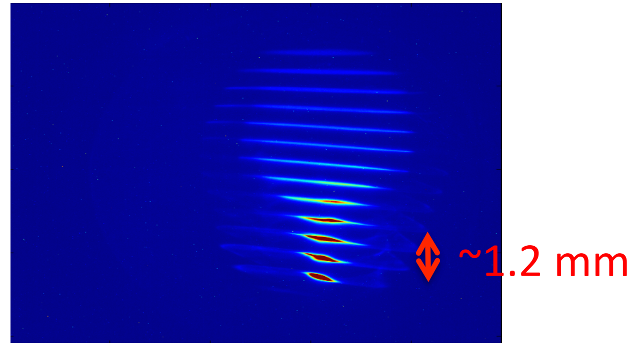
Q115: 0.8 A



Q115: 1.0 A

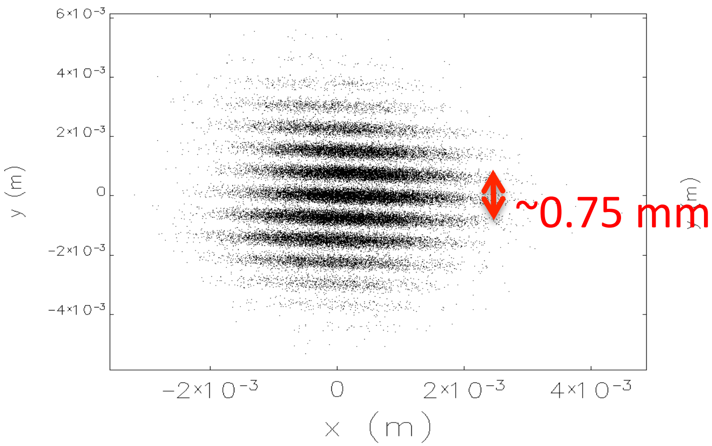


Q115: 1.2 A

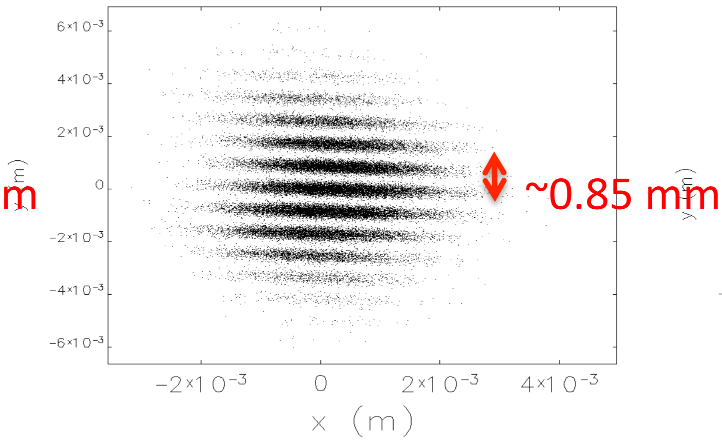


Elegant simulations

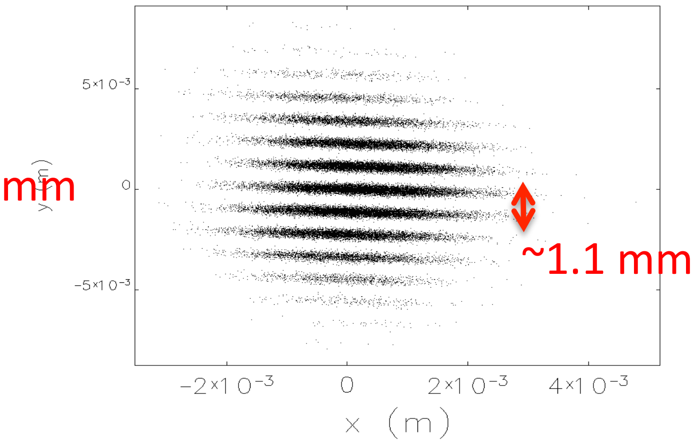
K=2.7 [1/m²]



K=3 [1/m²]

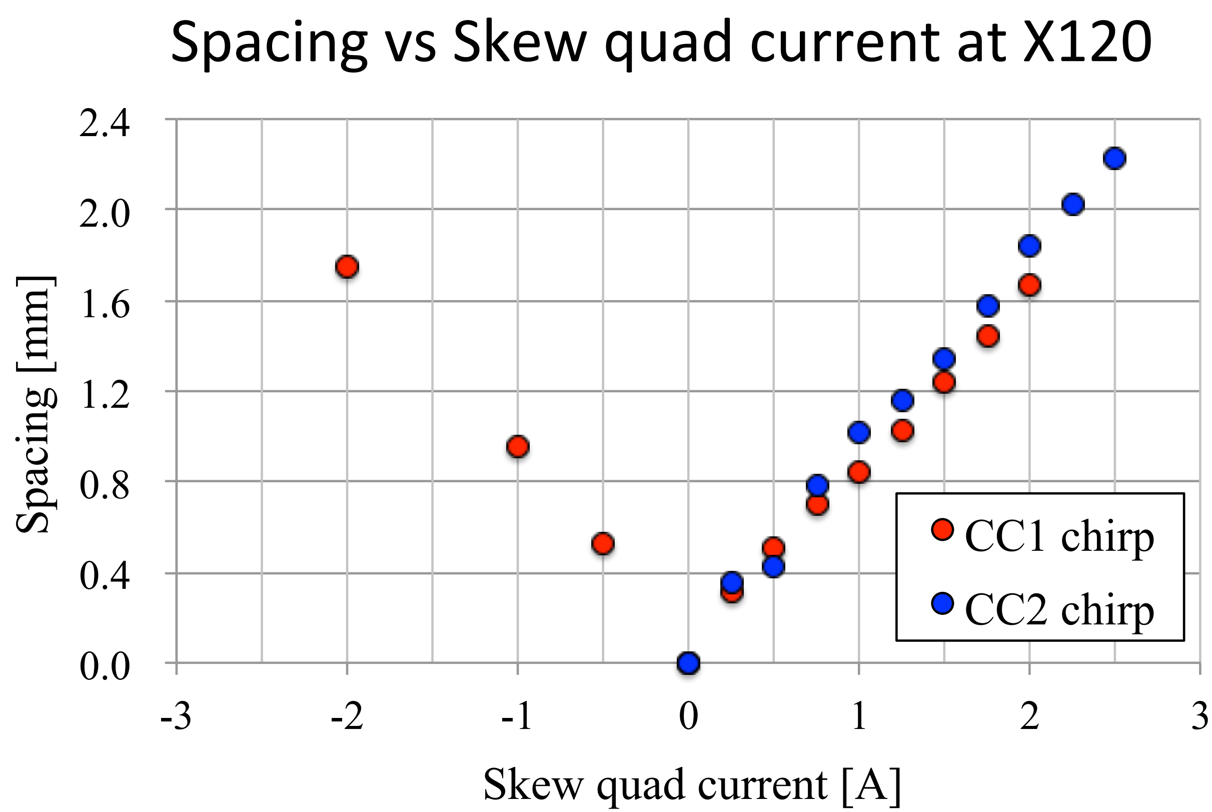


K=4 [1/m²]



Measured distributions are in reasonable agreement with simulations.

Vertical spacing depending on skew quad current (Study 4)

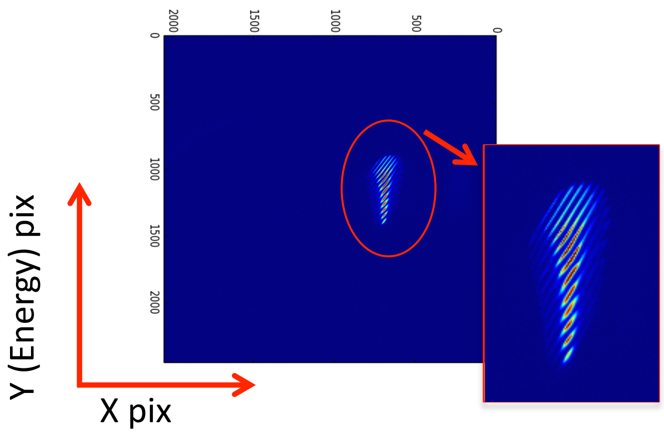


- Vertical spacing at X120 is in proportional to skew quad current.
- There is not big difference between CC1 chirp and CC2 chirp.

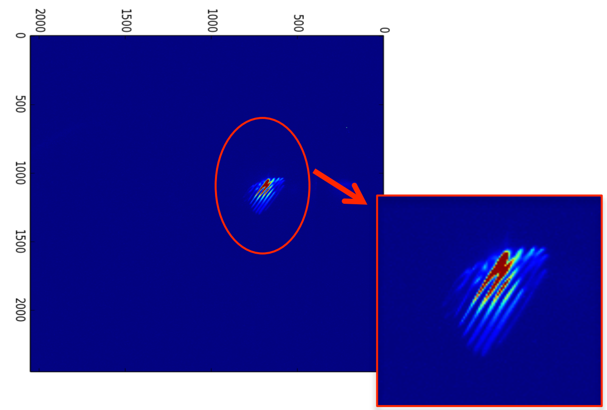
Indirectly measurements of micro-bunch beam at X124 (Study 5)

When electron beam is focused on X124 (before beam dump), a beam separation in y-plane occurs. (Orientation needs to be better understood, possibility optics differences.)

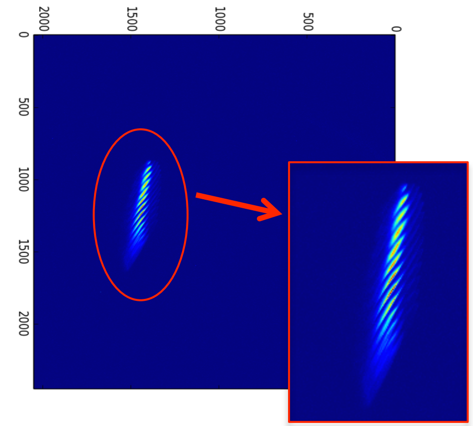
-30 deg.
(max. compression)



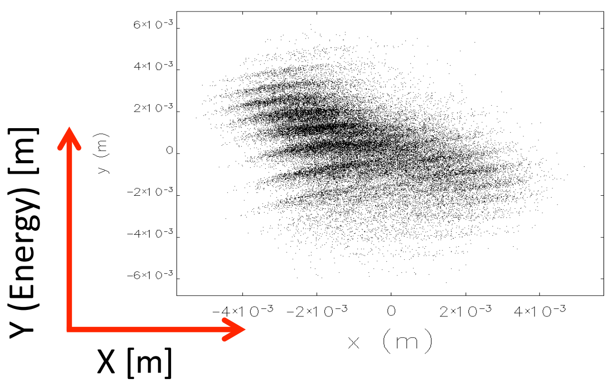
0 deg.
(min. energy spread)



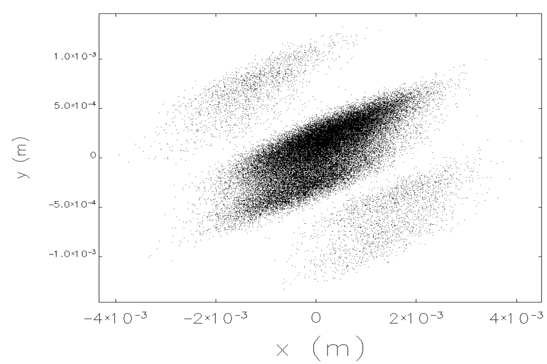
+30 deg.
(de-compression)



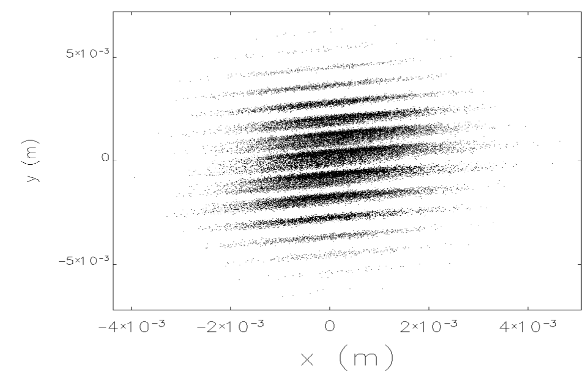
-30 deg. (simulation)



On-crest(simulation)



+30 deg.(simulation)



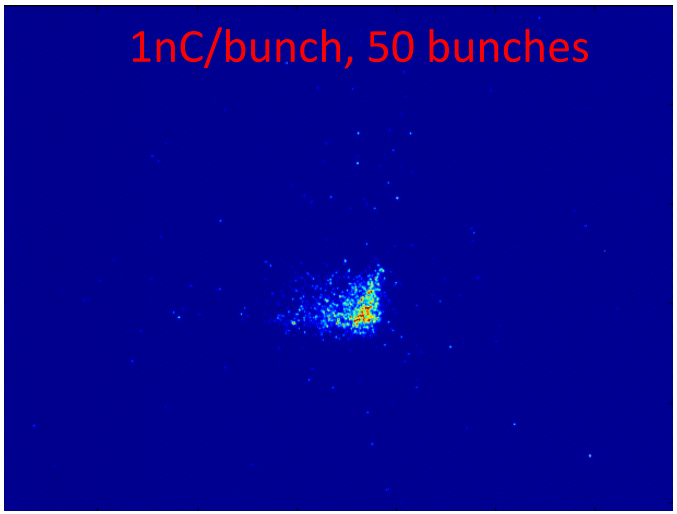
Measured distributions are in reasonable agreement with simulations.

Micro-bunch measurements with a streak camera (study 7)

Signals measured with a streak camera at X121

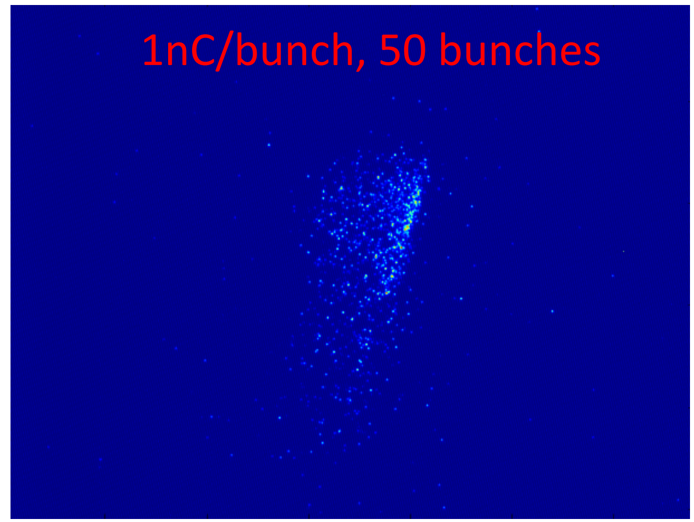
-30 deg. w/o slits
(max. compression)

Z



+40 deg. w/o slits
(de-compression)

Z



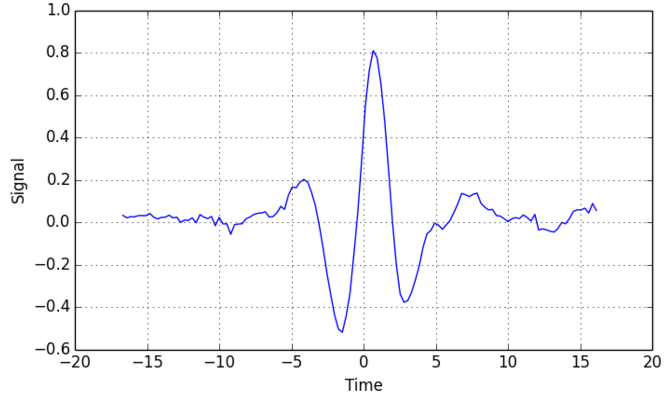
- At 50 nC w/o slits, signals were detected using a streak camera.
  But with slits, signals were not detected due to low transmission of <5%.
  It is also difficult to increase charge due to radiation level.

Micro-bunch beam measurements with a pyrometer (Study 8, 9)

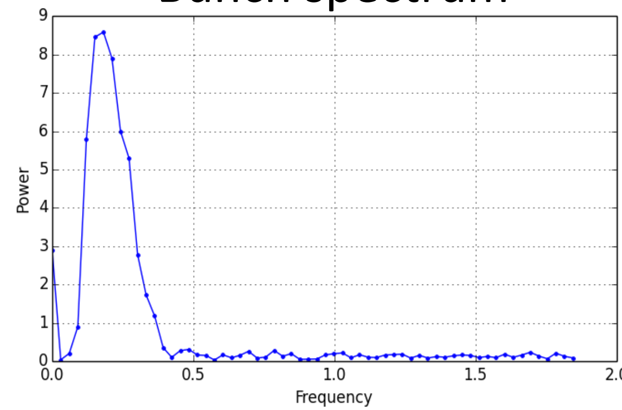
- Signals with a pyrometer at X121

Max. compression (-30 degs.) w/o slits, 50 nC

Auto correlation function

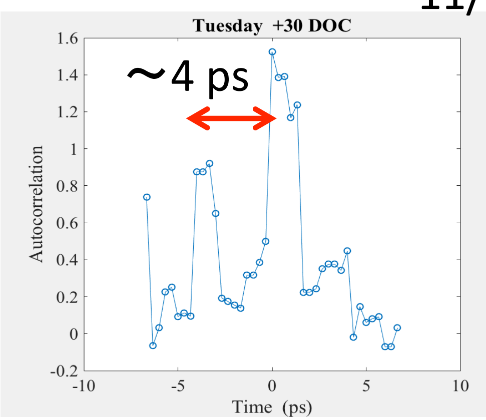


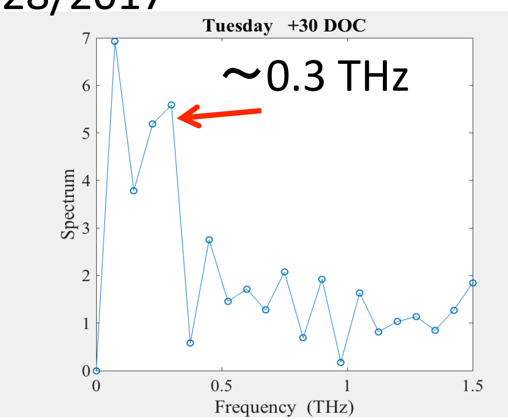
Bunch spectrum



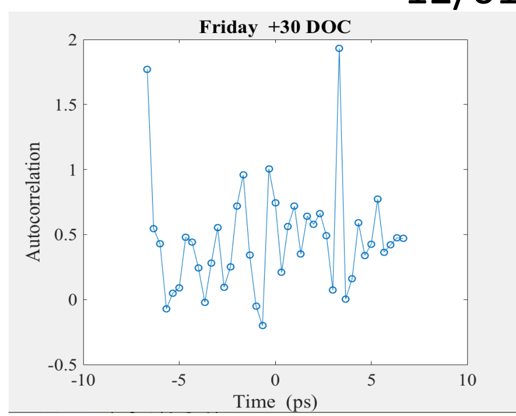
Max. de-compression (30 degs.) with slits, 50 nC

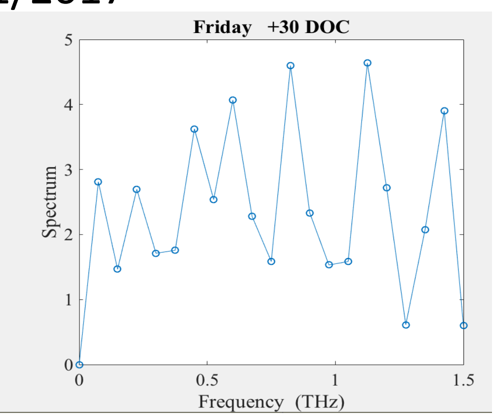
11/28/2017





12/01/2017





- Signals were measured at the almost same beam conditions in two shifts, but there was no reproducibility. (Bottom plots may be bremsstrahlung from slits)

Ongoing analysis

- Extraction of bunch length from transverse beam size vs RF phase.

- Detailed comparison of vertical images at X120 and X124 of theory, simulations with measurements (separation, width of each dark stripe)

- Geant4 simulations for beam transmission through slits with different transverse distributions from changes in the chirp.

- Expected improvements with flat beam optics.

Conclusions

Achieved

- Micro-bunch beams using slits in the chicane were produced.
- Images measured at X120 are in reasonable agreement with simulations.
- Images measured at X124 are in reasonable agreement with simulations.
- At max-compression without slits, THz radiations were detected using the pyrometer at 50 nC.

Failed

- But at max-decompression with slits, radiations could not be detected using a pyrometer (there was no reproducibility).
  → (Not enough sensitivity of the pyrometer)
- Streak camera could not detect micro-bunch signals due to low charge after slits.

Next

We need to measure the radiation from a micro-bunched beam directly.

- Measurements using a bolometer which is more sensitive than pyrometer. Observed at A0 with similar slits at 15 pC/bunch after 3% transmission
  Piot et al. Appl. Phys. Letter. 98, 261501 (2011)

- Measurements using a pyrometer.
  → Is it possible to increase radiation shields around chicane after slits?

- Measurements using low emittance beam (flat beam), higher energy beam (~50 MeV).

- Studies with both cavity off-crest phases (CC1 & CC2: -35 degs.)
  → Higher frequency (~1 THz)

Thank you for your attention

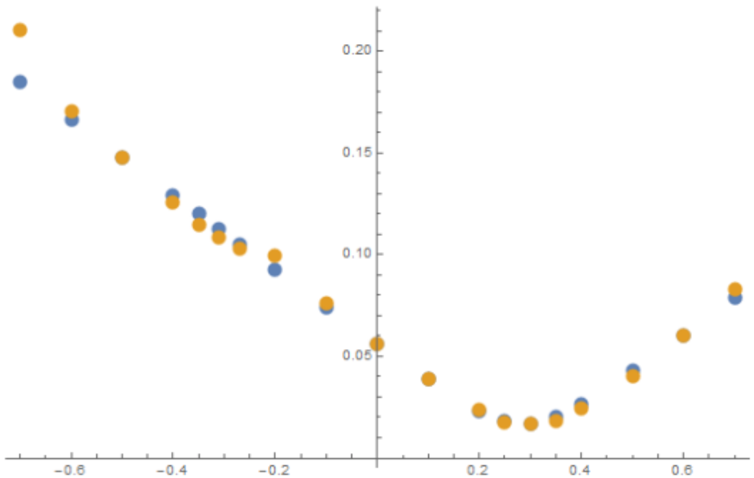
Beam emittance

E	$\epsilon_{x\,geometric}$	$\epsilon_{y\,geometric}$	$\beta_{x\,Q108}$	$\beta_{y\,Q108}$	$\alpha_{x\,Q108}$	$\alpha_{y\,Q108}$	$\epsilon_{x\,norm}$	$\epsilon_{y\,norm}$
32.3 MeV	(9.77×10^{-7}) cm	(5.42×10^{-7}) cm	557. cm	3710. cm	-0.587	-6.13	0.618 μm	0.342 μm

Check

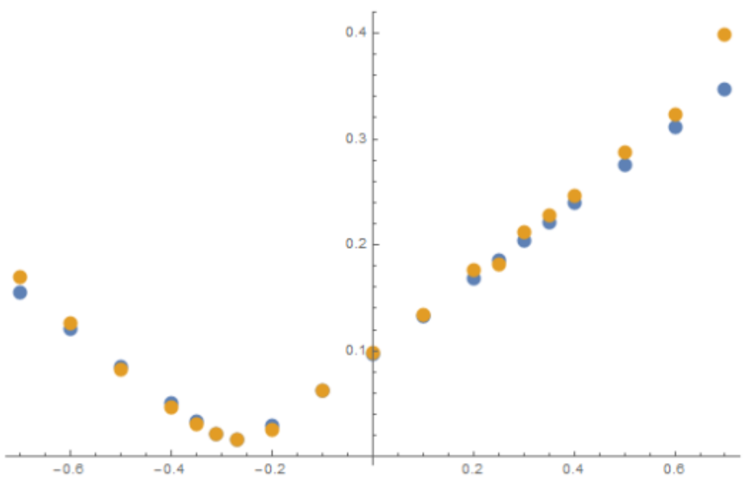
In[427]:= `ListPlot[{Transpose[{expI, √Transpose[modM /. sol[[2]]][[1]]}], Transpose[{expI, √Transpose[expM][[1]]}]}, PlotRange → All]`

Out[427]=

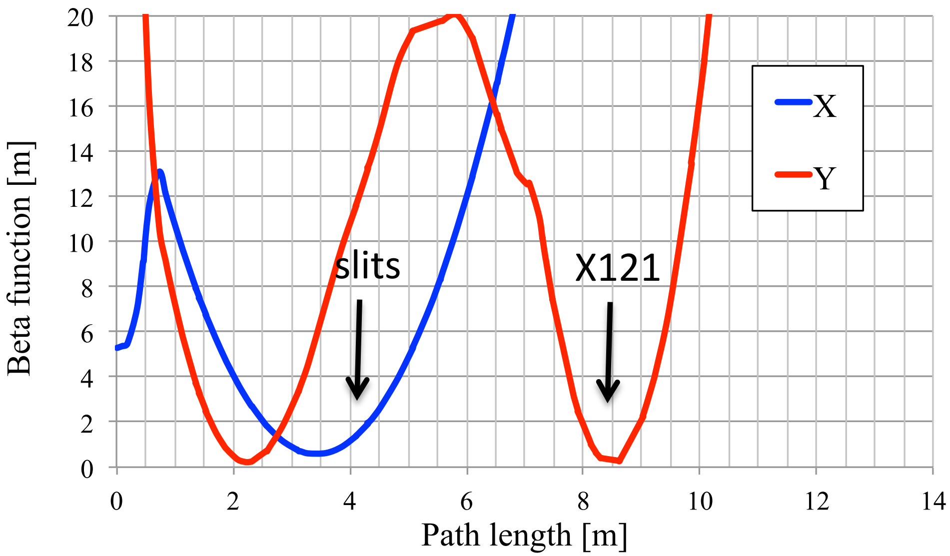


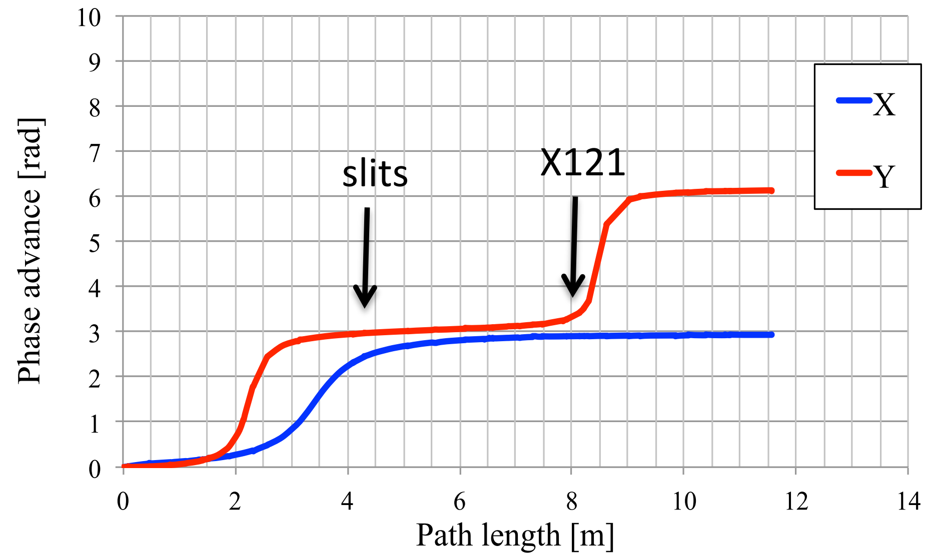
In[428]:= `ListPlot[{Transpose[{expI, √Transpose[modM /. sol[[2]]][[2]]}], Transpose[{expI, √Transpose[expM][[2]]}]}]`

Out[428]=

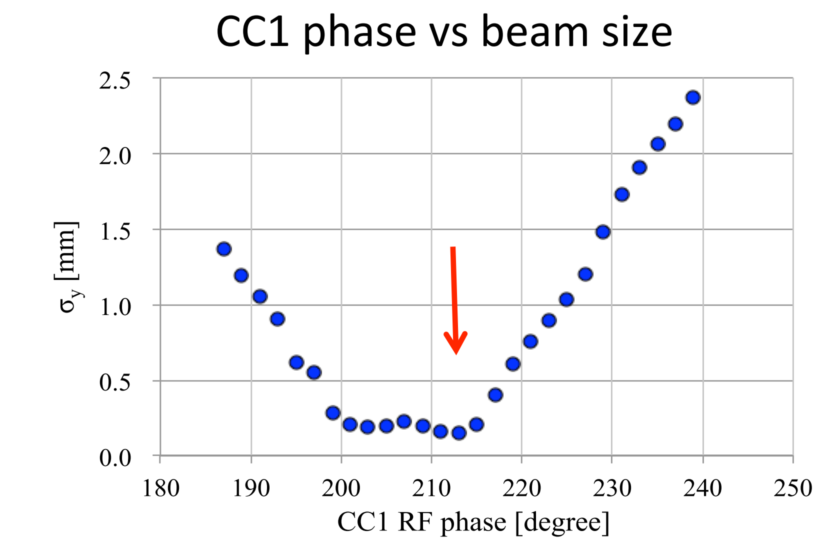


Beta functions and phase advances

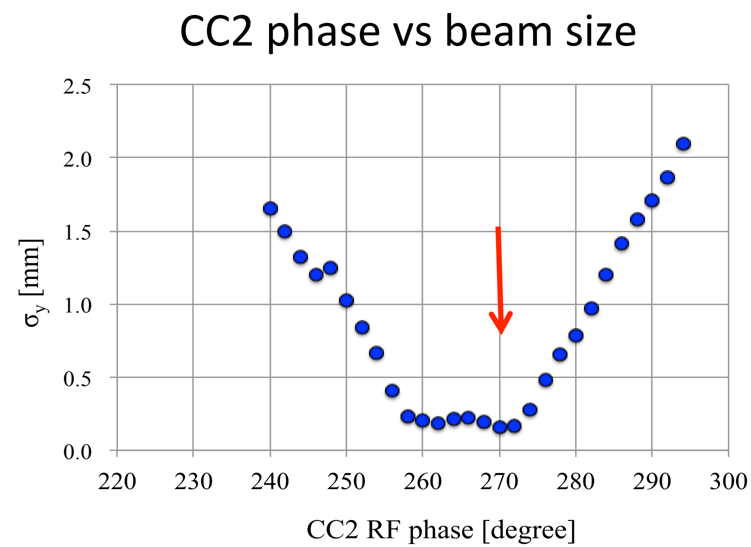




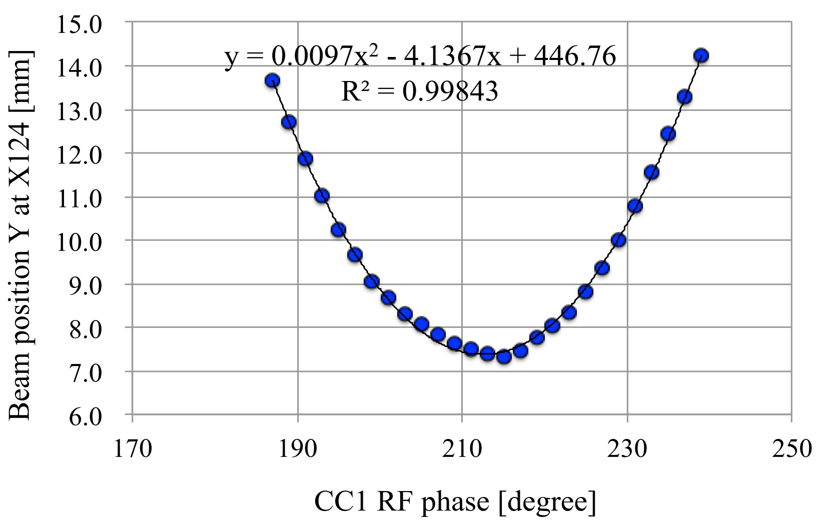
Min. energy spread and on-crest phases



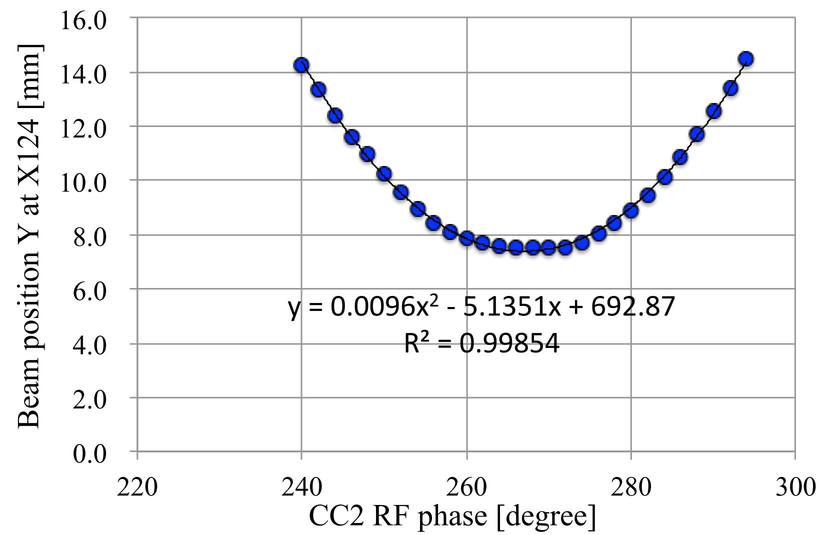
CC1 phase = 211 degrees (min. energy spread)



CC2 phase = 270 degrees (min. energy spread)



On-crest CC1 phase = 213 degrees



On-crest CC2 phase: =267degs.