

# Observation of Emittance Growth at KEK PS

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Our concern is the beam loss during the injection period.  
Transverse beam profiles right after injection has been  
measured using flying wire monitors to search for the cure.

# Contents

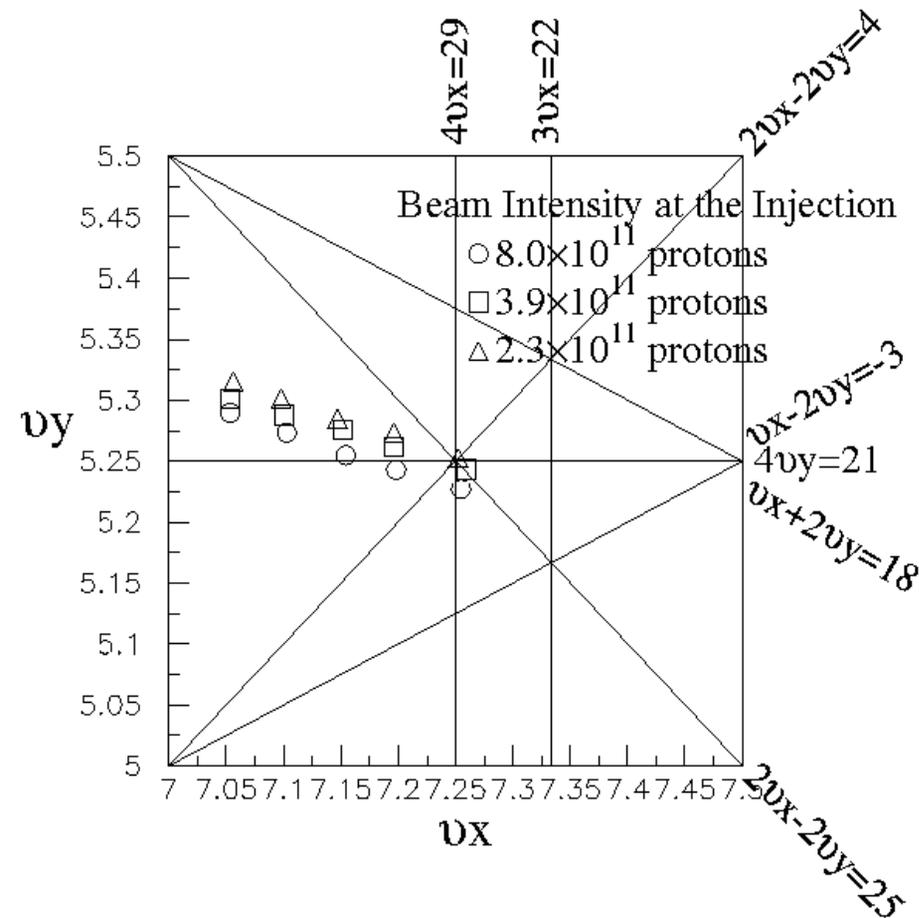
- KEK PS Main Ring and Measurement Conditions
- Horizontal profile measurements at injection using the flying wire
- ACCSIM Simulations
- Summary



# Incoherent Tune Shift in the Injection Period

- $E = 500 \text{ MeV}$
  - $2\pi RN = 8 \times 10^{11} \times 9$  : Intensity
  - $4\pi\sigma^2/\beta = 12 \pi \text{ mm mrad}$  : Emittance
  - $B_f = 0.3$  : Bunching factor
- $$\Delta\nu = \frac{2\pi RN r_0}{4\pi\sigma^2 / \beta (v/c)^2 \gamma^3 B_f} = 0.47$$
- The highest operating intensity is  $1.4 \times 10^{12}$  protons per bunch.
  - The effect of the image field or dispersion is not considered.

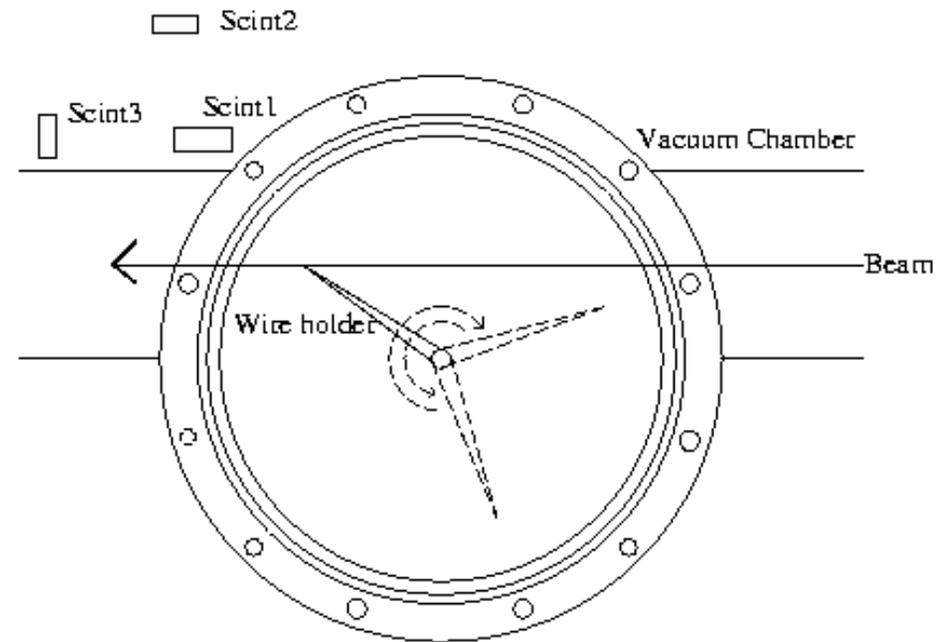
# Tune Diagram and Measurement Conditions



- Profiles were measured at 4 ms after injection for the intensity of  $8.0$ ,  $3.9$  and  $2.2 \times 10^{11}$  protons per bunch.
- Tune measurements were based on FFT results of BPM signals right after injection.
- Resonance lines of up to fourth order (normal mode) are shown.

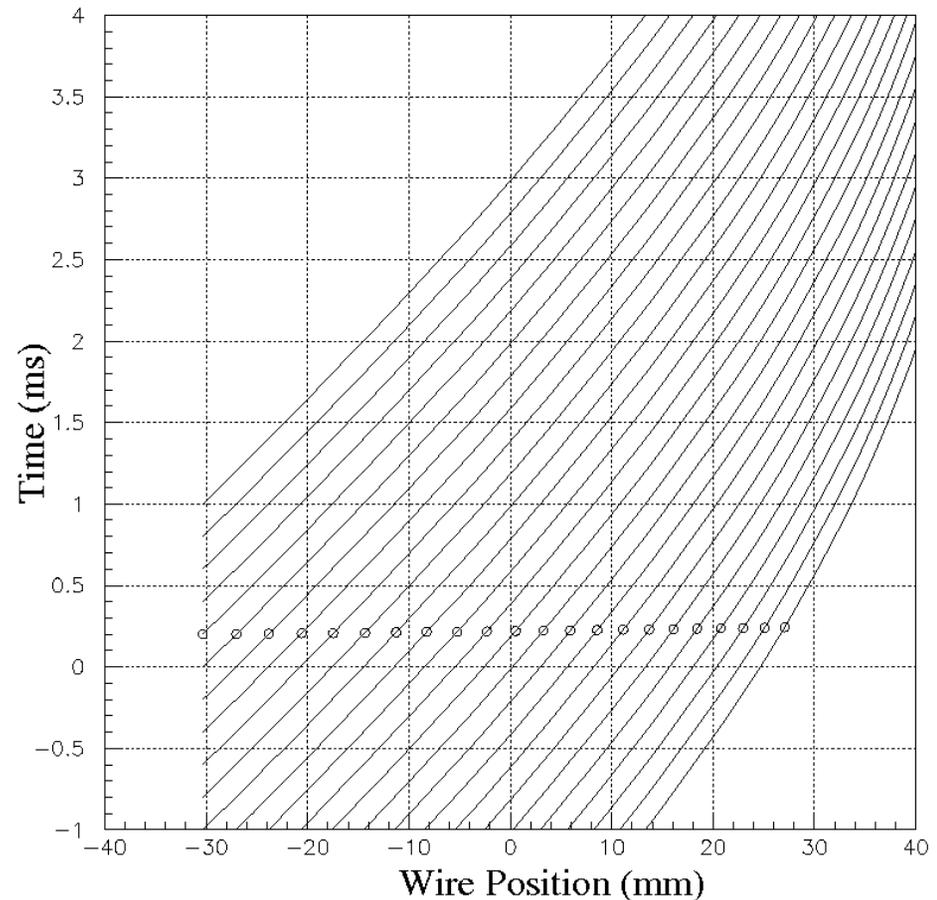
# Flying Wire Transverse Beam Profile Monitors

- Carbon fiber of 7  $\mu\text{m}$  in diameter.
- Maximum wire scanning speed of 20 m/s.
- Secondary particles from the beam-wire scattering are detected to reconstruct the beam profile.
- About 4 ms is necessary to scan the beam.



# Flying Wire

- An analysis procedure is developed to reconstruct beam profiles that rapidly change with a time scale of 1 ms or less.
- A series of profile data are acquired by changing the trigger setting with an increment of 0.2 ms.
- They are then rearranged to reconstruct the profiles after the beam injection.
- Circles in the figure indicate the data points used to reconstruct the profile at 0.2 ms after the injection.

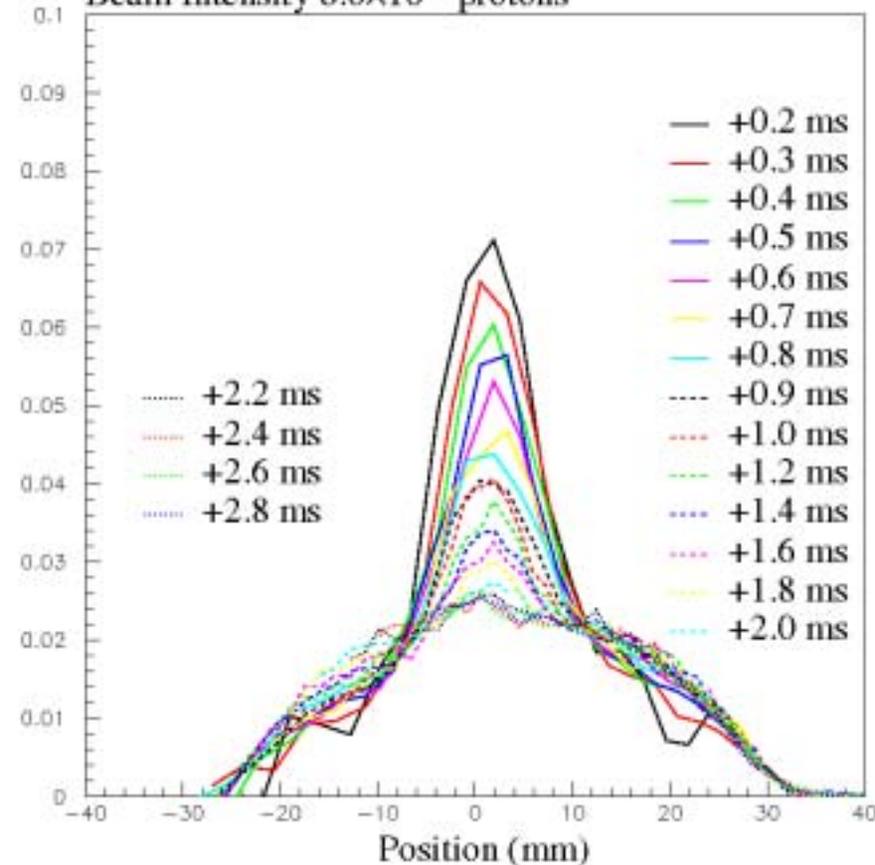


# Horizontal Beam Profiles

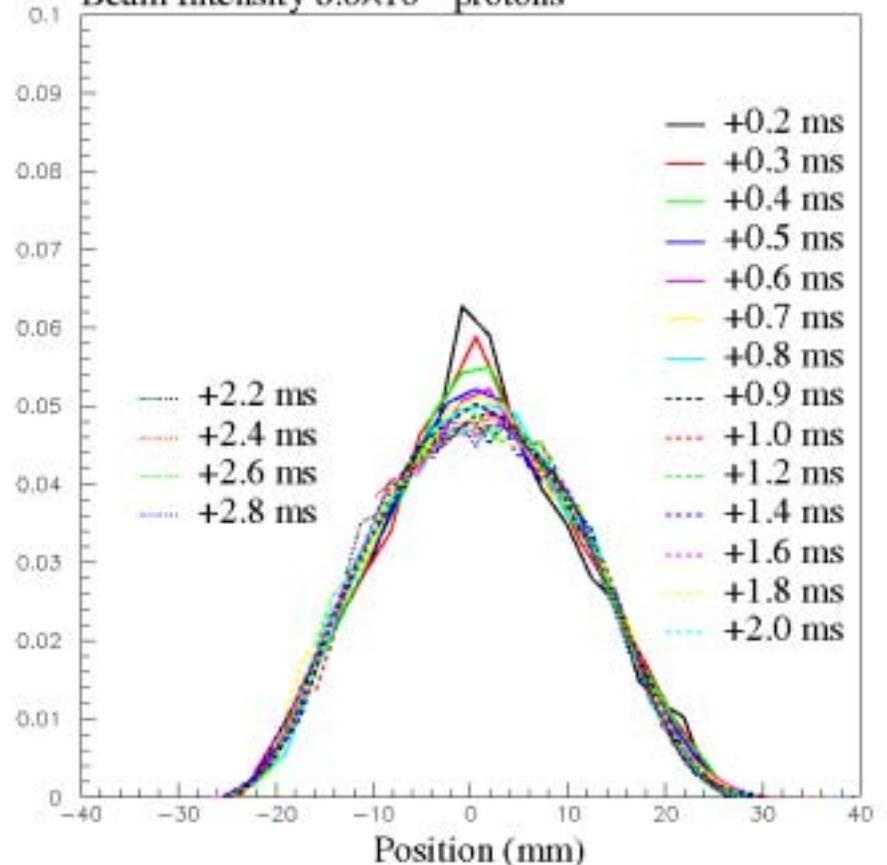
0.2 ms ~ 2.8 ms after Injection

Beam Intensity  $8.0 \times 10^{11}$  protons

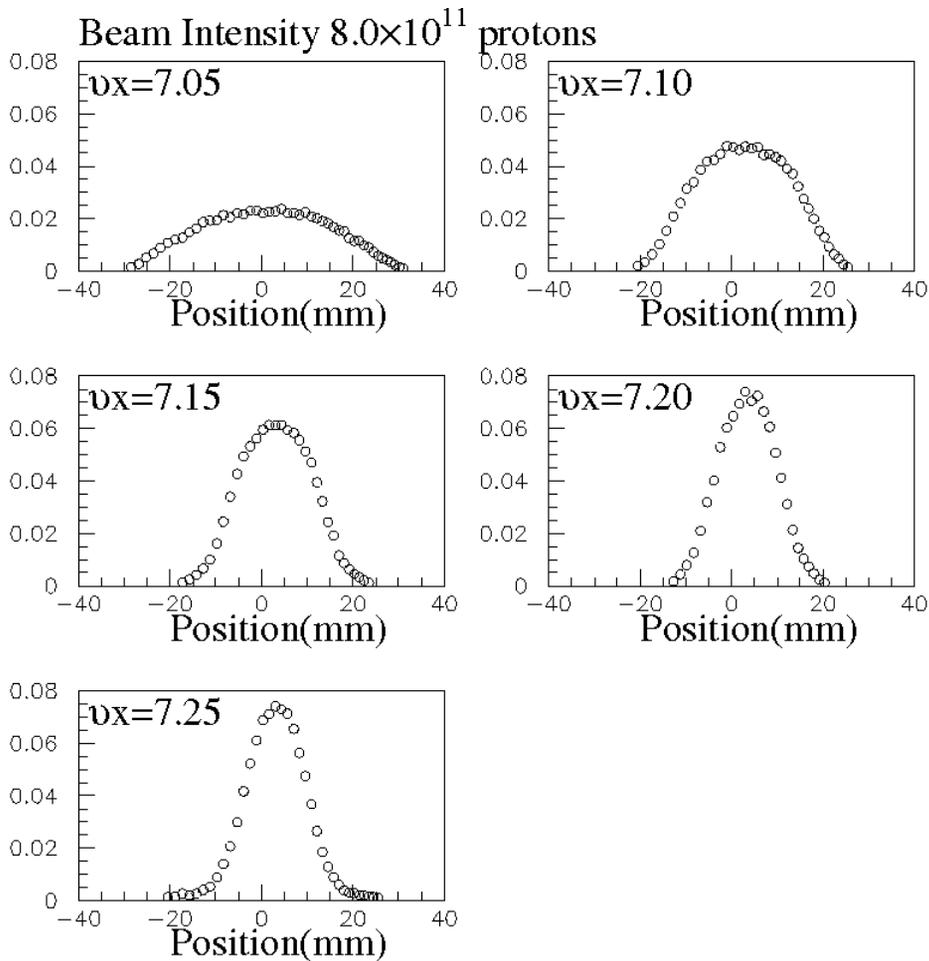
Horizontal Beam Profiles,  $v_x = 7.05$   
Beam Intensity  $8.0 \times 10^{11}$  protons



Horizontal Beam Profiles,  $v_x = 7.11$   
Beam Intensity  $8.0 \times 10^{11}$  protons



# Horizontal Beam Profiles



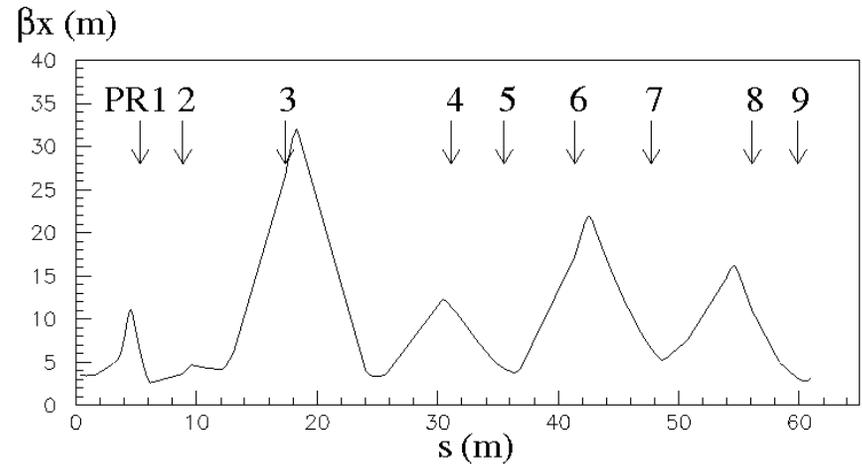
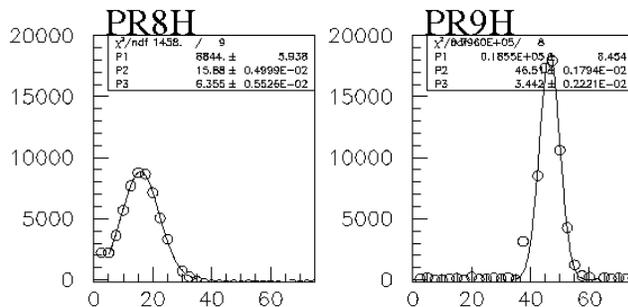
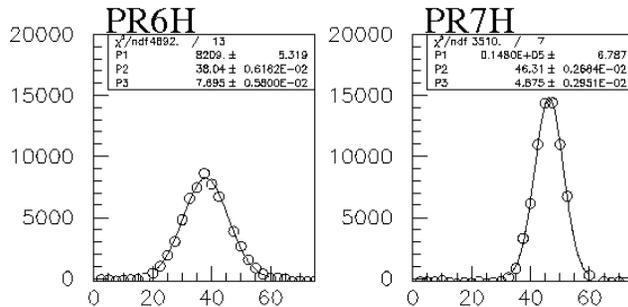
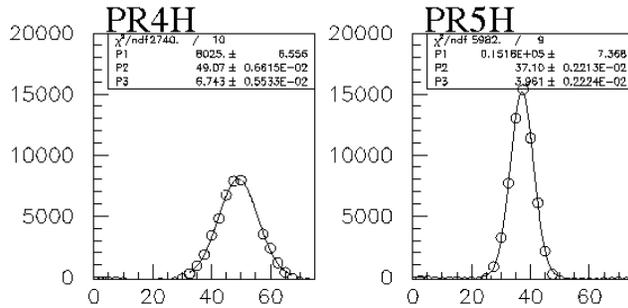
- 4 ms after injection
- Intensity:  $8.0 \times 10^{11}$  protons
- Horizontal tune: 7.05~7.25

# Injection Beam Emittance

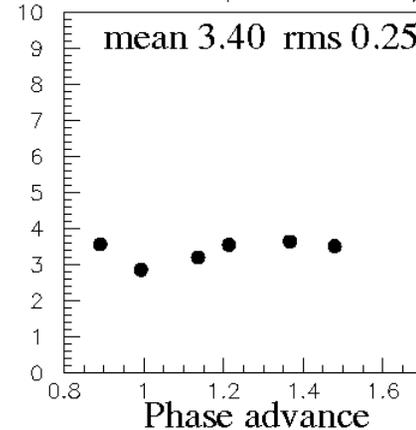
Beam transfer line profile measurements

Preliminary! About 20 % uncertainty

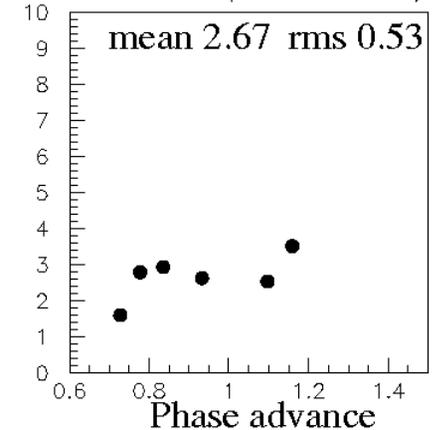
No dependence on the intensity of  $2\sim 8\times 10^{11}$  protons



Hori.  $\sigma$  emit ( $\pi$  mm mrad)

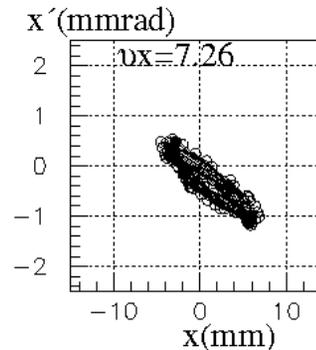
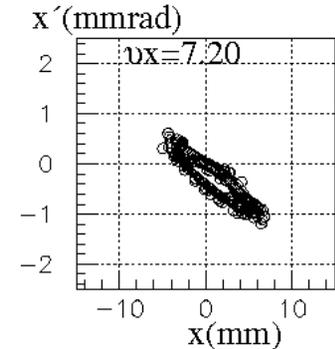
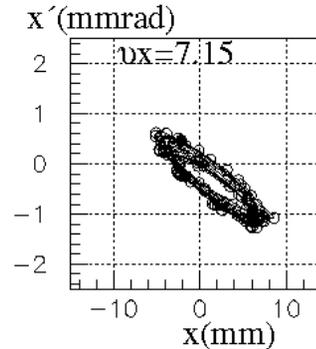
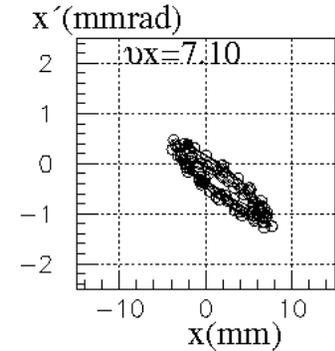
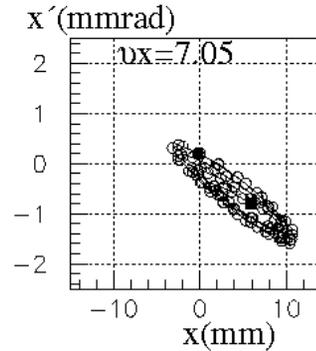


Vert.  $\sigma$  emit ( $\pi$  mm mrad)

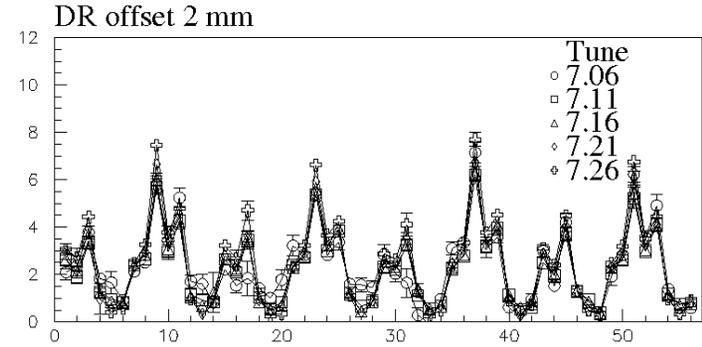
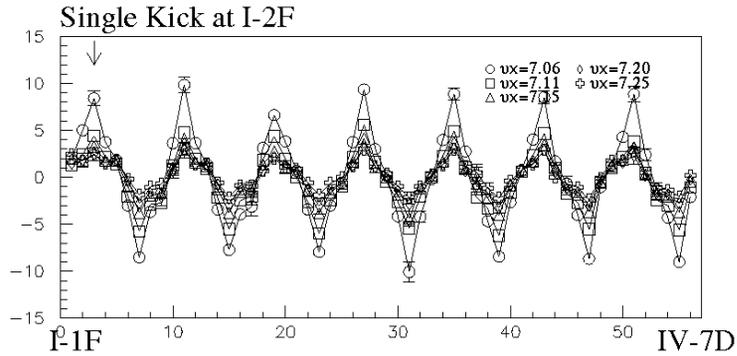


# Injection Mismatch

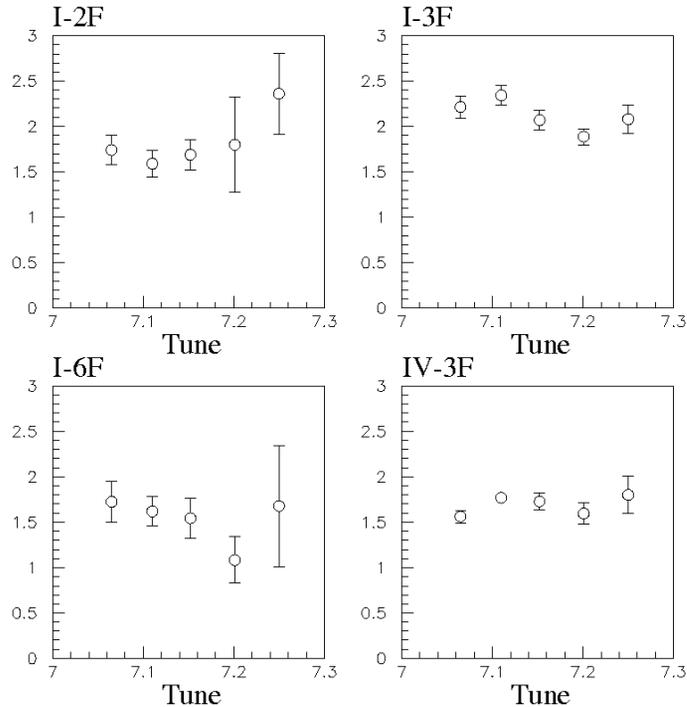
- Injection steering error
- Betatron function mismatch
- Dispersion function mismatch
- Not much tune dependence was observed.



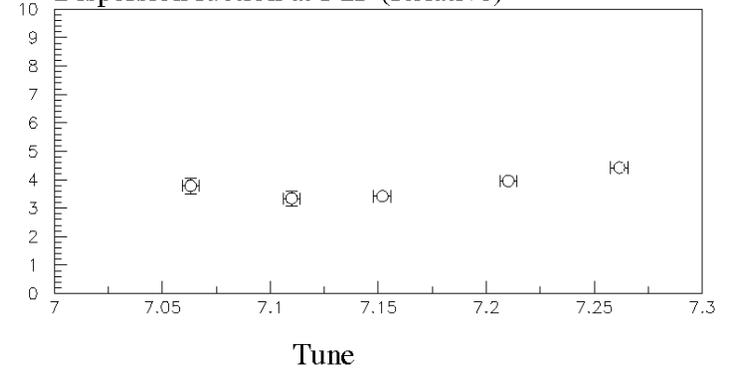
# Injection Mismatch



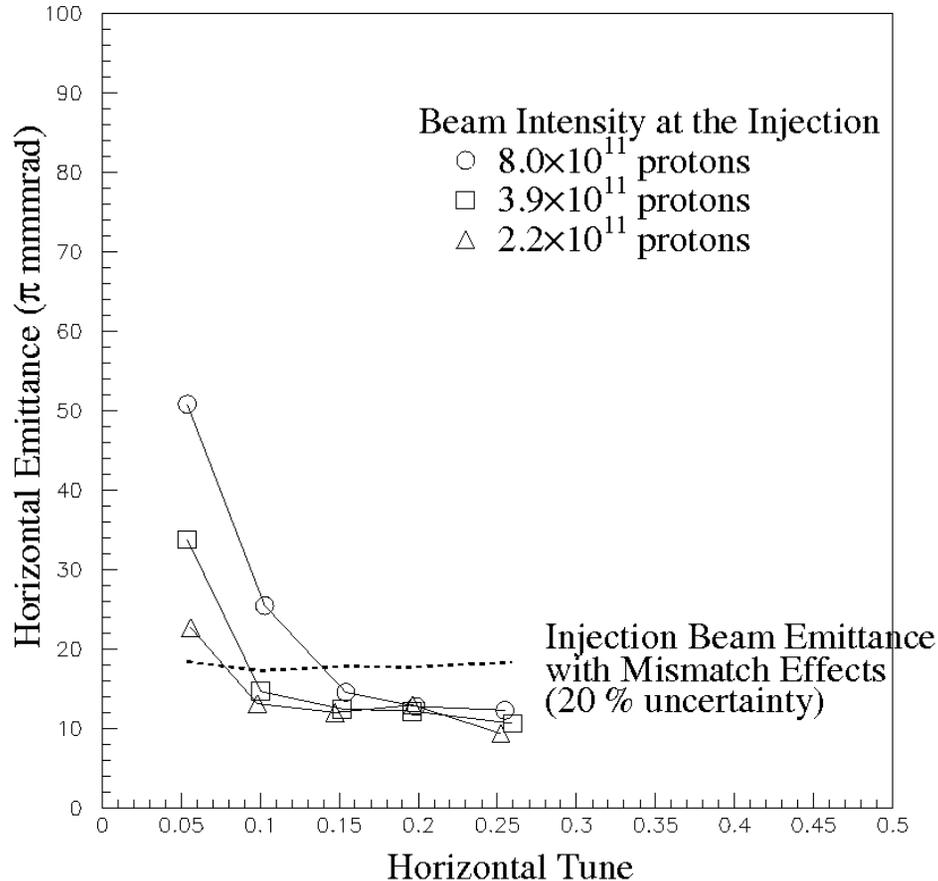
$\beta$  Function Modulation (relative)



Dispersion function at I-2F (Relative)

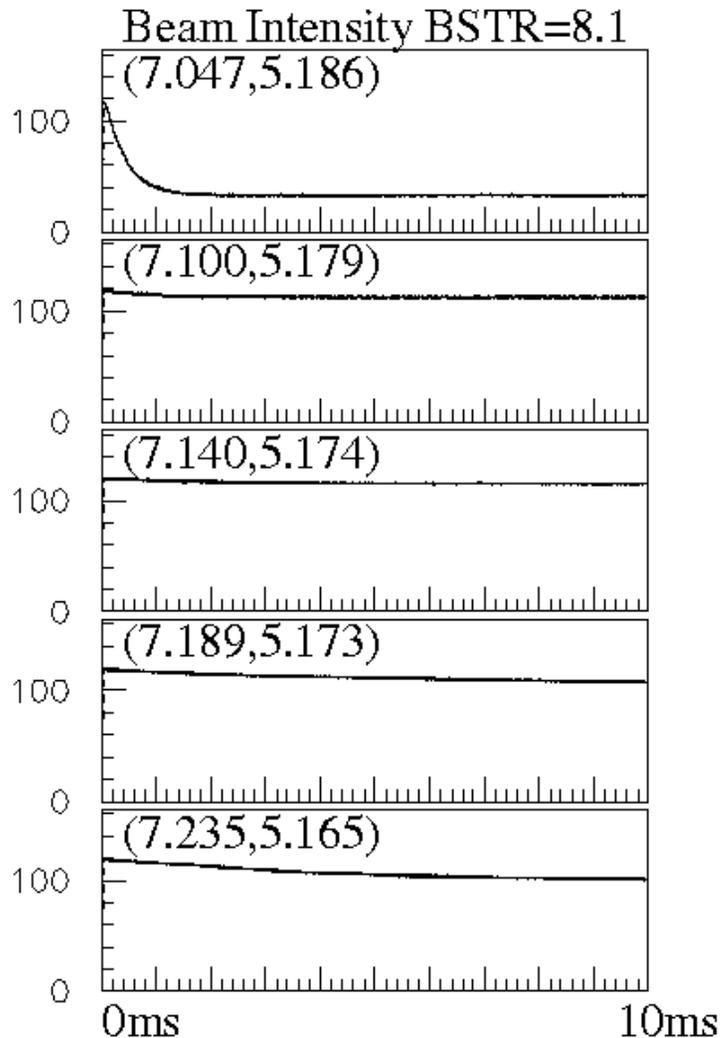


# Horizontal Emittance



- Horizontal 87% emittance as a function of the horizontal tune.
- Intensity:  $8.0, 3.9, 2.2 \times 10^{11}$  protons.
- Intensity dependence is significant when the tune is close to the integer.
- Injection beam emittance with mismatch effects are shown with the dashed line.
- Injection beam emittance measurement has uncertainty and needs to be confirmed.

# Beam Intensity



- Injection Beam Intensity:  $8.1 \times 10^{11}$  protons.
- 0~10 ms after injection.
- Beam loss is significant when the tune is close to the integer.

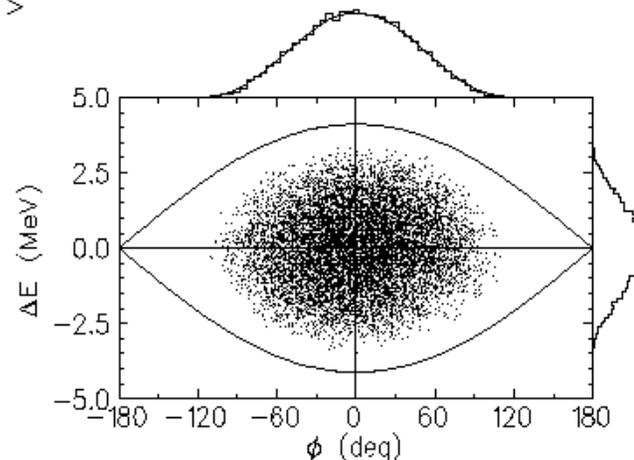
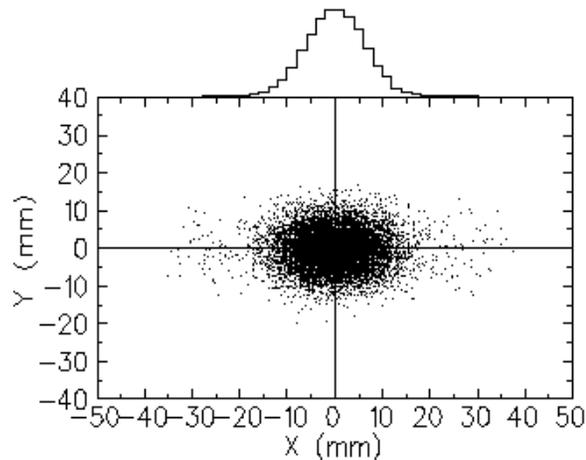
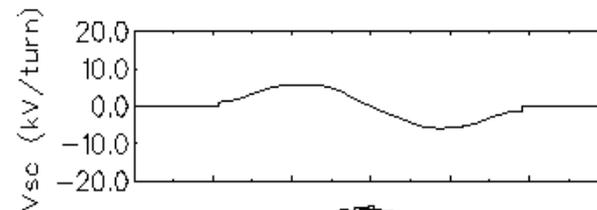
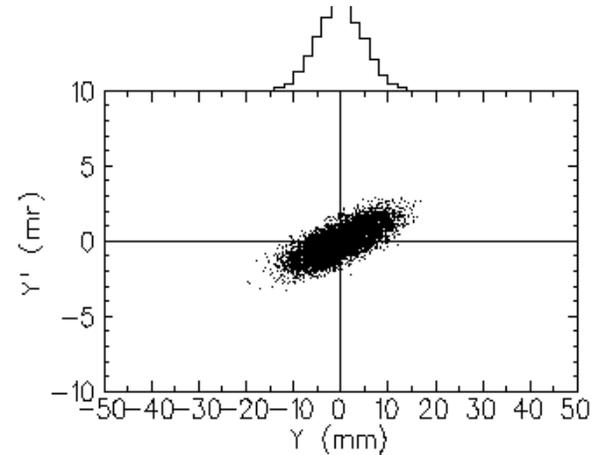
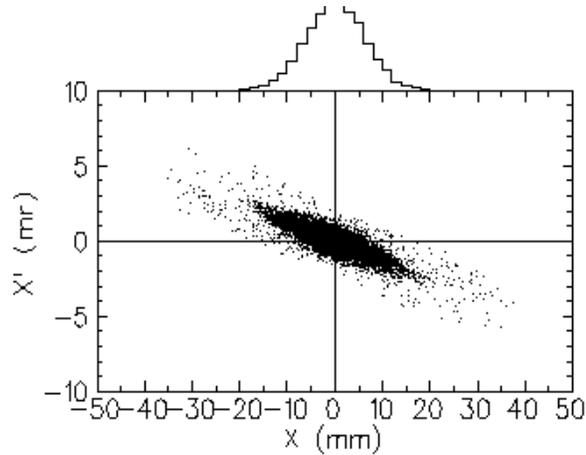
# ACCSIM Conditions

## Simulation of the Injection Period of the KEK PS Main Ring

- 3D Multiparticle simulation: 10000 Macro Particles.
- Beam Intensity: 2, 4 and  $8 \times 10^{11}$  protons
- Transverse distribution of the injection beam: Gaussian,  $12 \pi$  mmrad for both horizontal and vertical 87% emittance.
- Longitudinal distribution of the injection beam: Truncated Gaussian, Vrf set to produce the bunching factor of 0.3.
- Space charge effects (Hybrid fast-multipole technique)
- 1 mm  $\times$  1 mm grid
- 0.7575 m step, 448 steps for circumference of 340 m
- Sextupole and octupole magnets
- Thin lens kick to simulate a septum fringe field
- About 12 hours for 400 turns by HP workstation.

# ACCSIM Simulations

$8 \times 10^{11}$  protons, (7.05, 5.21), 10 turn after the injection



# ACCSIM Simulations

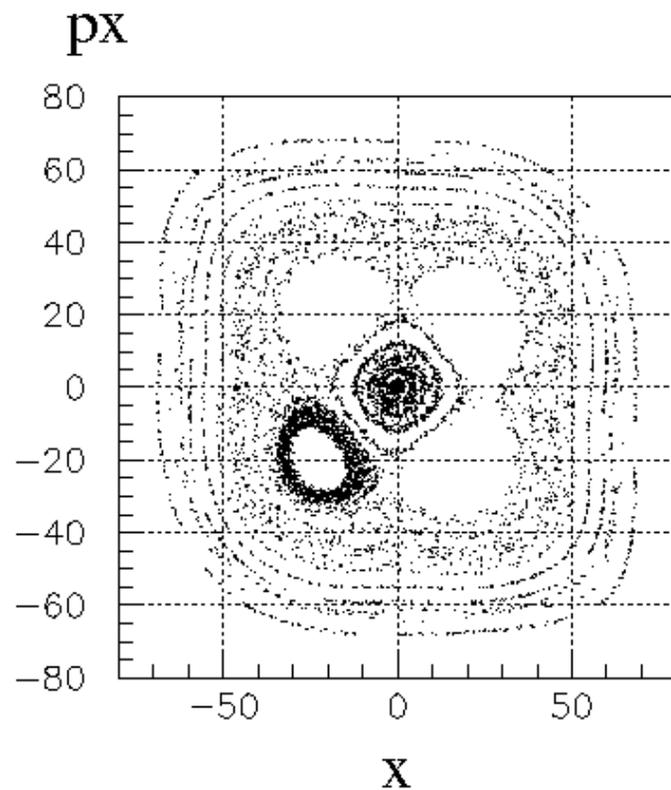


Figure 1

Phase space plot of 20 test particles for 400 turns.

Intensity  $8 \times 10^{11}$  protons

(7.05, 5.21)

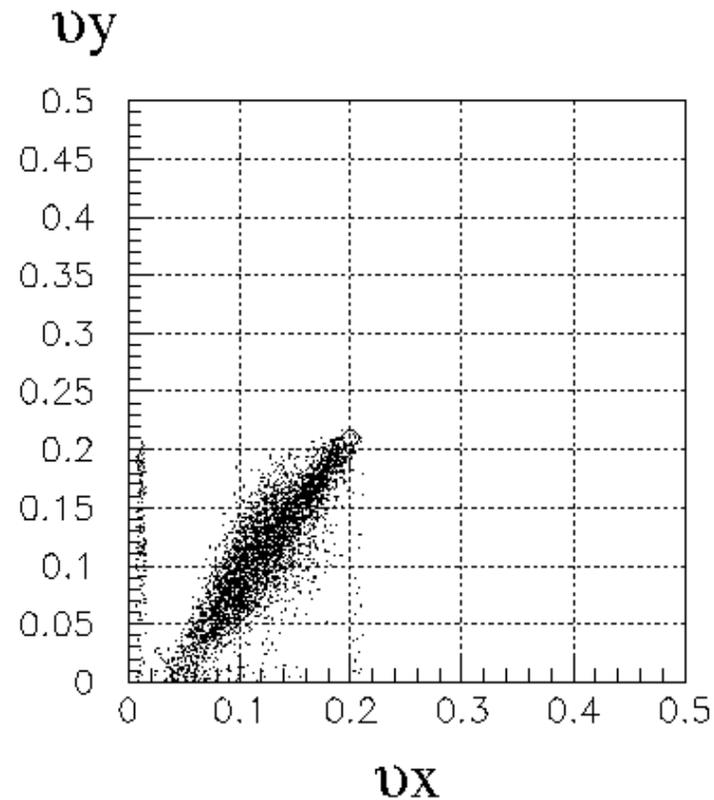


Figure 2

FFT results of 128 turns of 10000 macro particles.

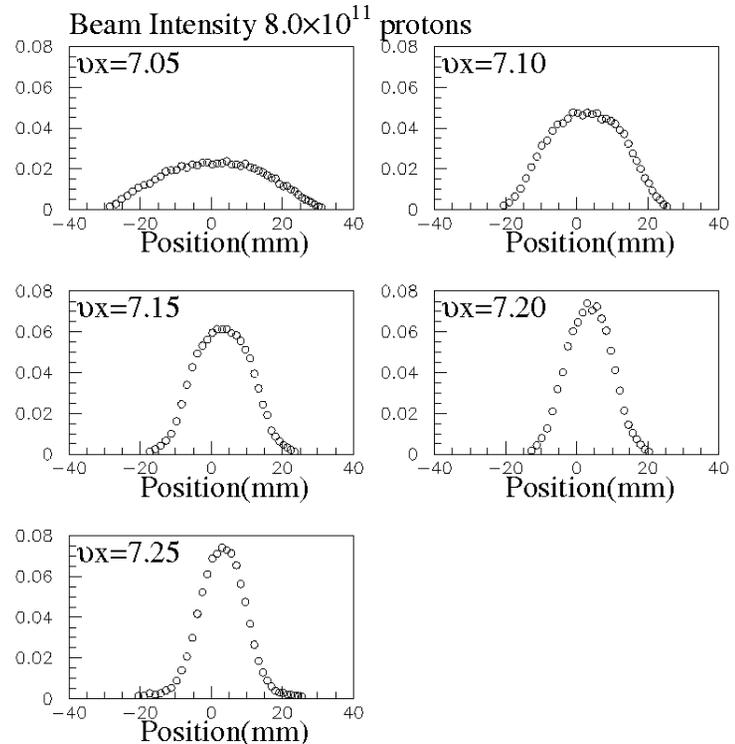
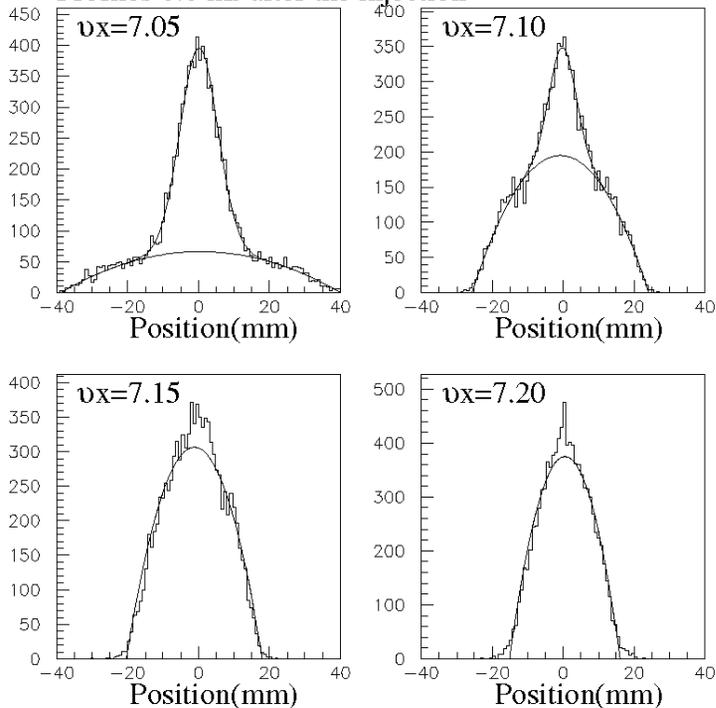
$4 \times 10^{11}$  protons

(7.20, 5.21)

# ACCSIM simulations

## Horizontal Profiles for the horizontal tune of 7.05~7.20

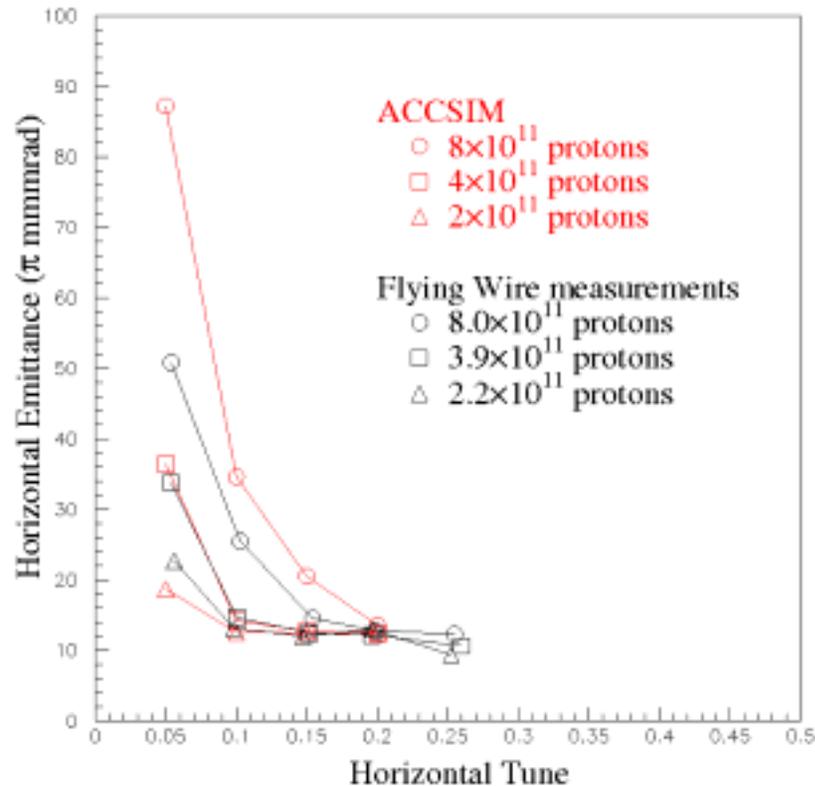
ACCSIM simulations, Intensity  $8 \times 10^{11}$  protons  
Profiles 0.6 ms after the injection



- ACCSIM profiles are fitted with a Gaussian plus a parabolic function for the tune of 7.05 and 7.10, and with a parabolic function for the tune of 7.15 and 7.20.
- Only the parabolic distribution are assumed to remain after 4 ms and to be compared with the measured profiles.

# Horizontal Emittance

## ACCSIM and Flying Wire Measurements



- Emittance is defined to include the fraction of 87 %.
- The agreement is good for the intensity of  $4 \times 10^{11}$  protons.
- ACCSIM results are about 1.4 times of the measured emittance for the intensity of  $8 \times 10^{11}$  protons.

# Summary

- Modulations of the transverse beam profiles depending on the intensity and tune have been observed during the injection period of the KEK PS main ring.
- Fourth order resonance created by the space charge force causes the modulations.
- The effects have been qualitatively reproduced by the ACCSIM simulations.
- The quantitative comparison will be homework.
  - Injection beam emittance measurement has to be revisited.
  - Mechanism to modify the resonance width may be considered such as effects of the betatron function modulation.