Resonances and envelope instability in high intensity linear accelerators

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Challenges for high intensity accelerators

- High intensity linear accelerators are designed and constructed to accelerate high intensity beams.
- Stringent beam loss requirement is needed for a hands-on maintenance : < 1W/m.

- Beam halo is the major source of the beam loss.
- Significant studies have been done to better understand the beam halo formation from space charge effects.

Resonances in linear accelerators

- Resonances come from the nonlinear terms of the potential function.
- For high intensity linac beams, the potential from the beam's self field is the source of nonlinear terms :

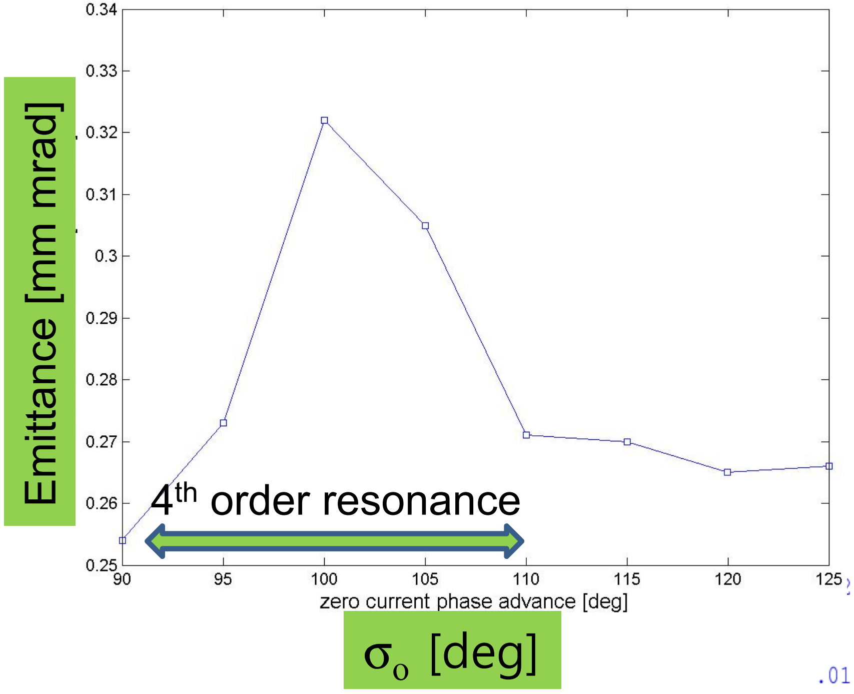
  $V = V_{lattice} + V_{beam}$

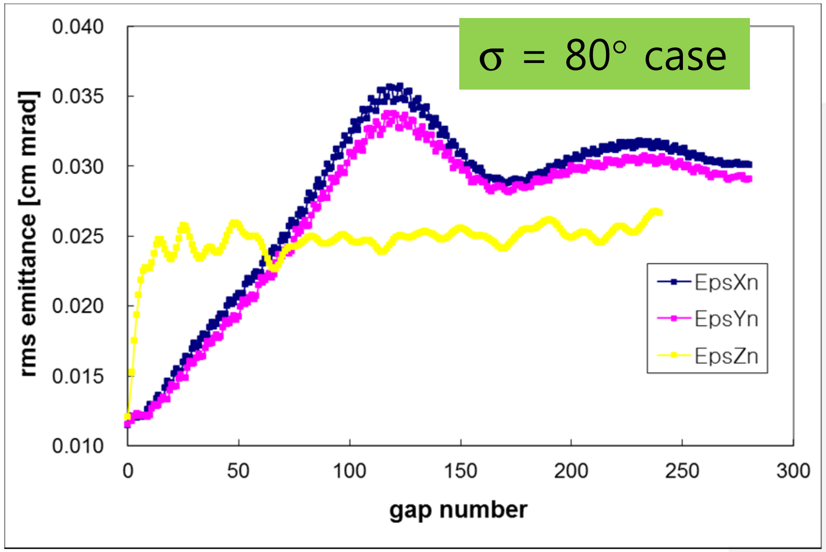
- The space charge $4\sigma = 360^{\circ}$ fourth order resonance was found for high intensity linear accelerators (D. Jeon et al, PRST-AB 2009).
- It was verified through the experiment using the heavy ion linac at GSI, Germany (L. Groening et al, PRL 2009).
- It was verified through the experiment using the SNS linac (D. Jeon, PRAB 2016).
- The space charge $6\sigma = 720^{\circ}$ sixth order resonance was found for high intensity linear accelerators (D. Jeon et al, PRL 2015).

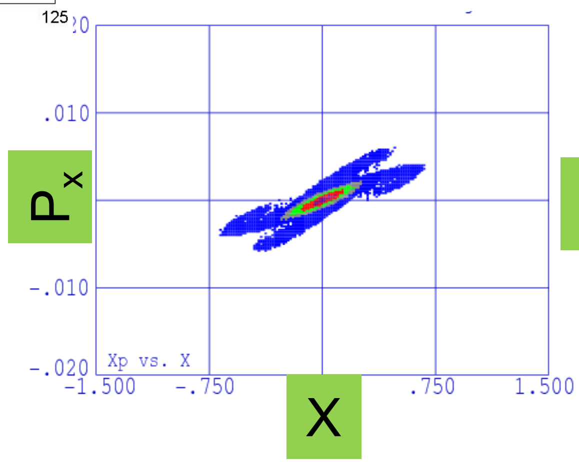
The 4th order resonance
for high intensity linear accelerators

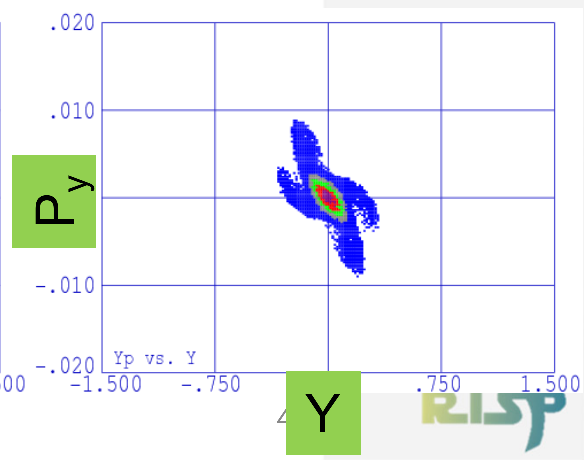
D. Jeon et al, PRST-AB **12**, 054204 (2009)

The resonance was predicted for 90° – $\Delta\sigma \leq \sigma \leq$ 90°, where σ is the depressed phase advance per cell.





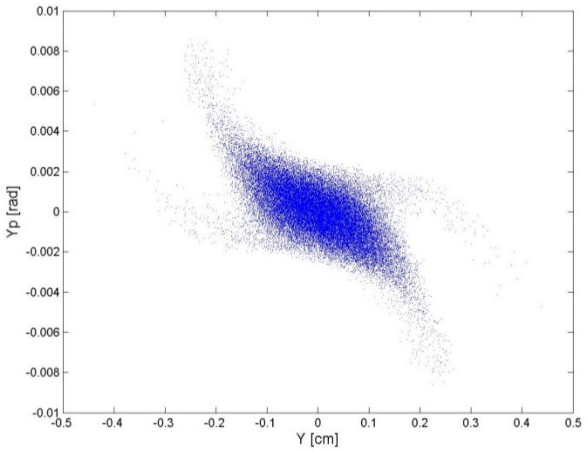




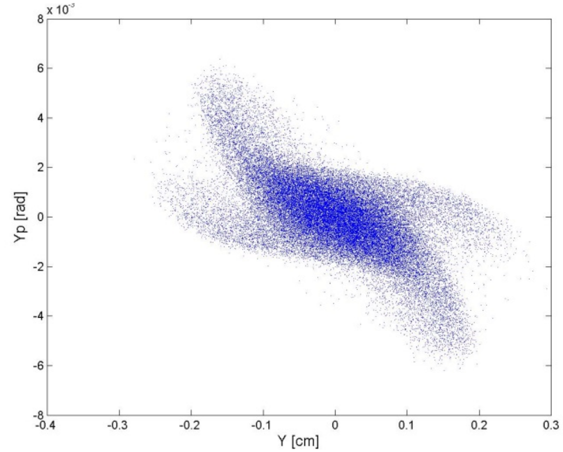
The 4^{th} order resonance

Confirmation of the resonance

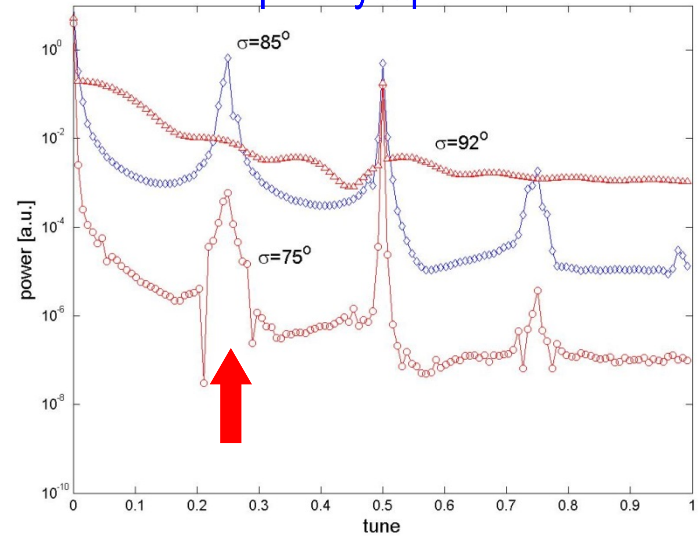
Cross from below



Cross from above



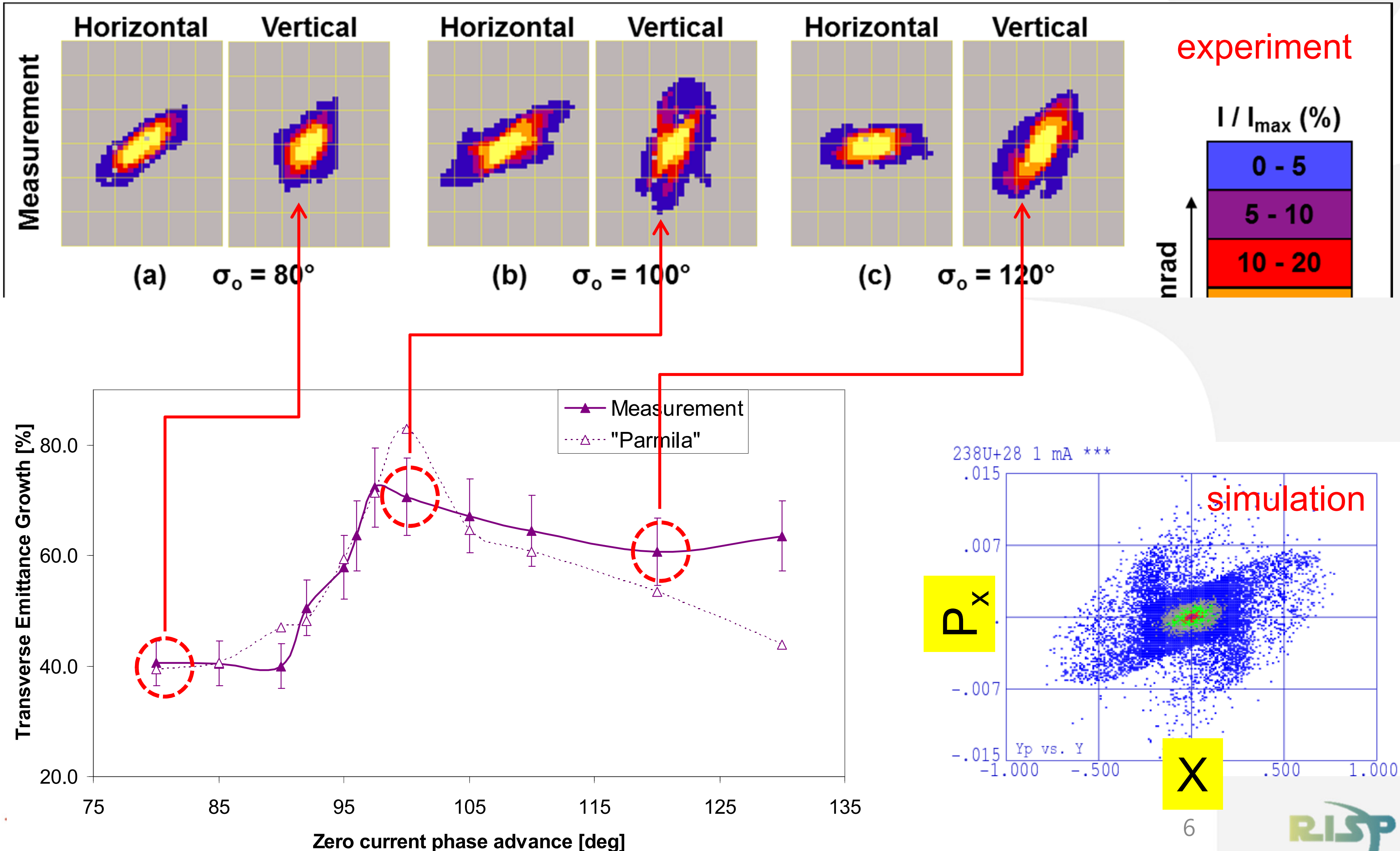
Frequency Spectrum



- Linac resonance exhibits difference depending on whether to cross the resonance “from above” or “from below”, just like the ring resonance.
- This difference is due to the stable fixed points of the resonance.
- The resonant frequency component is observed at the tune 1/4 (90°/360°) confirming that this is a $4\sigma=360°$ resonance.

Experiment of the 4th order resonance (I)
using GSI UNILAC

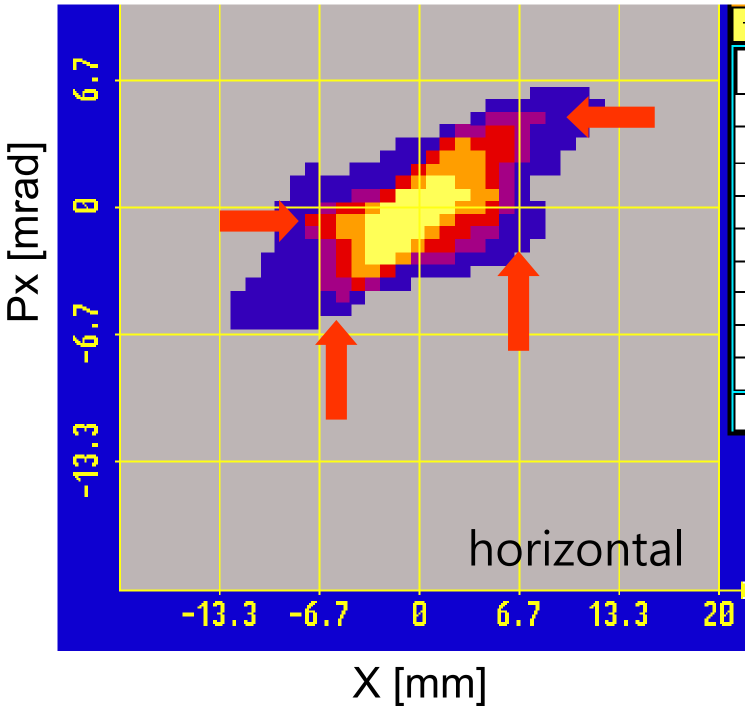
L. Groening et al., PRL **102**, 234801 (2009)

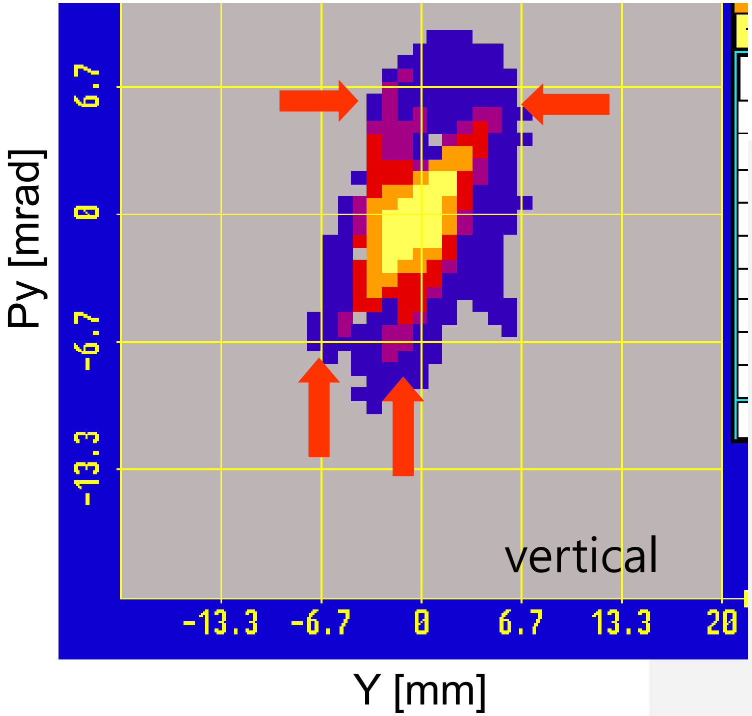


Experiment of the 4th order resonance (I)

emittance data at σ_o=100°

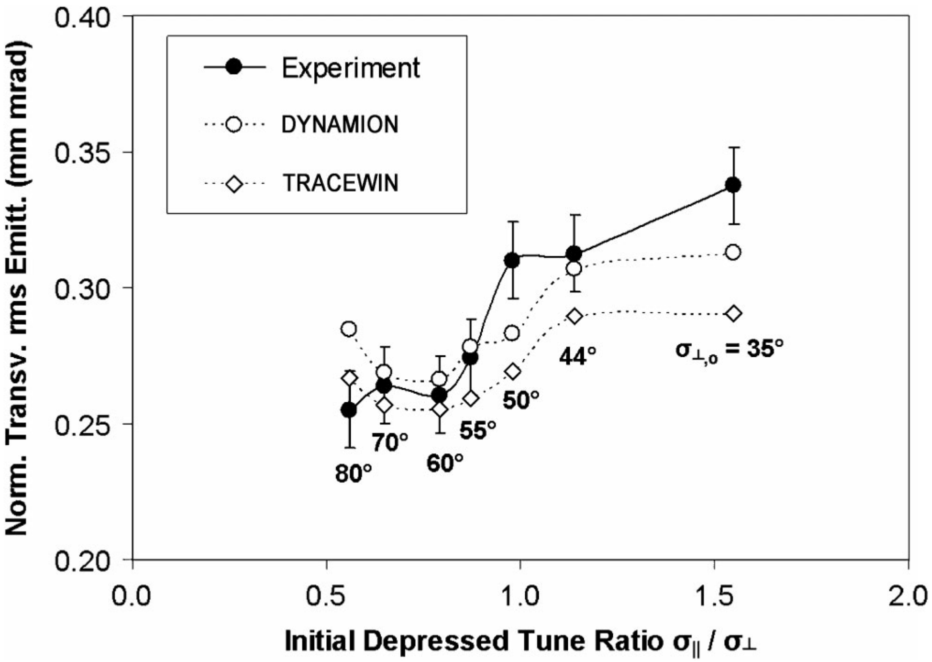
Signs of the fourth order resonance





Experiment of the coupling resonance (I)
using GSI UNILAC

L. Groening et al., PRL **103**, 224801 (2009)

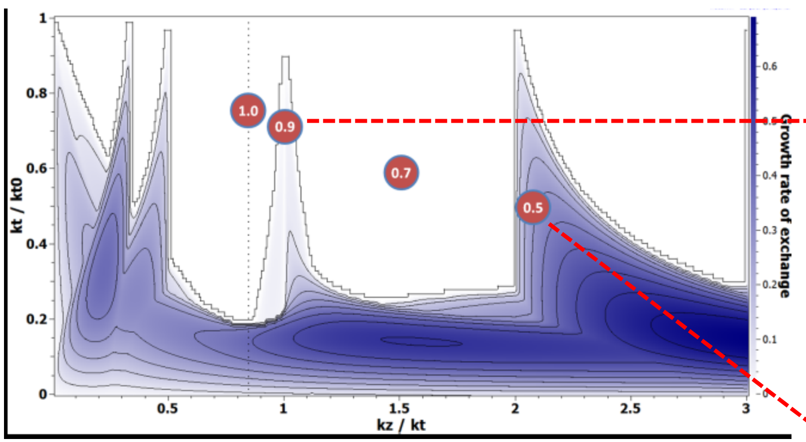


- Space charge coupling resonance was verified through the emittance measurement using the GSI UNILAC.

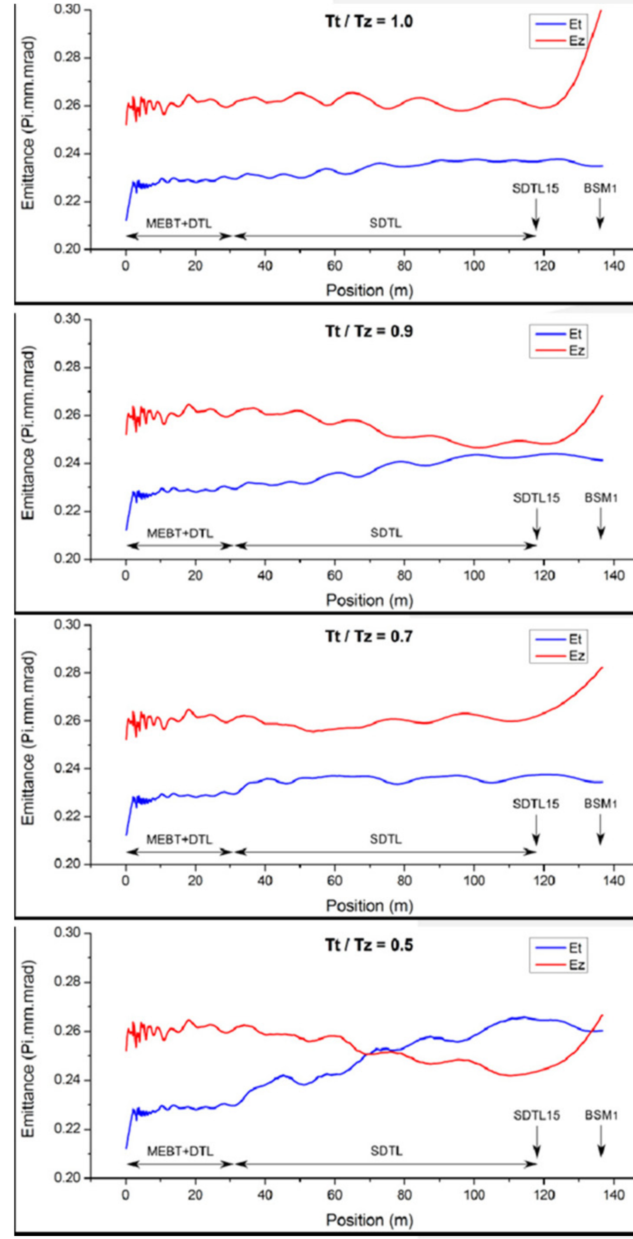
Experiment of the coupling resonance (II)
using J-PARC Linac

C. Plostinar et al., Proc. of IPAC2103

- C. Plostinar et al. measured the emittance change due to the space charge coupling resonance using wire-scanners & BSM.
- $T_t/T_z = \varepsilon_t\sigma_t / \varepsilon_z\sigma_z$ where T known as "temperature"



T_t/T_z	ε_t (π mm mrad)	ε_z (π mm mrad)
1.0	0.216	0.269
0.9	0.229	0.233
0.7	0.253	0.223
0.5	0.293	0.161



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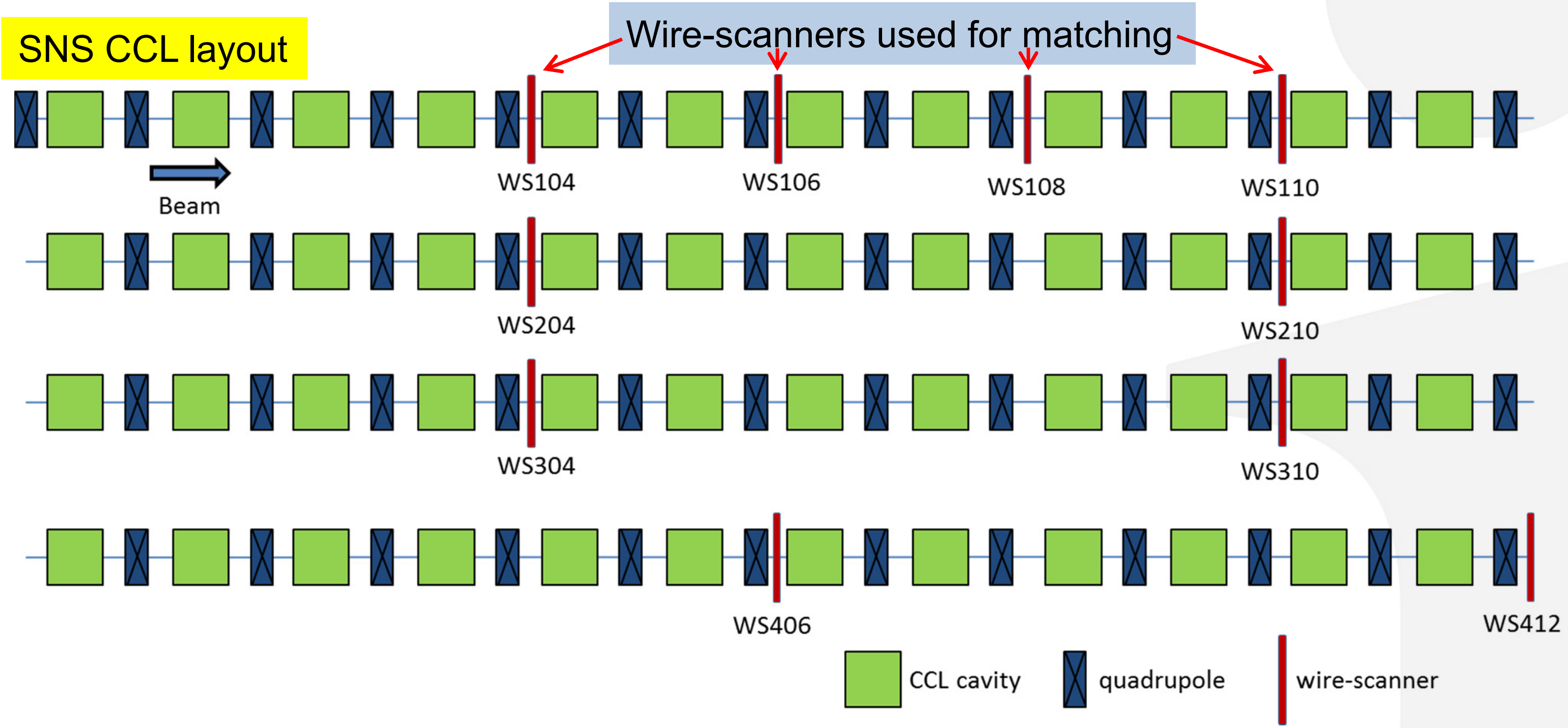
Further Experiment on the 4^{th} order resonance and coupling resonance

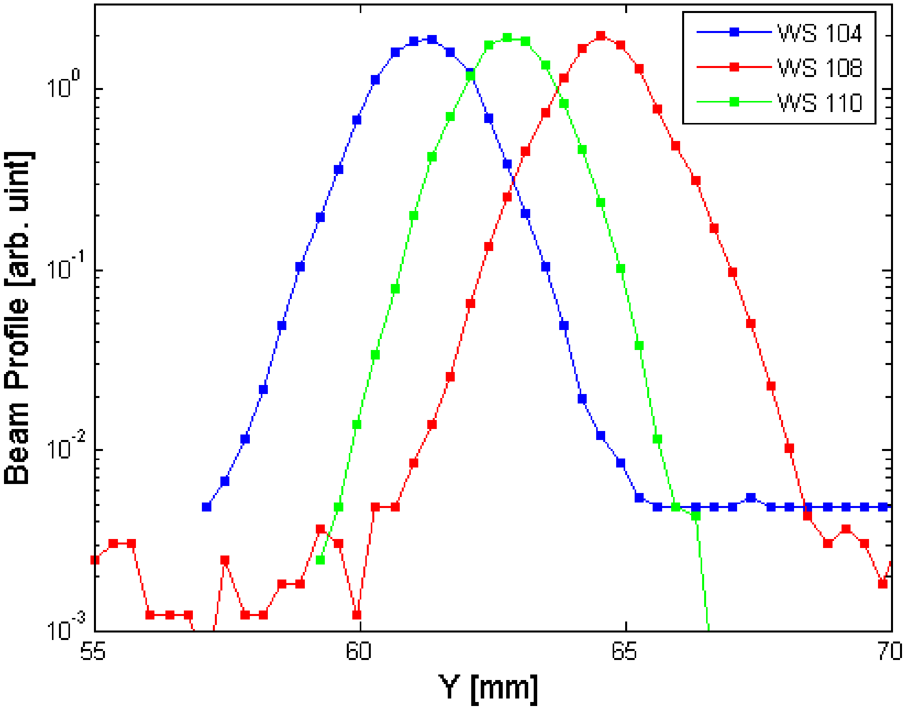
Experiment of the 4th order resonance (II)
using SNS CCL



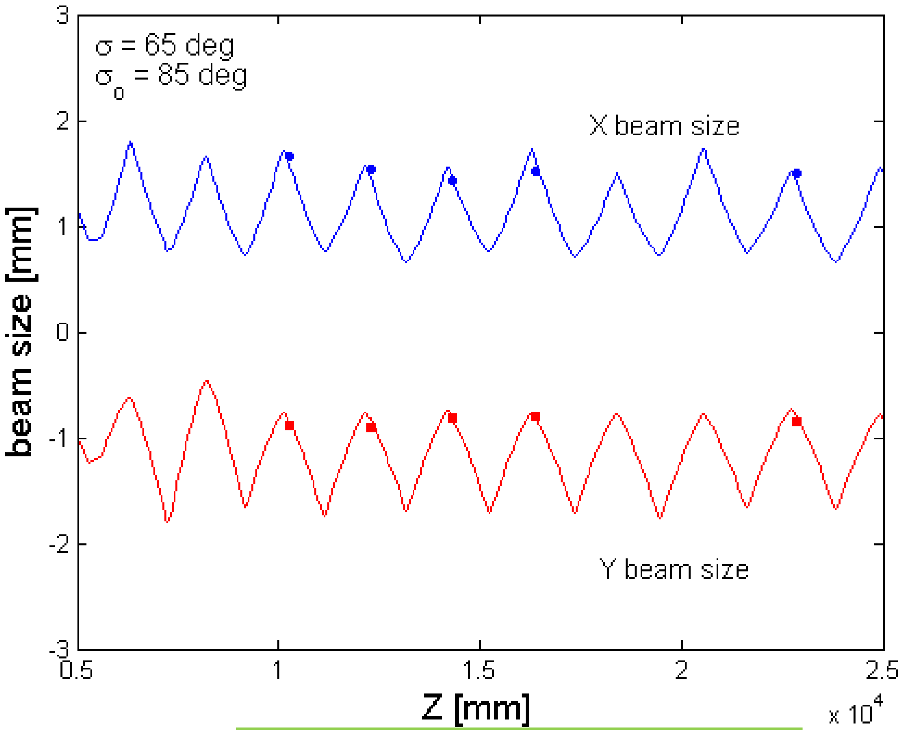
- Schematic layout of the SNS CCL showing the wire-scanners used for the experiment.
- Halo of incoming beams were carefully controlled by matching and the MEBT round beam optics.

Experiment of the 4th order resonance (II)

Halo of incoming beam was minimized



Beam profiles at the CCL entrance

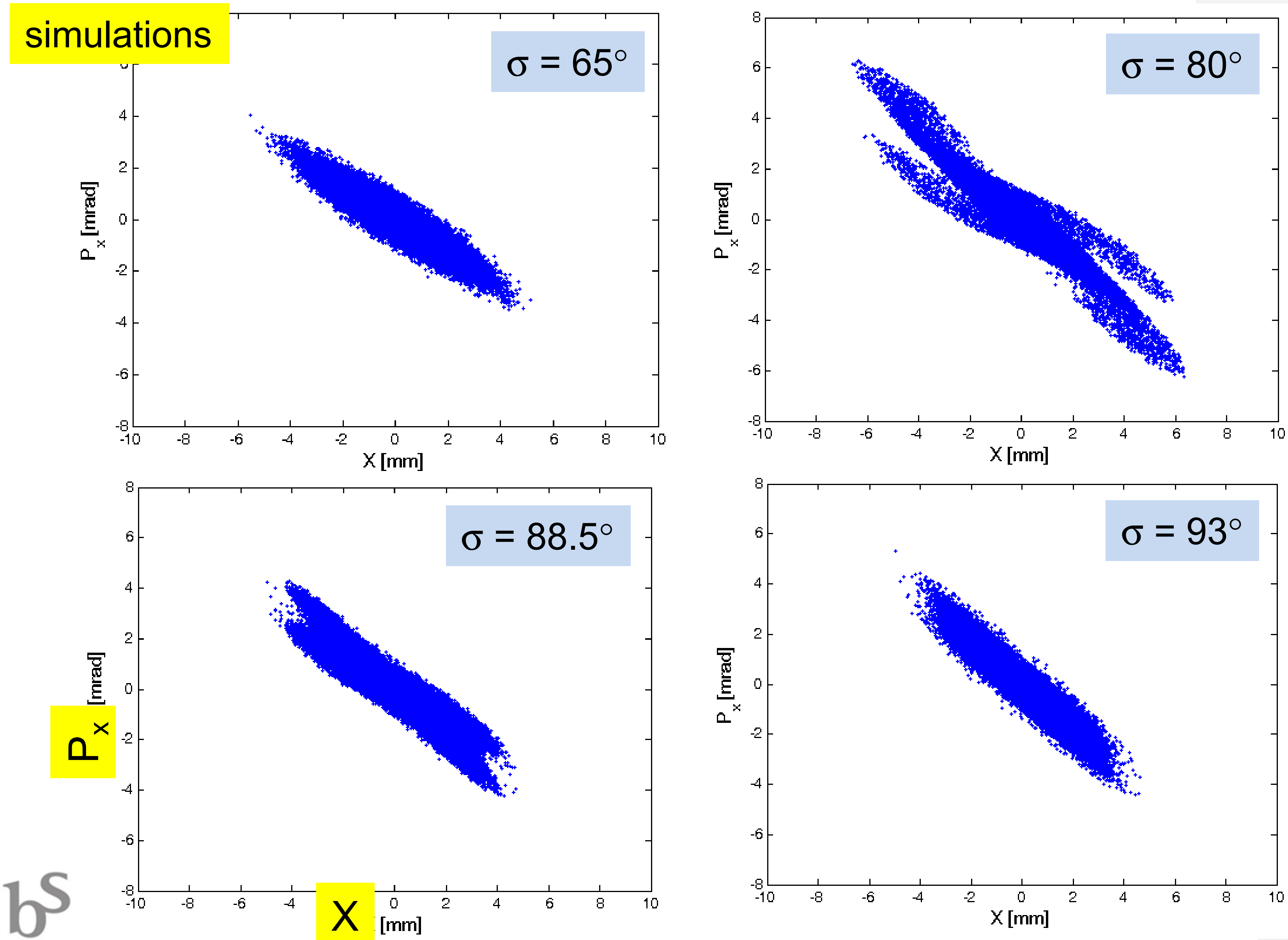


Beam matching to the CCL

- Round beam optics (MEBT) was used to minimize halo formation in the upstream.
- Matching between linac sections was done to avoid the mismatch.
- The beam entering the CCL has little tails.

Experiment of the 4th order resonance (II)

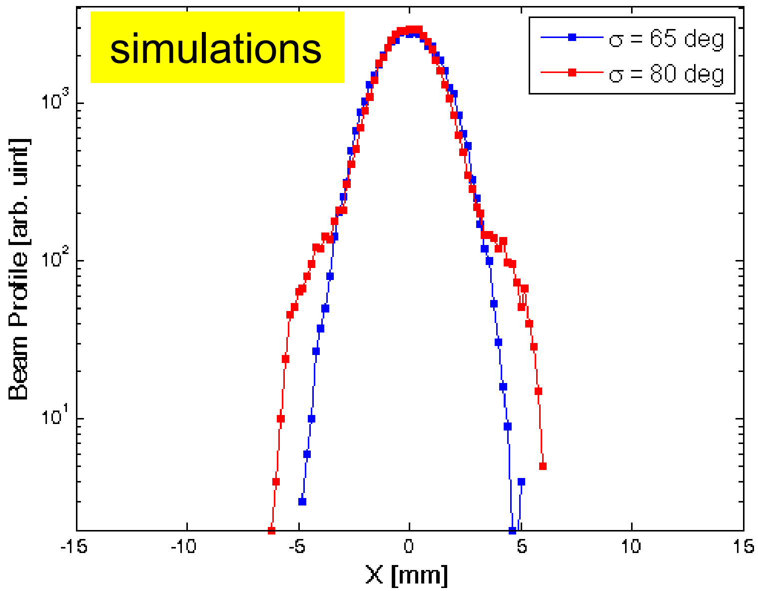
Simulations

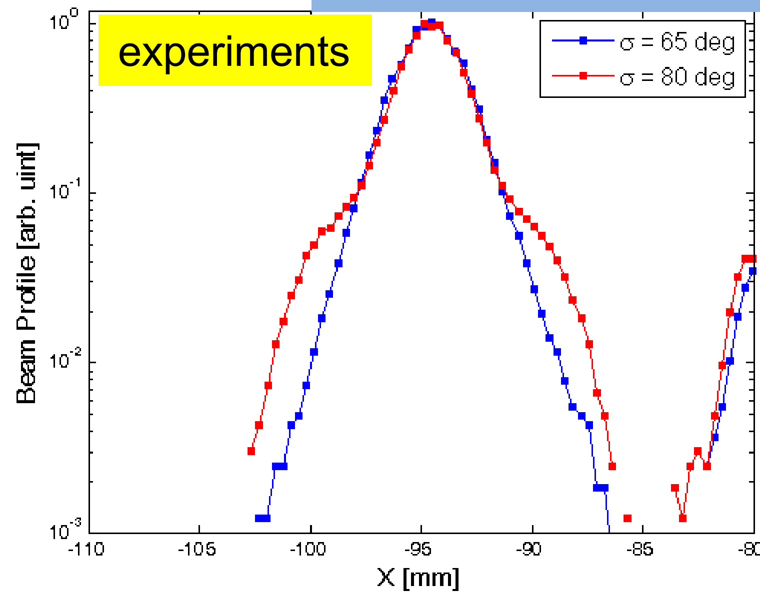


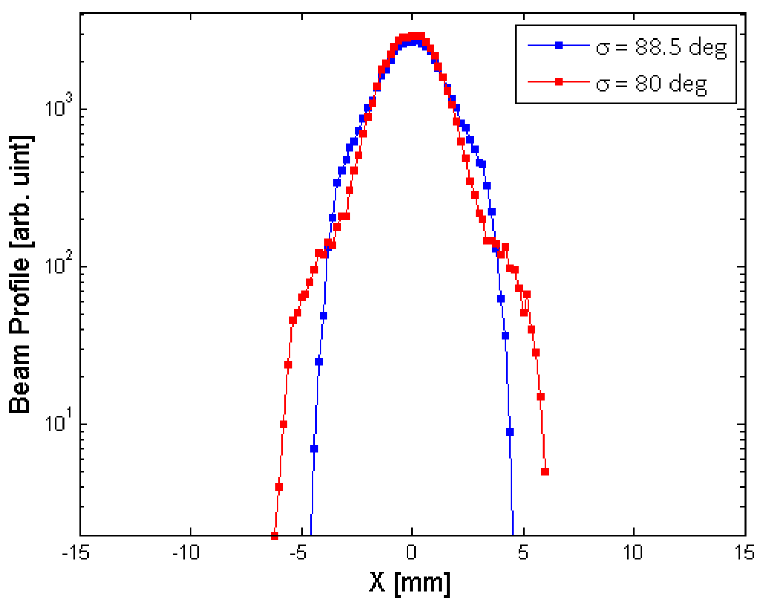
Experiment of the 4th order resonance (II)

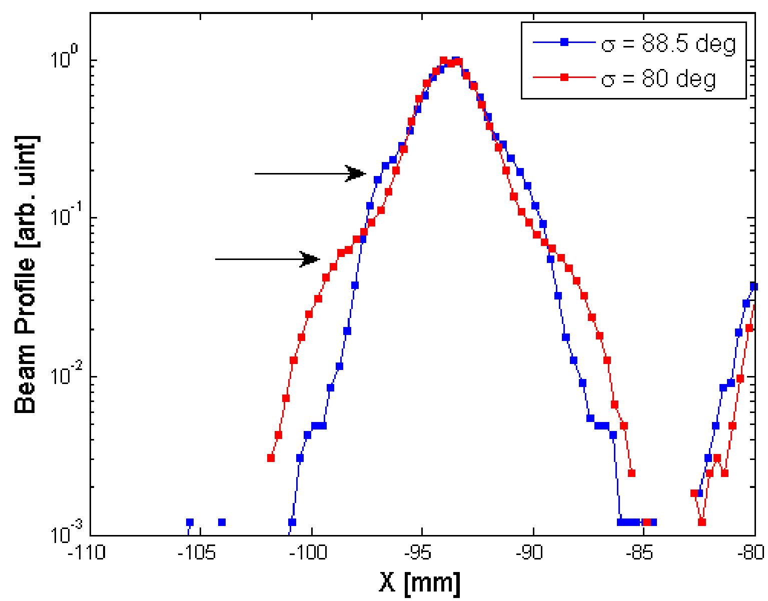
Experiments and Simulations

D. Jeon, PRAB **19**, 010101 (2016)









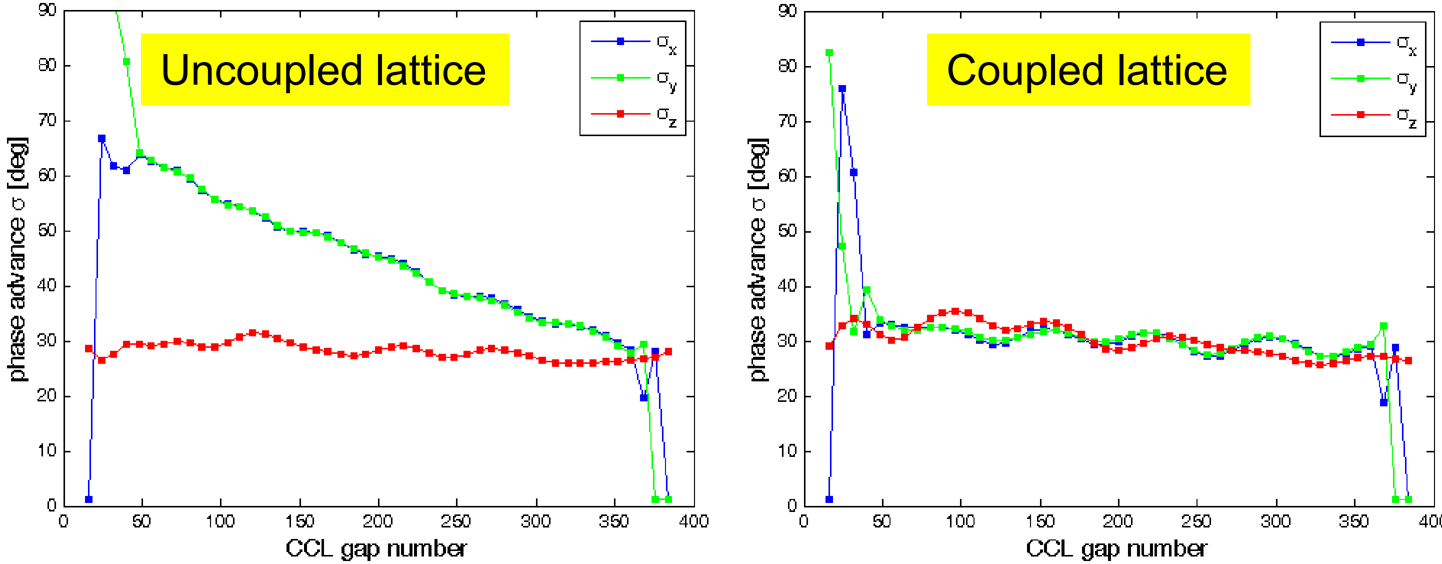
Experiment of the coupling resonance (III) using SNS CCL

- The experiment on the $2\sigma_{x(y)} - 2\sigma_z = 0$ coupling resonance was verified using the SNS linac.
- The CCL lattice was modified to maximize the coupling between the transverse and the longitudinal planes.

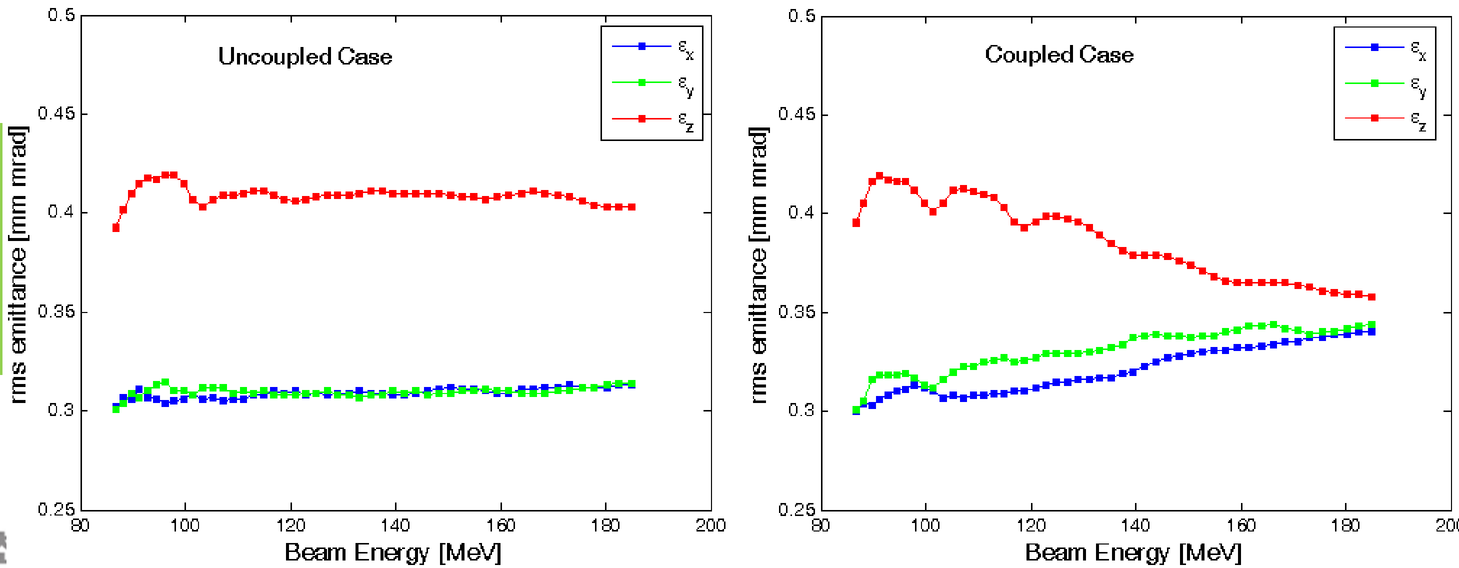
- It was crucial for the incoming beam to have little halo.
- Incoming beams to the CCL had little halo though employing
  - Round beam optics in the MEBT
  - Matching between the linac sections

Experiment of the coupling resonance (III)
using SNS CCL

Phase advances

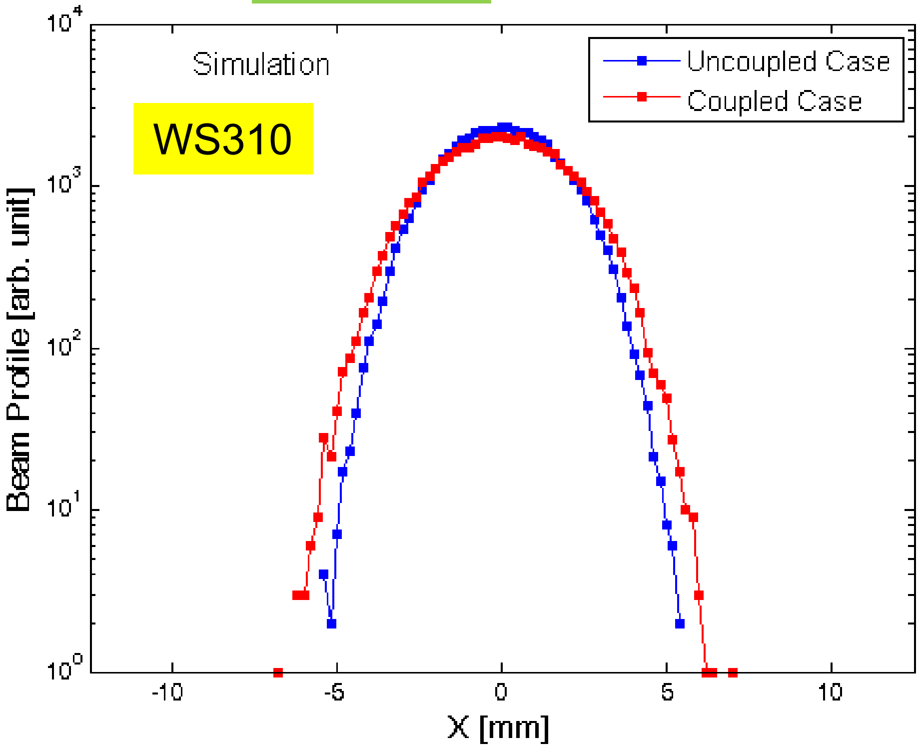


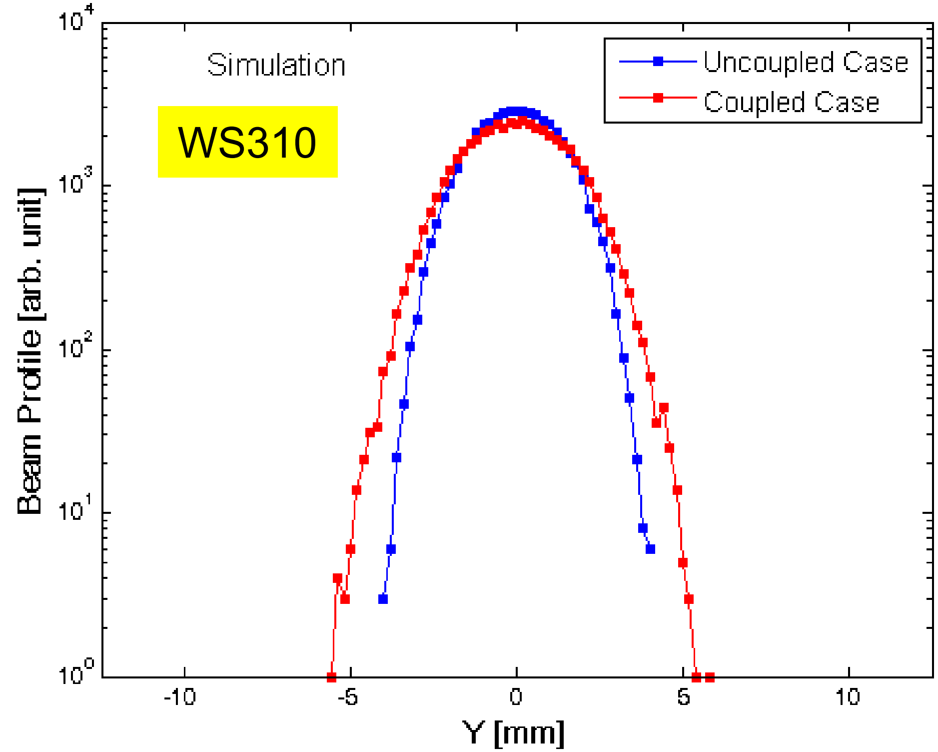
Emittances



Experiment of the coupling resonance (III)
Simulation using SNS CCL

Simulation



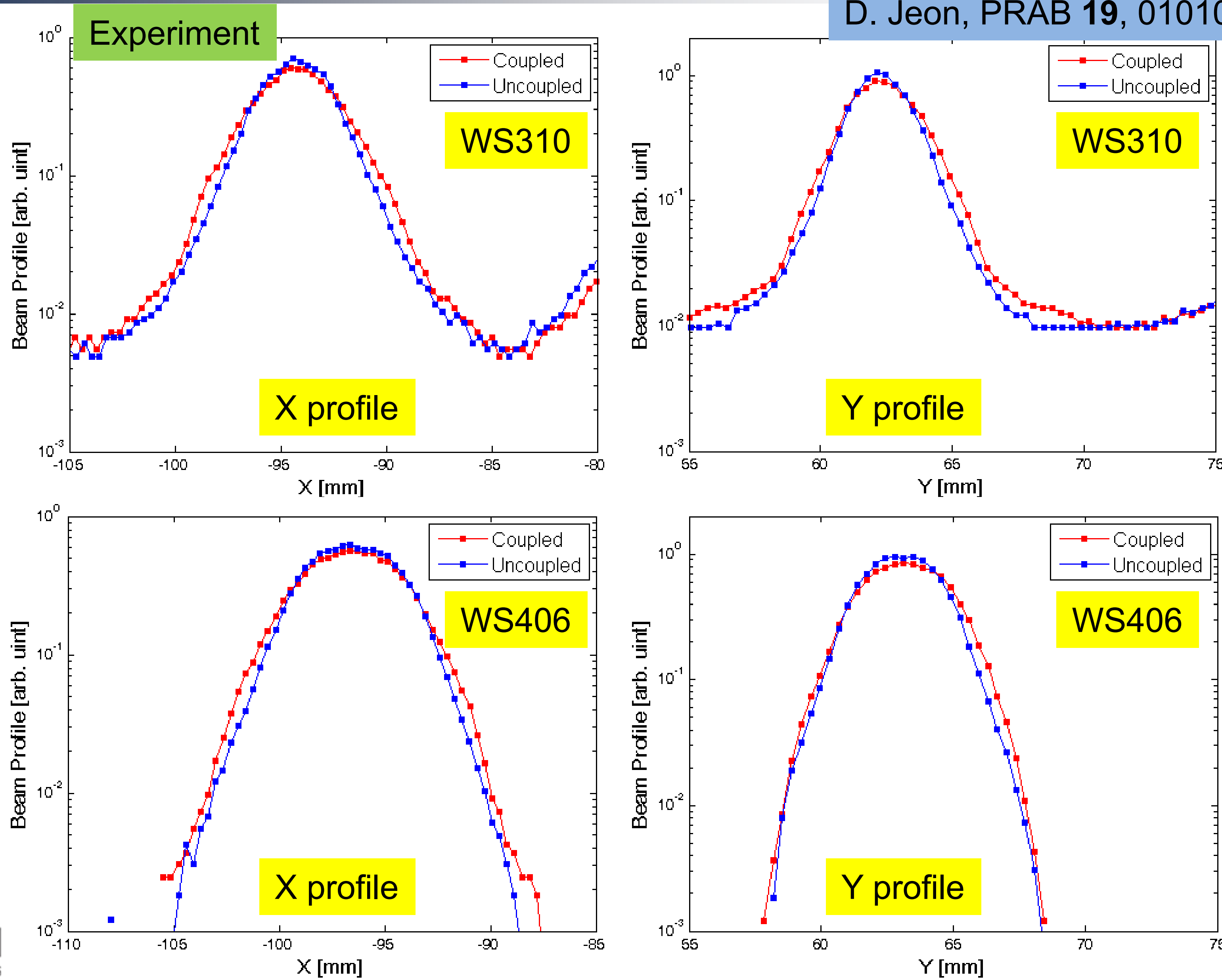


- Simulations show that the coupling resonance increases the transverse emittances and widens the beam profiles in x and y planes.

Experiment of the coupling resonance (III)

Experiment using SNS CCL

D. Jeon, PRAB **19**, 010101 (2016)



Interplay of the 4^{th} order resonance and the envelope instability

4th order resonance and envelope instability

- The 4th order resonance and the envelope instability are completely different mechanisms.

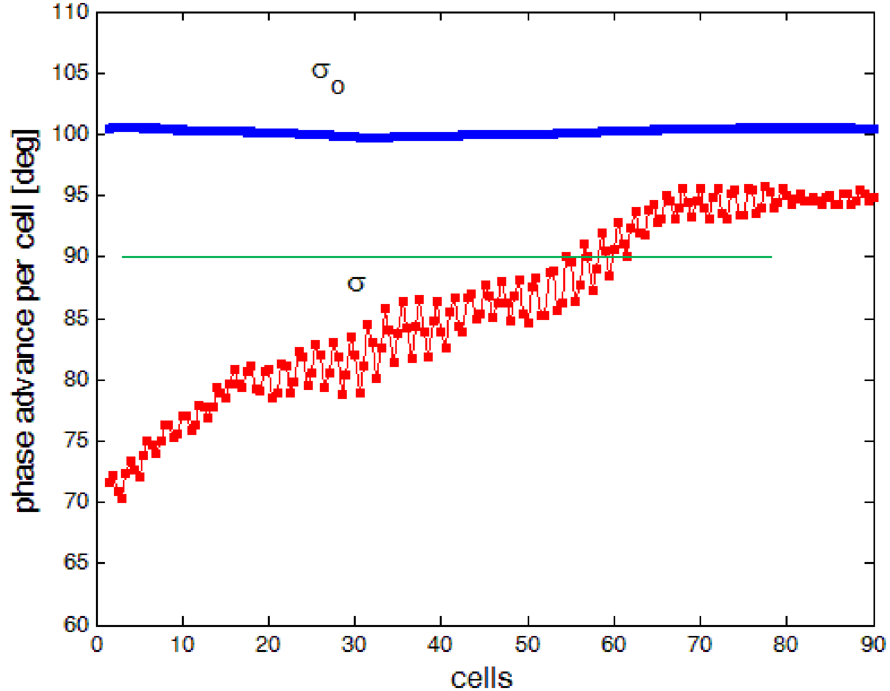
- Linear accelerators were designed with $\sigma_o < 90°$ to avoid the better-known envelope instability.
  BUT…

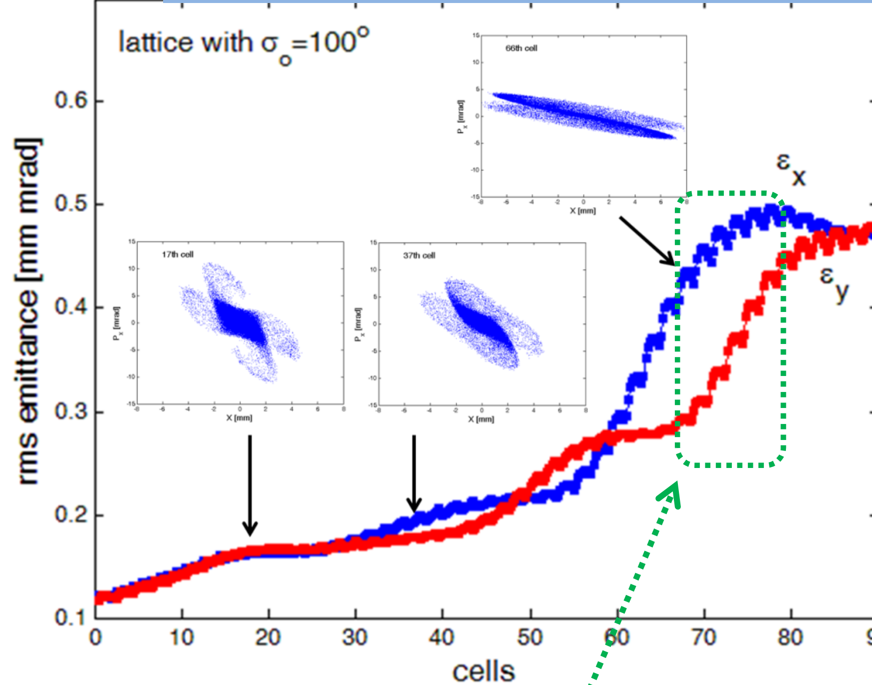
- [D. Jeon et al, PRST-AB 2009] showed that the 4th order resonance dominated over the envelope instability.
- [I. Hofmann et al, PRL 2015] showed that the envelope instability develops from the mismatch by the fourth order resonance.

- Questions were raised whether the 4th order resonance always dominates over the envelope instability.
- Further studies were conducted.

4^{th} order resonance and envelope instability

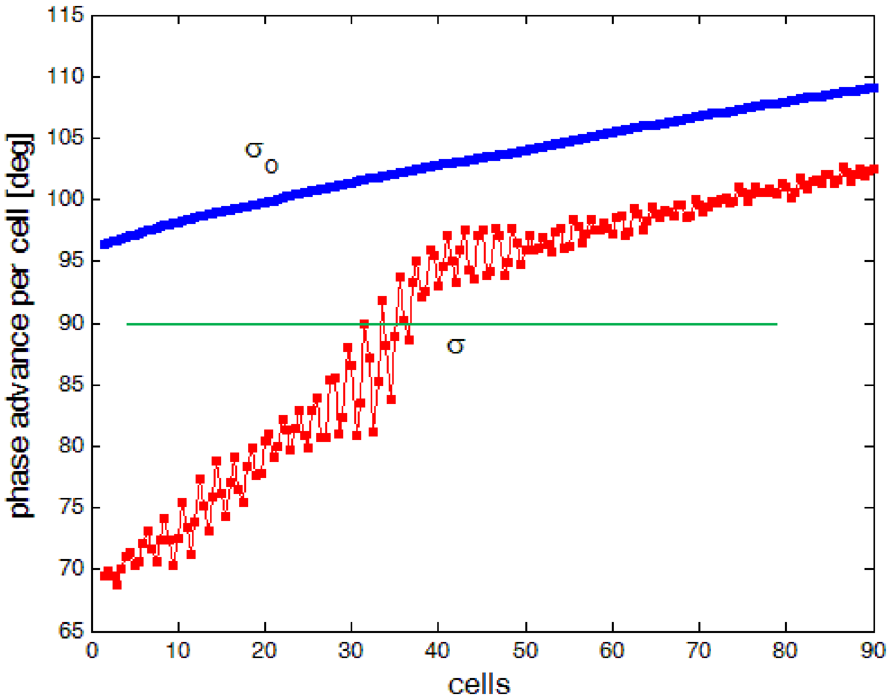
D. Jeon et al., NIM A **832** (2016) 43

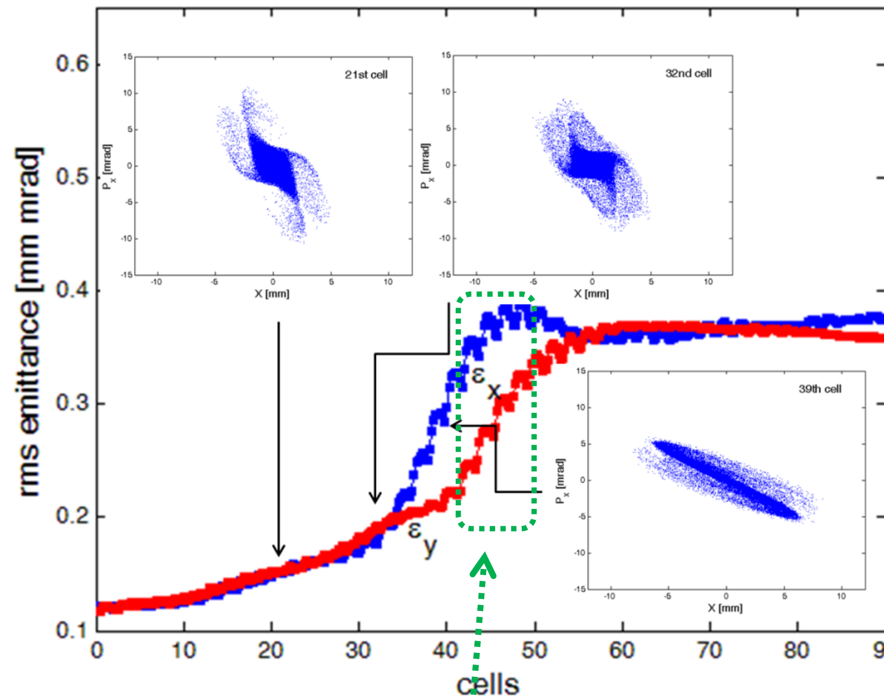




- When σ_o is kept constant, the envelope instability follows the 4^{th} order resonance.
- The envelope instability starts to develop (when $\sigma \approx 85°$) when σ increases approaching 90° (the extent of the resonance shrinks).
- The envelope instability takes effect even for $\sigma > 90°$.

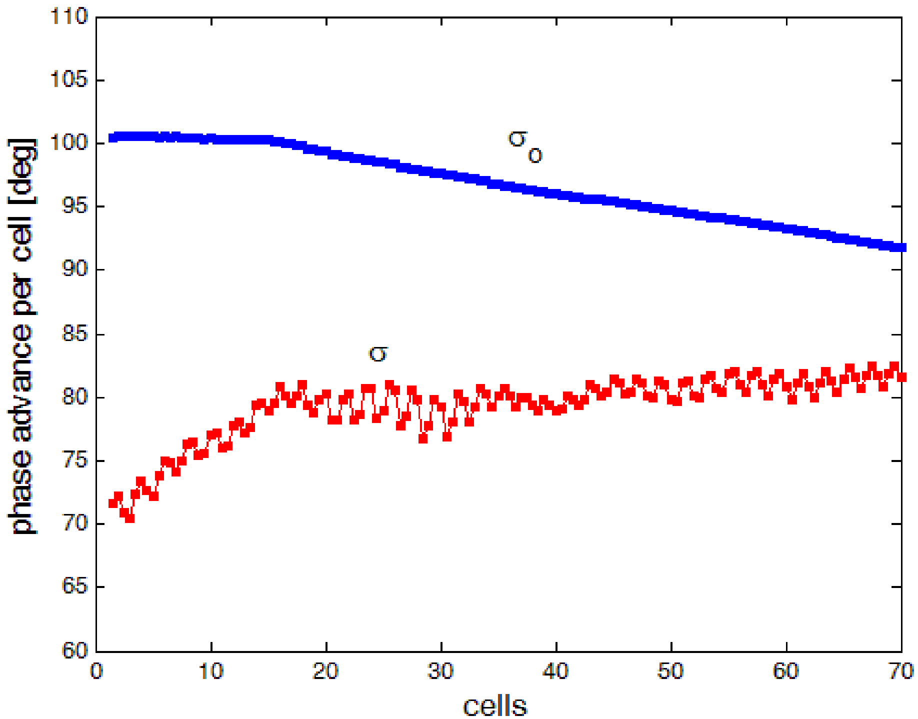
4^{th} order resonance and envelope instability

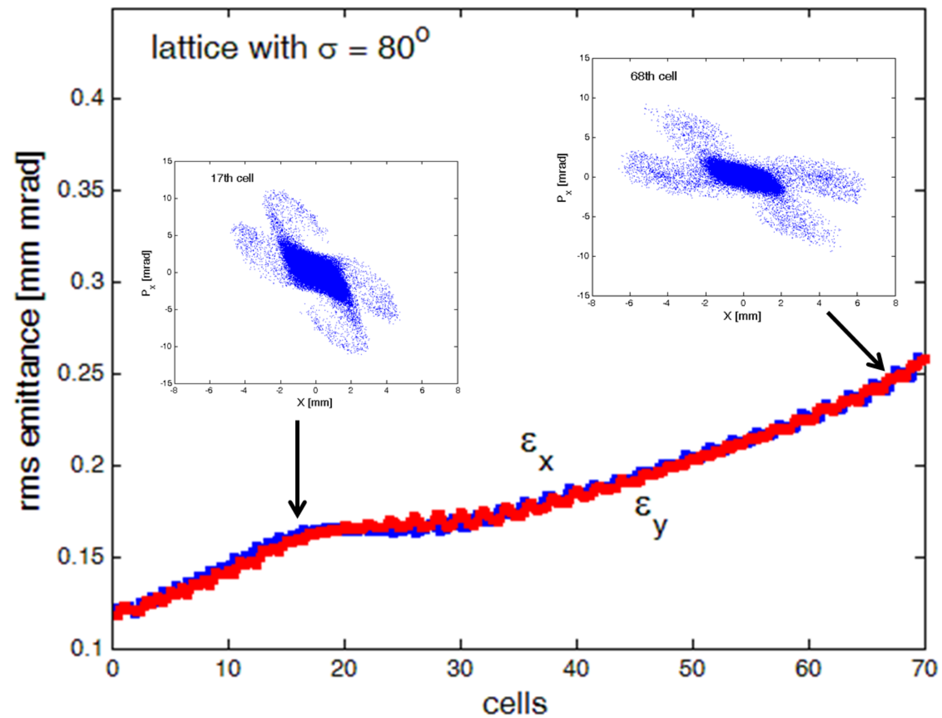




- When σ_o increases slowly, the envelope instability follows the 4^{th} order resonance.
- The envelope instability starts to develop (when $\sigma \approx 85°$) when σ increases approaching 90° (the extent of the resonance shrinks).
- The envelope instability takes effect even for $\sigma > 90°$.

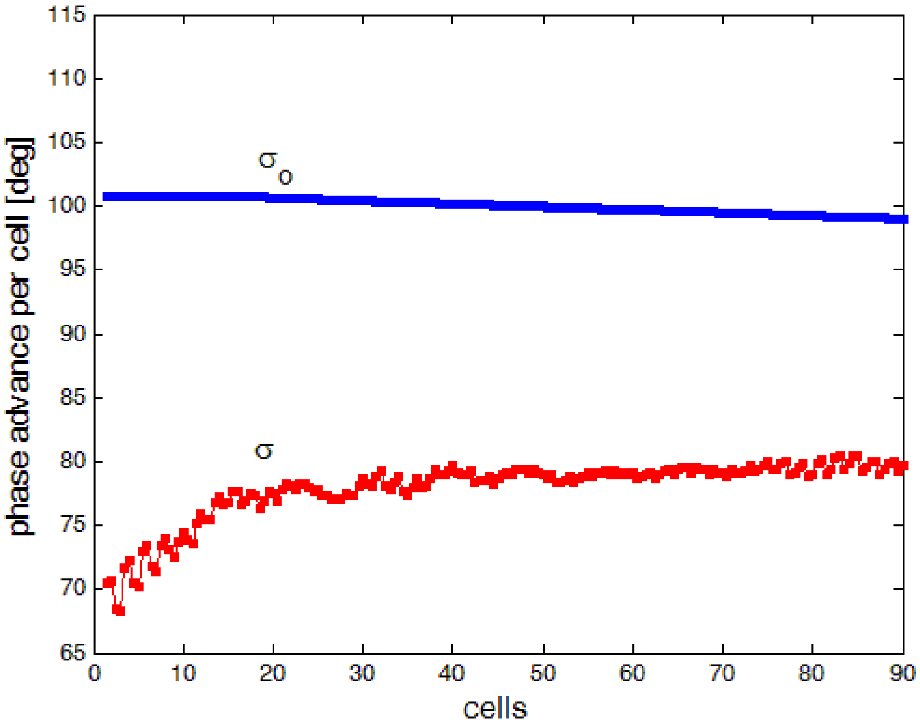
4^{th} order resonance and envelope instability

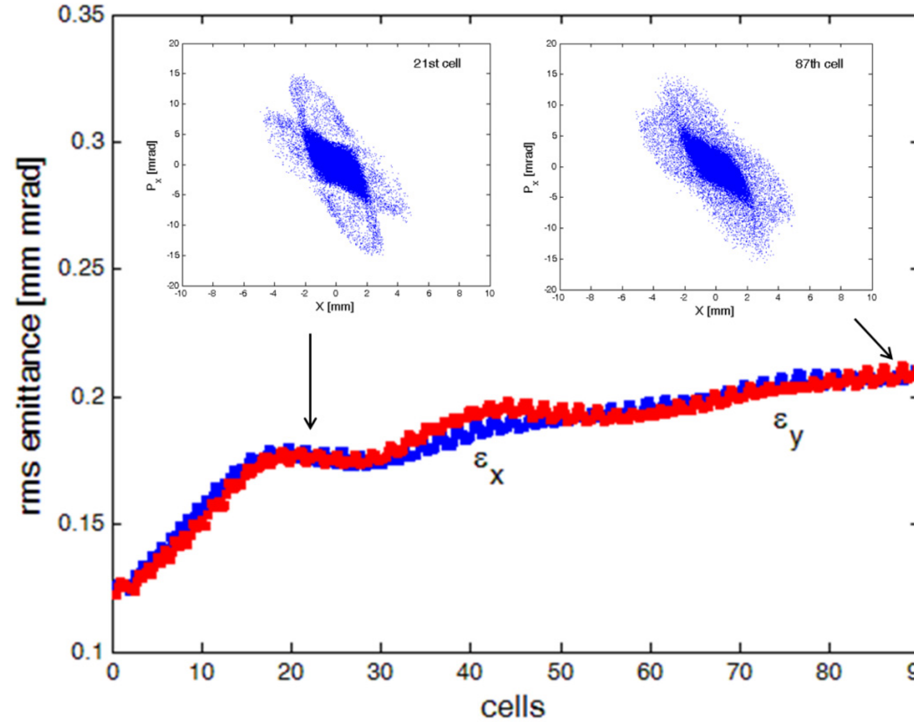




- When σ is kept constant, the resonance islands do not shrink (extent of the resonance is maintained) and the envelope instability is suppressed.
- The beam gets out of the influence of the envelope instability when σ_o decreases and gets close to 90°.
- The 4^{th} order resonance persists all the way.

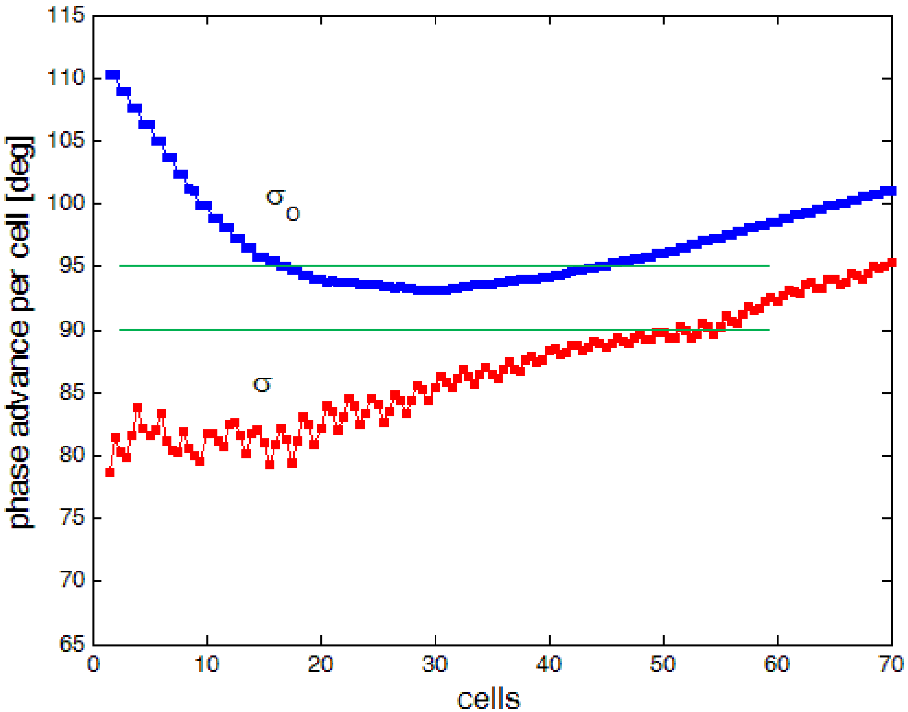
4^{th} order resonance and envelope instability

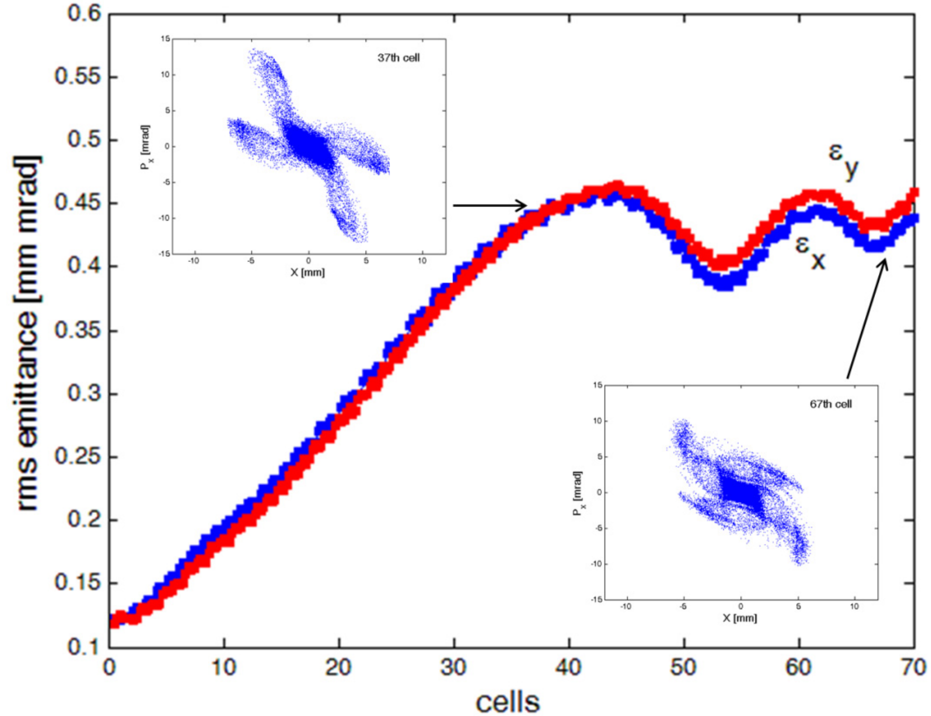




- Both σ_o and σ are maintained almost constant without acceleration (setting the synchronous phase to –90°).
- The envelope instability is suppressed.
- The 4^{th} order resonance seems to dominate over the envelope instability.
- As σ increases from 77° to 80°, the resonance islands shrink a bit and the four-fold structure becomes a bit blurred.

4^{th} order resonance and envelope instability

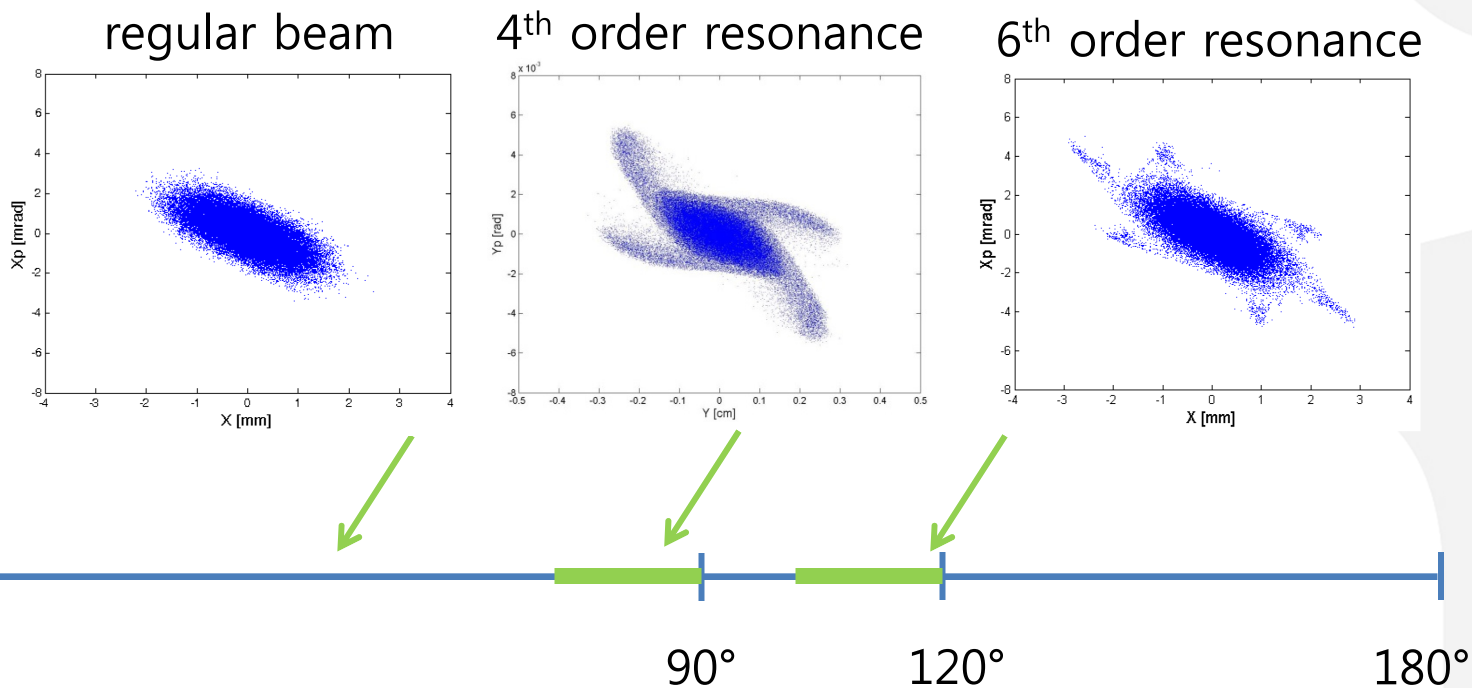




- When σ_o decreases and gets close to 90°, the envelope instability is suppressed even though σ increases approaching 90°.
- And the four-fold structure persists.
- This seems to indicate that the beam gets out of the influence of the envelope instability when σ_o decreases and gets close to 90°.

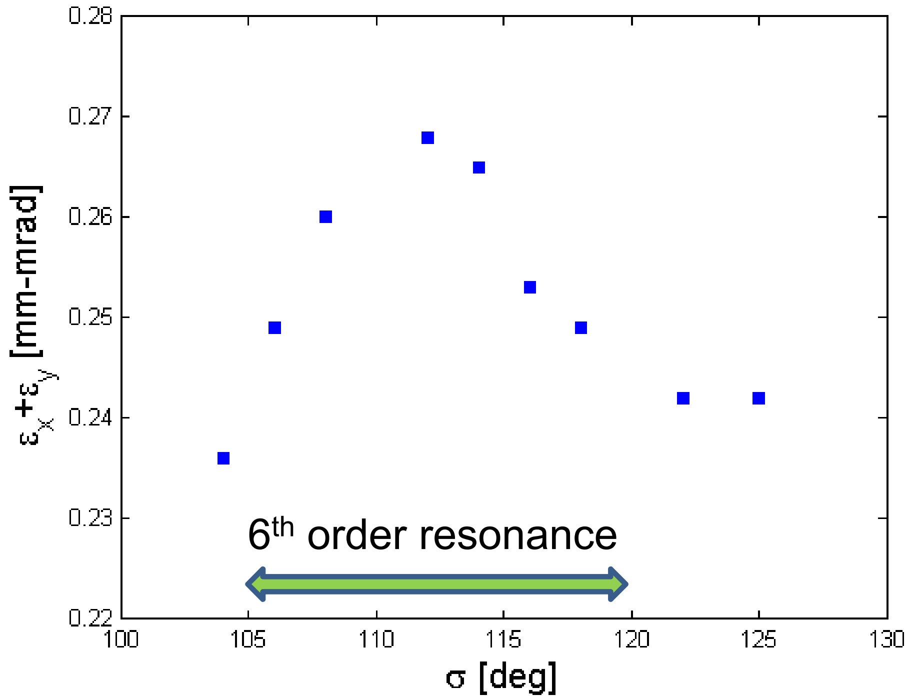
The 6th order resonance
for high intensity linear accelerators

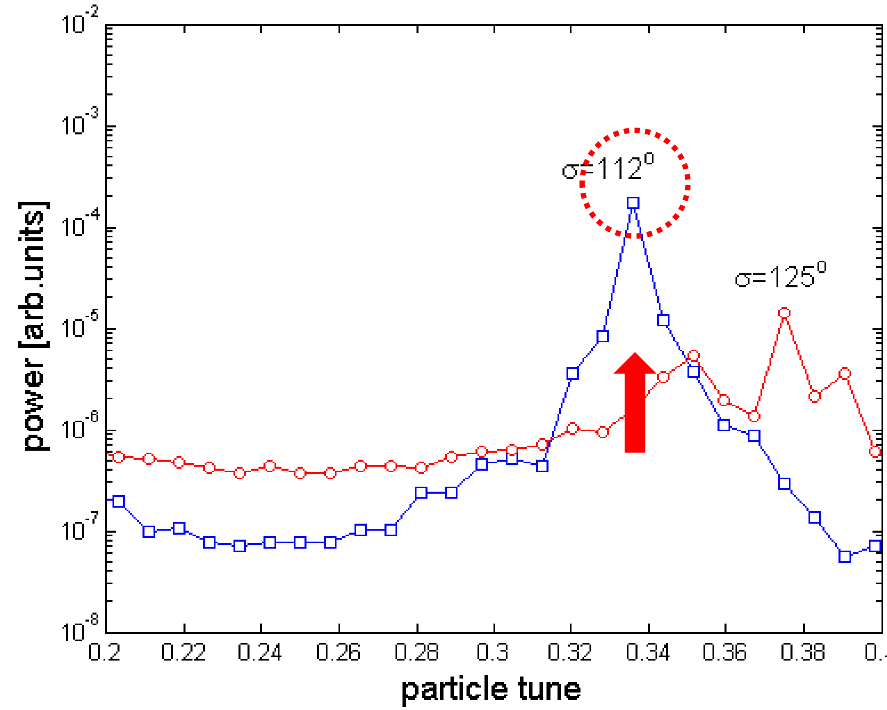
D. Jeon et al., PRL **114**, 184802 (2015)



- The 6th order resonance was found in high intensity linear accelerators ($6\sigma = 720^\circ$ resonance).
- The 6th order resonance is excited for $120^\circ - \Delta\sigma \leq \sigma \leq 120^\circ$.

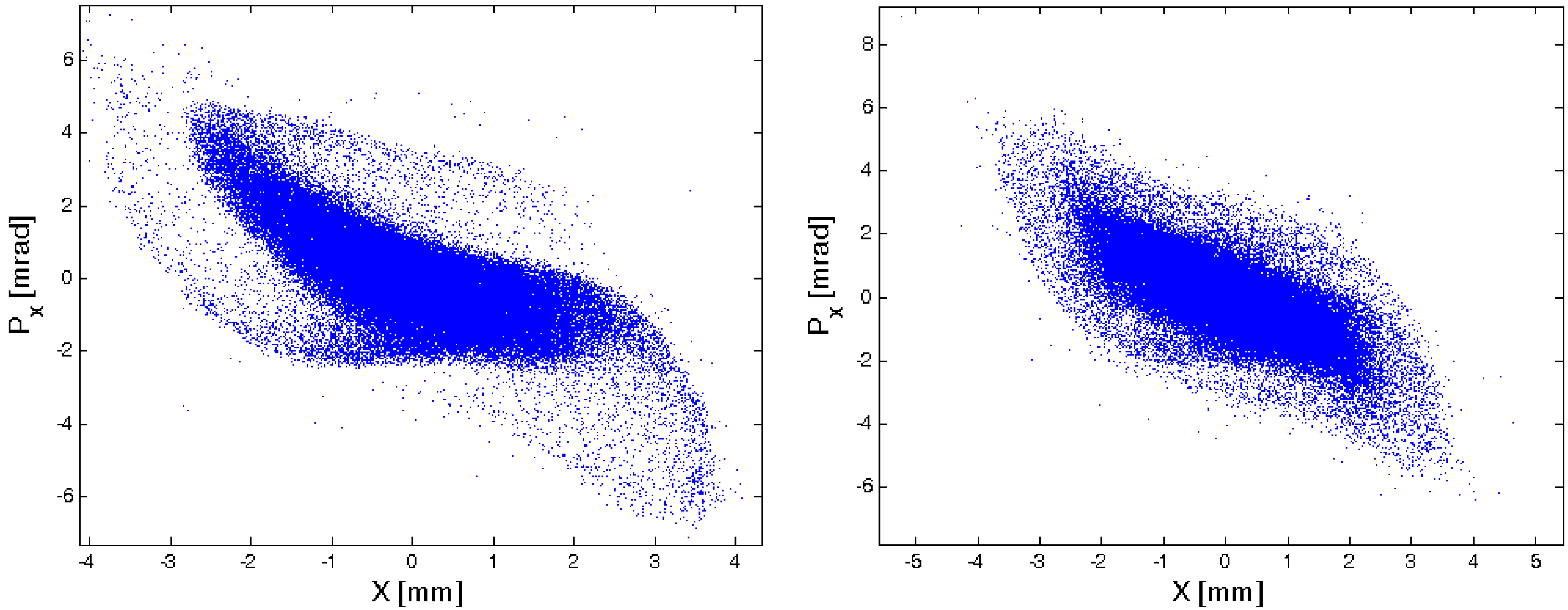
The 6th order resonance
for high intensity linear accelerators





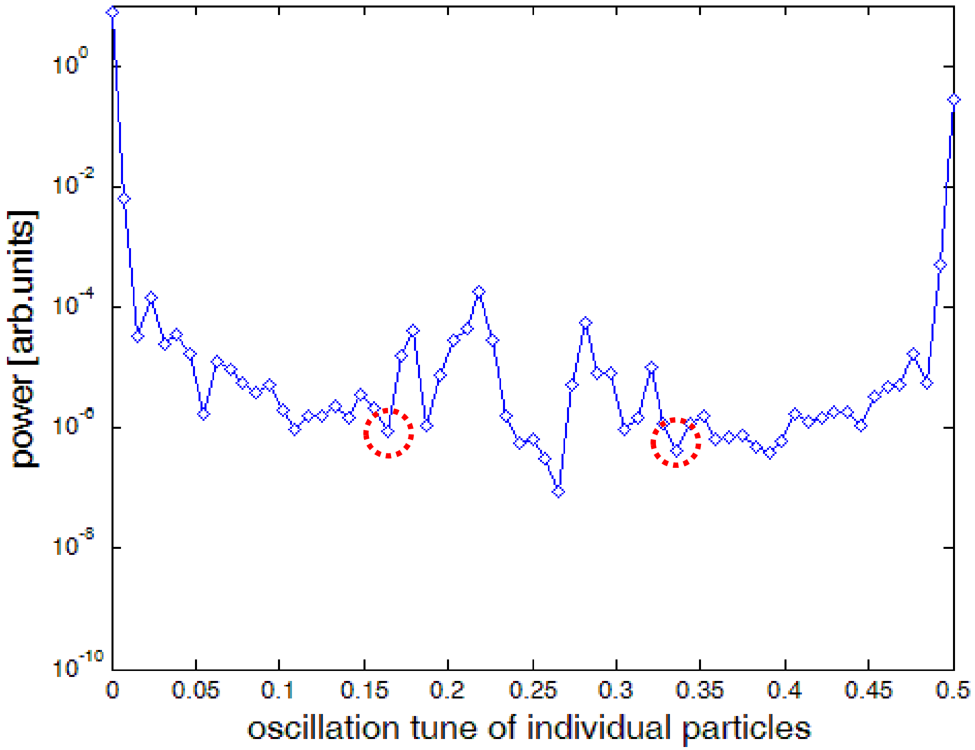
- No resonance effects for σ > 120° (result of the Hamiltonian property).
- Frequency analysis shows a peak at 1/3 = 120°/360°.
- This resonance arises from the perturbation of 2:1 and 4:1 space charge resonances.

The 3rd order instability
for high intensity linear accelerators



- A third order instability is reproduced for σ_o = 92° and σ = 40° (90 mA beam).
- Arises from the space charge potential ~ x^3 or ~y^3.
- These terms are not present a priori in the symmetric beam distributions.
- Arises from the noise of the initial distributions.
- Very sensitive to the initial distributions and not always observed.

The 3rd order instability
for high intensity linear accelerators



- This is not a resonance and does not show any resonance peaks around 1/3 or 1/6 in the tune.

Summary

- The envelope instability was found in 1983 and designers for high intensity linear accelerators avoided $\sigma_o > 90^\circ$ in fear of the envelope instability.
  BUT…

- The following resonances were found in high intensity linear accelerators:
  - The 4th order resonance was found in 2009 and experimentally verified through two different experiments.
  - The 6th order resonance was found in 2015.

- Space charge coupling resonances were experimentally verified through three experiments.

Summary

- Interplay of the 4th order resonance and the envelope instability was studied for well-matched initial beams.
- The envelope instability is excited 1) when σ_o is kept constant or increases slowly, and 2) when the extent of the resonance shrinks, as σ increases approaching 90°.
- The envelope instability is excited by the mismatch generated by the 4th order resonance.
- The envelope instability is suppressed when σ is kept constant (maintaining the resonance) or when σ_o decreases and gets close to 90° (getting out of the envelope instability).

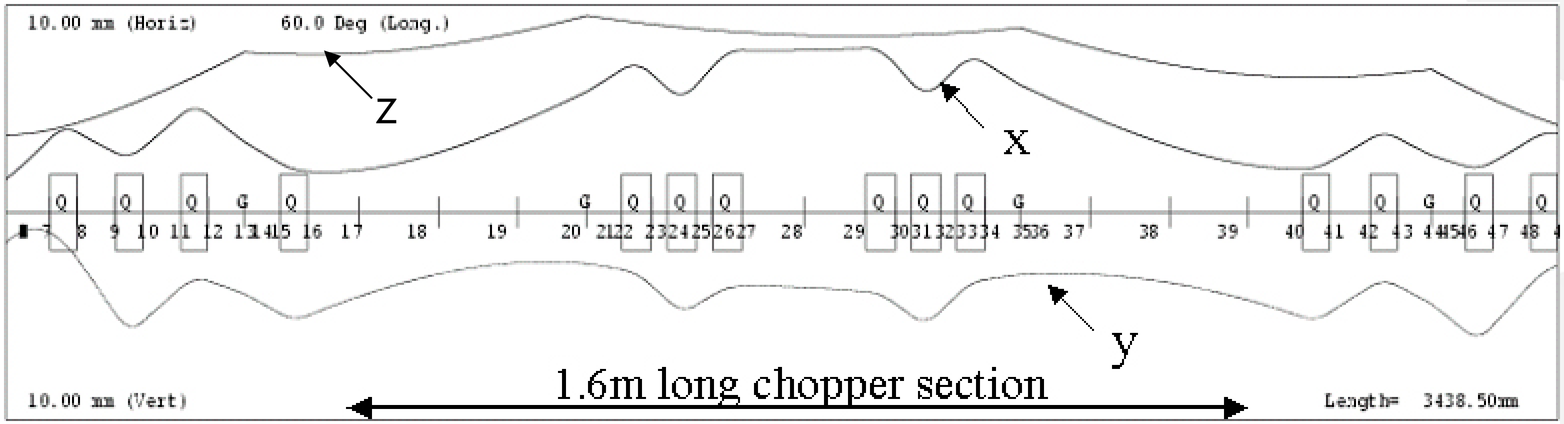
- The 3rd order instability arises from the space charge potential $\sim x^3$ or $\sim y^3$ which are not present a priori in the symmetric beam distributions.
- The 3rd order instability is very sensitive to the initial beam distributions (arises from the noise) and "sometimes" arises.


Thank you for your attention!
Tack!
Merci!
Danke!
감사합니다

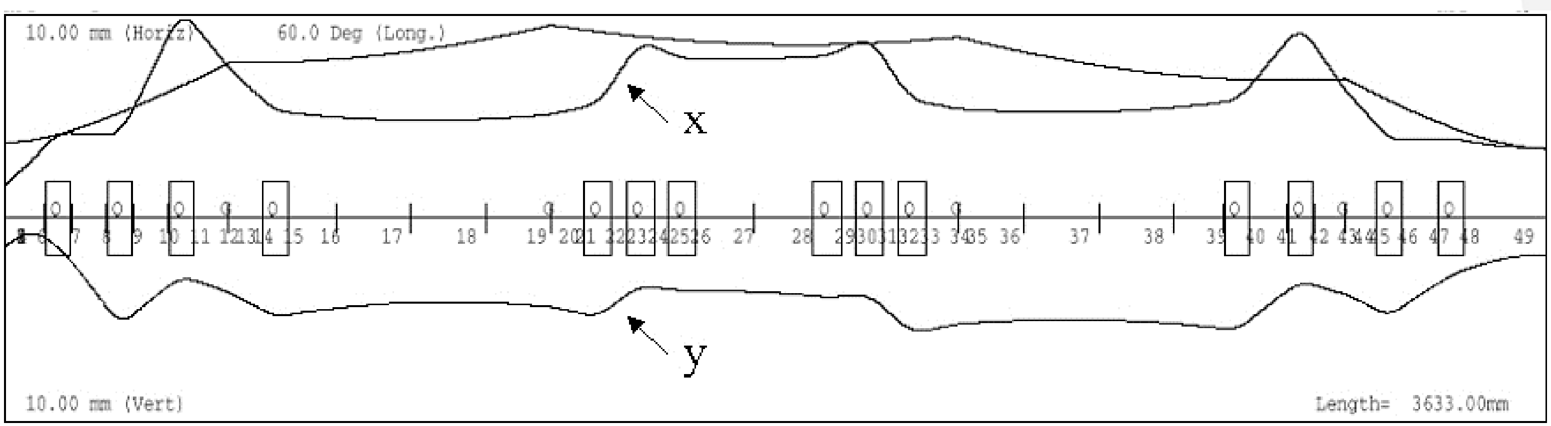
Halo induced by non-round beam

SNS MEBT

D. Jeon et al, PRST-AB **5**, 094201 (2002)

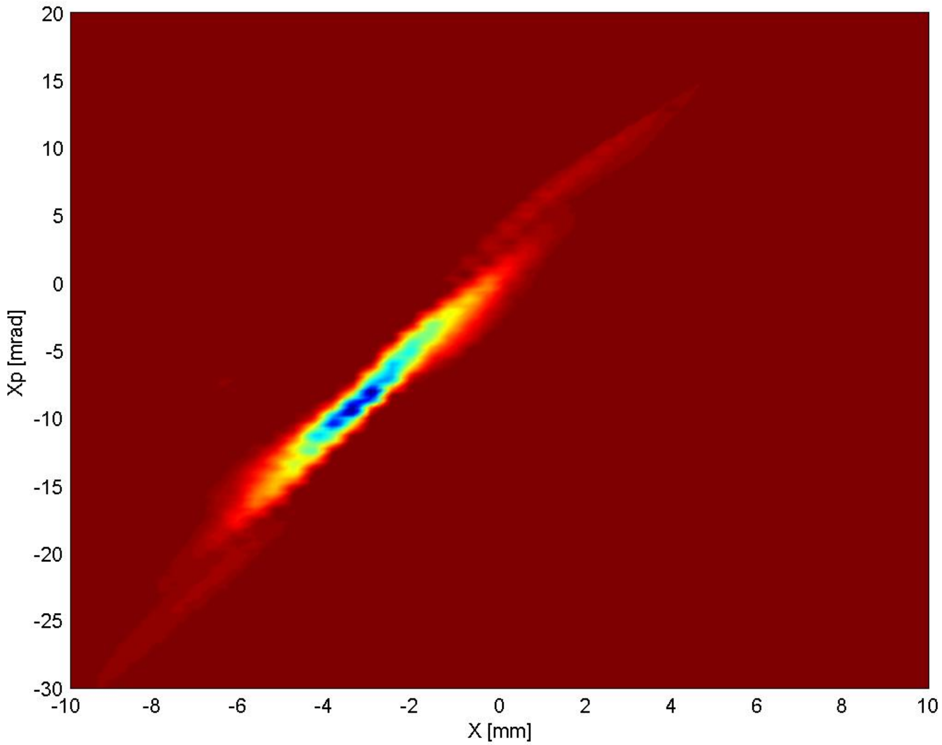


Nominal Optics Generates Halo!!



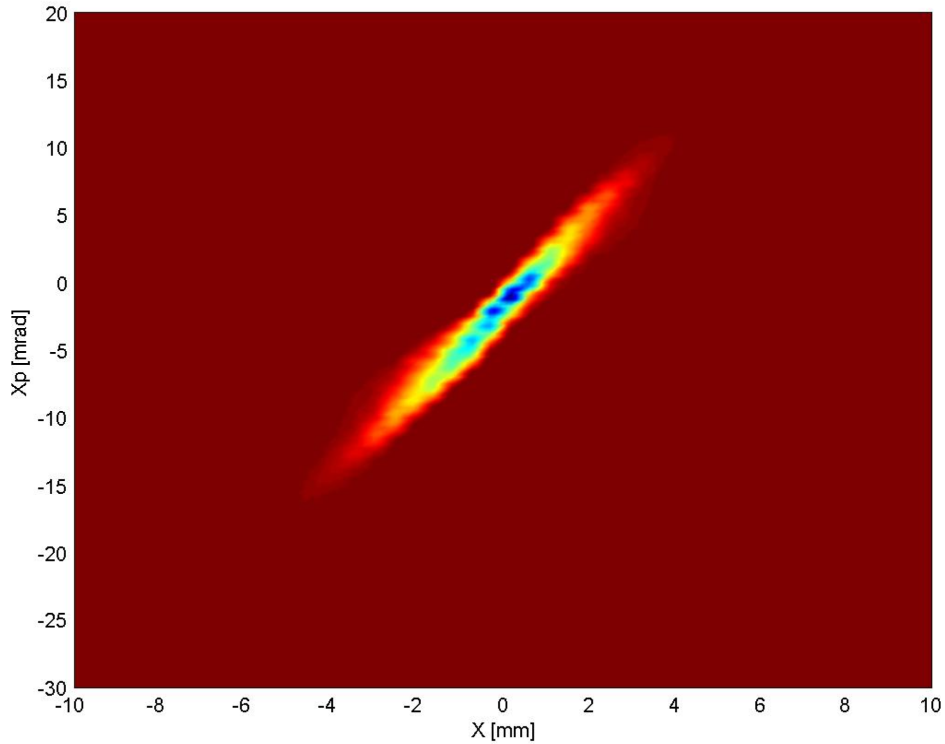
Round Beam Optics Suppresses Halo!!

Round Beam Optics improves beam quality
(Emittance Measurement)



Nominal Optics

ε_X= 0.349 mm-mrad (1% threshold)
0.454 mm-mrad (0% threshold)



Round Beam Optics

ε_X= 0.231 mm-mrad (1% threshold)
0.289 mm-mrad (0% threshold)

- Round Beam Optics reduces halo and rms emittance significantly.