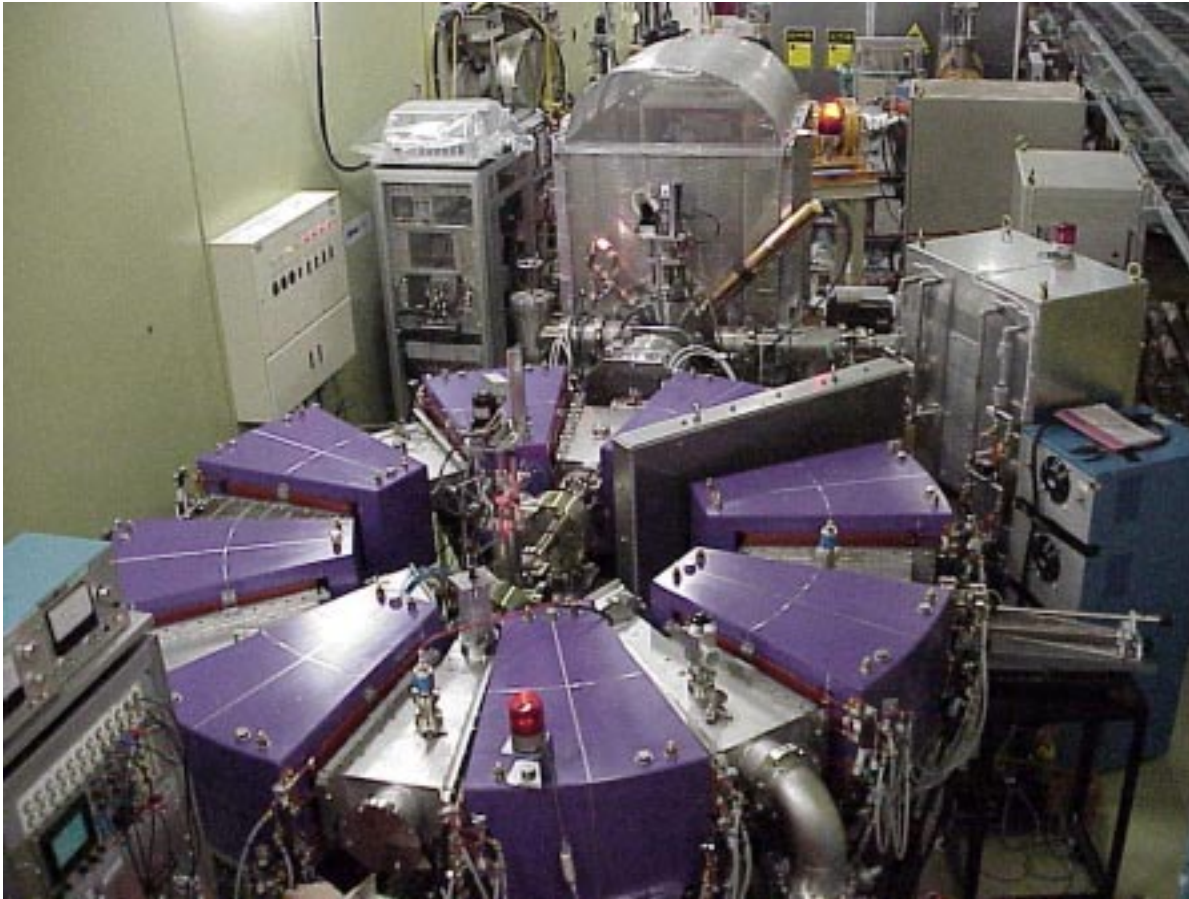


Status of PoP-FFAG Beam Study

Masahiro Yoshimoto @ KEK FFAG group

- contents ! -



1.introduction

2.hardware

3.measurements of
the machine parameters

- betatron tune

- fast acceleration

- multi-turn injection

4.studies of

the beam dynamics

- Acceptance Survey

- RF knockout &

betatron tune

- fast acceleration &

resonance crossing

5.summary

Introduction

*What is the PoP-FFAG synchrotron?

- It is the world first FFAG proton synchrotron .
- It was constructed in KEK in 2000.

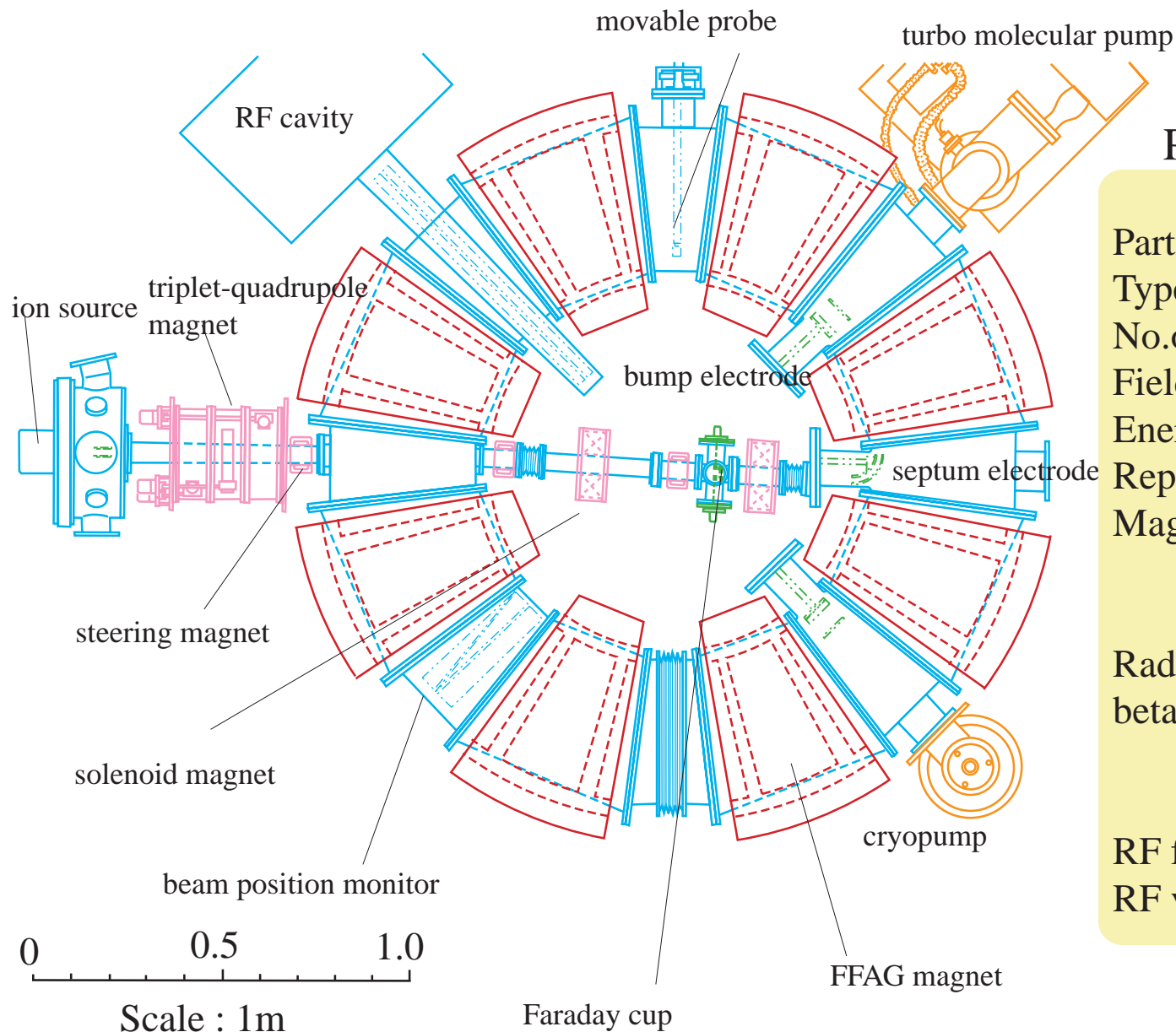
*Why did we construct the PoP-FFAG ?

- It was demonstrated that the proton could be accelerated within 1msec in FFAG synchrotron.

*What is today's topics ?

- the measurements of the machine parameters
- the studies of the beam dynamics in the PoP-FFAG

Top View of PoP-FFAG Accelerator

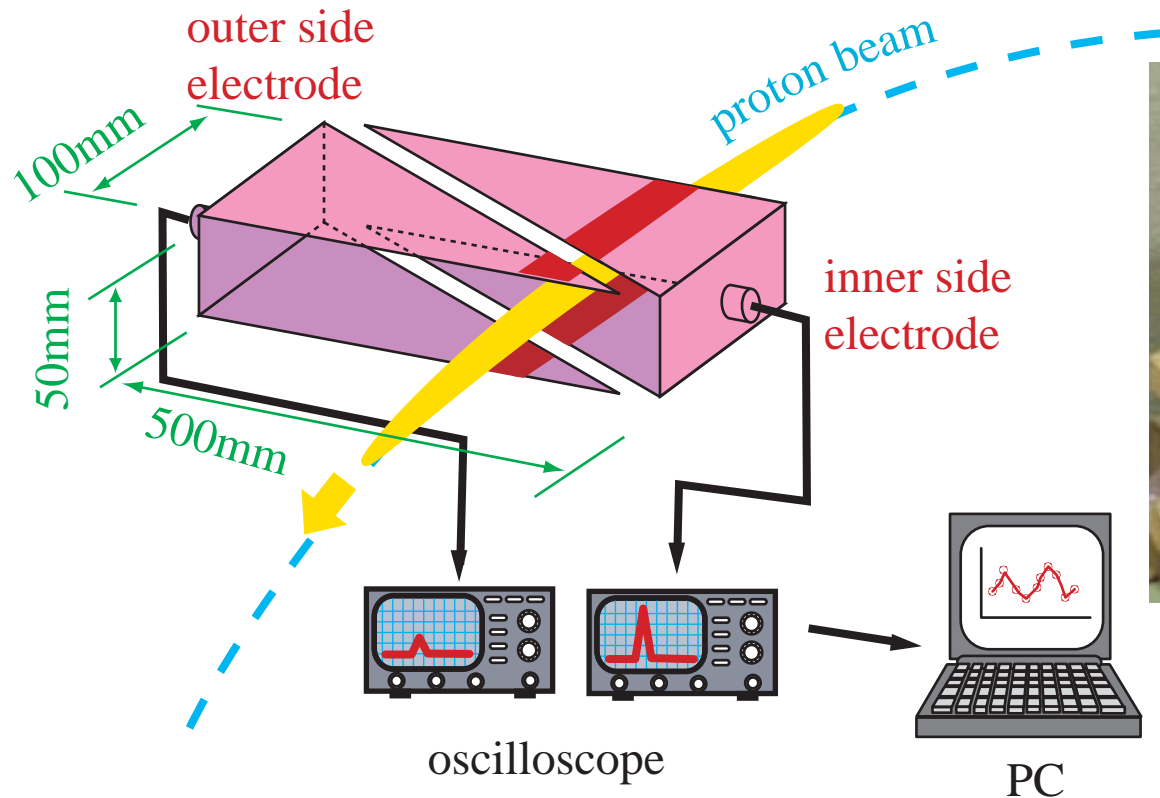


PoP-FFAG parameter table

Particle	proton
Type of magnet	radial sector type
No. of sector	8
Field index	$k=2.5$
Energy	50keV => 500keV
Repetition rate	1kHz
Magnetic field	
Focus-mag.	0.14 - 0.32 T
Defocus-mag.	0.04 - 0.13 T
Radial of closed orbit	0.81 - 1.14m
betatron tune	
horizontal	2.17 - 2.22
vertical	1.24 - 1.26
RF frequency	0.61 - 1.38MHz
RF voltage	1.3 - 3.0kVp

Beam Position Monitor (BPM)

horizontal BPM

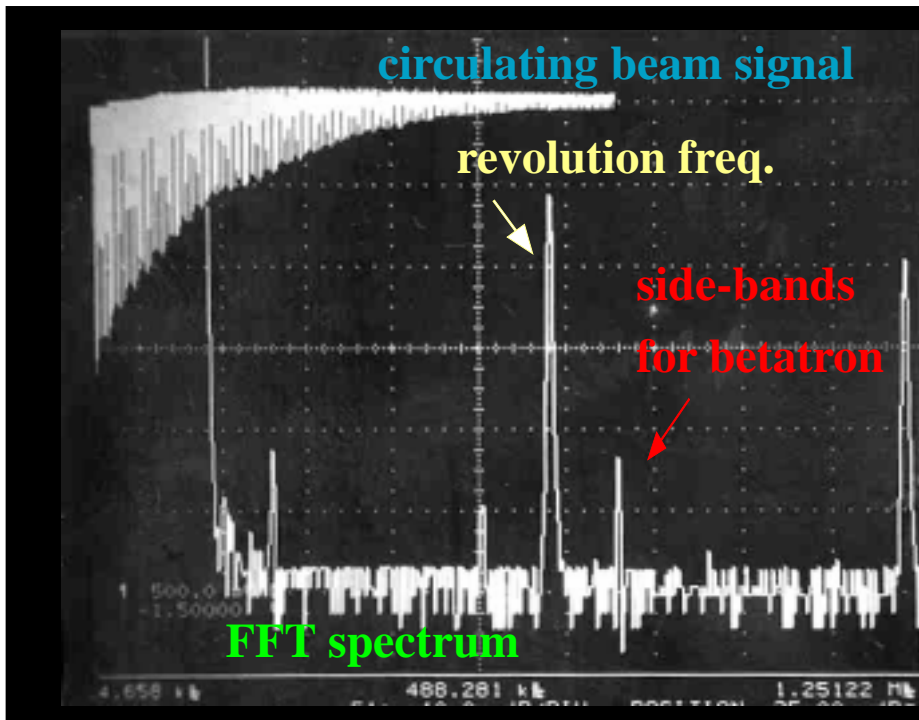


**In FFAG, beam orbit shifts during the acceleration.
=> BPM must have large horizontal aperture.**

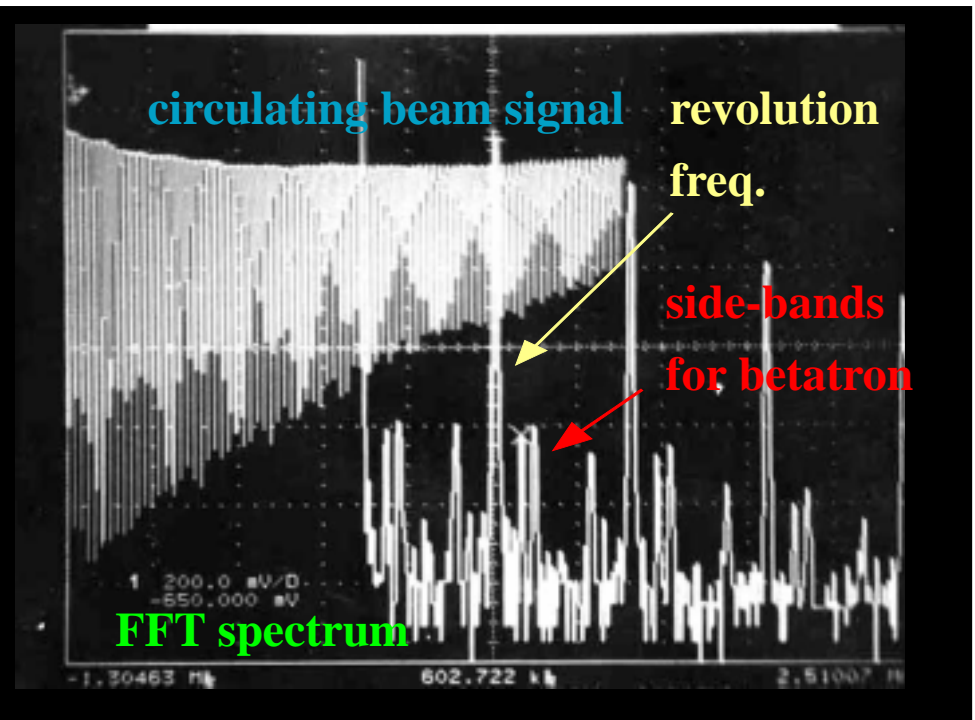
The measurements of the machine parameters.

Betatron Tune (1)

Horizontal beam signal



Vertical beam signal



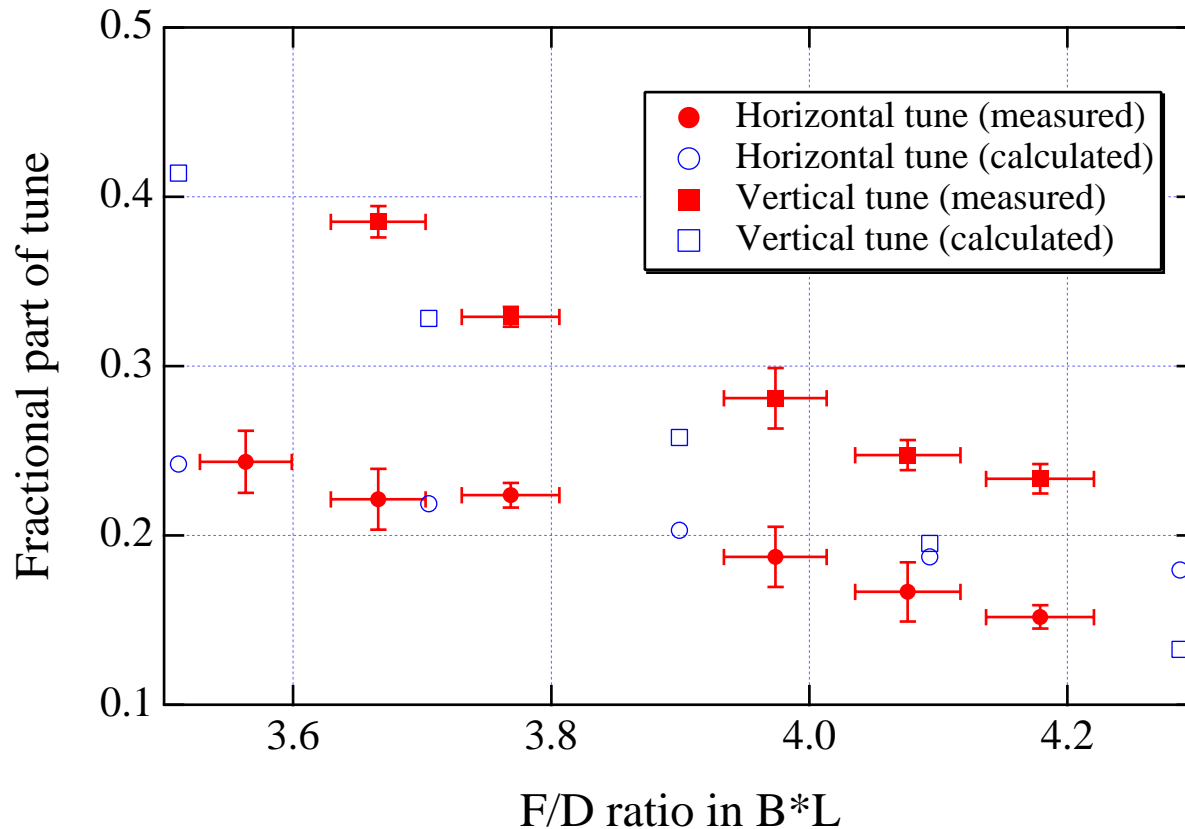
fractional part of betatron tune

$$\mu_h = 0.199$$

$$\mu_v = 0.289$$

Betatron Tune (2)

betatron tune vs F/D ratio



Betatron tune shift as a function of F/D ratio:

- vertical

=> shift !!

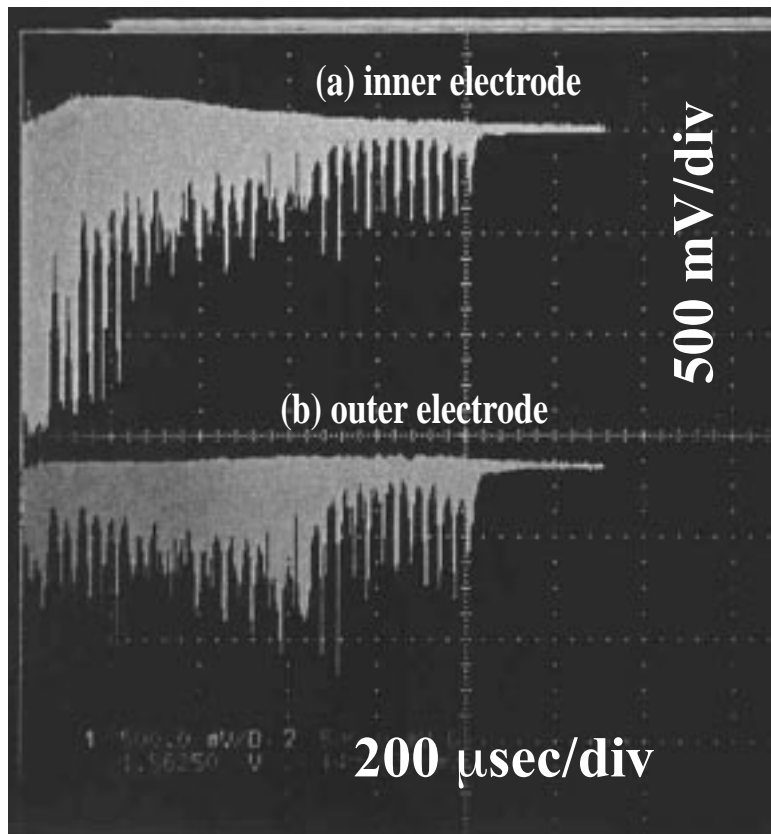
- horizontal

=> almost constant !!

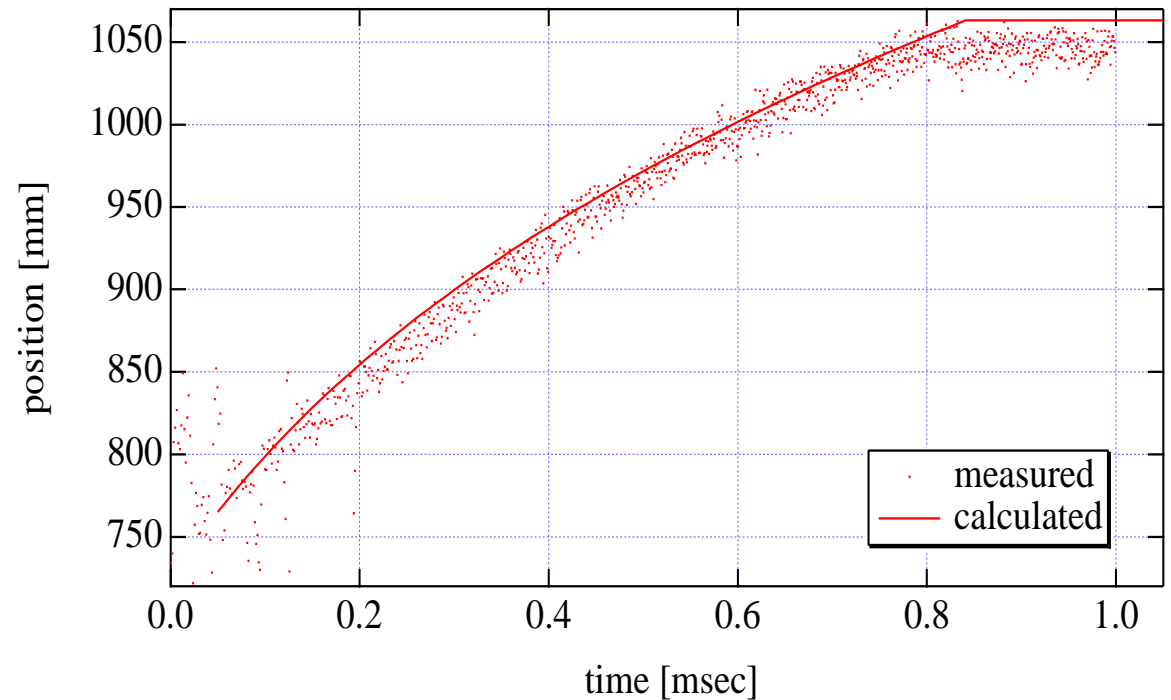
The vertical betatron tune is adjustable changing F/D ratio !

Beam Acceleration

BPM signals during the acceleration



beam orbit shift

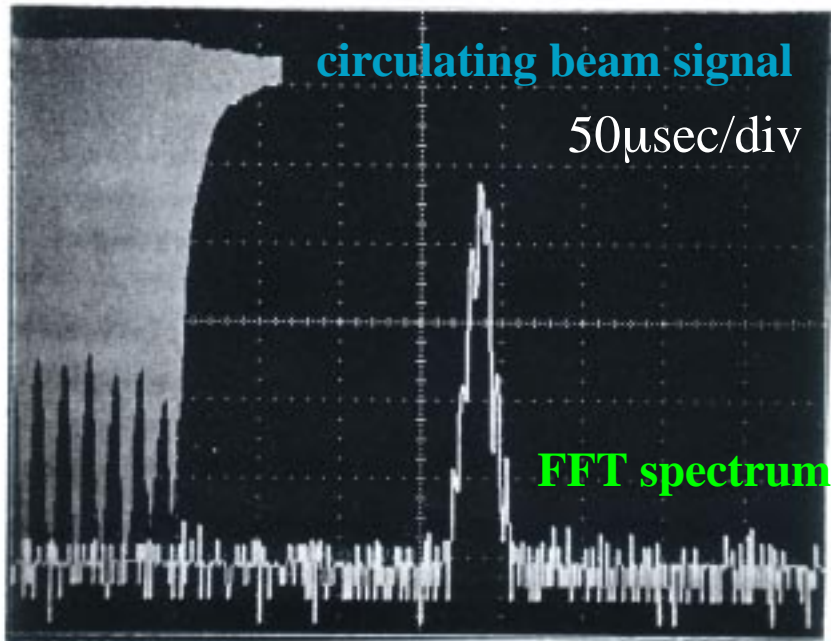


The beam is accelerated from 50keV to 500keV within 1msec.

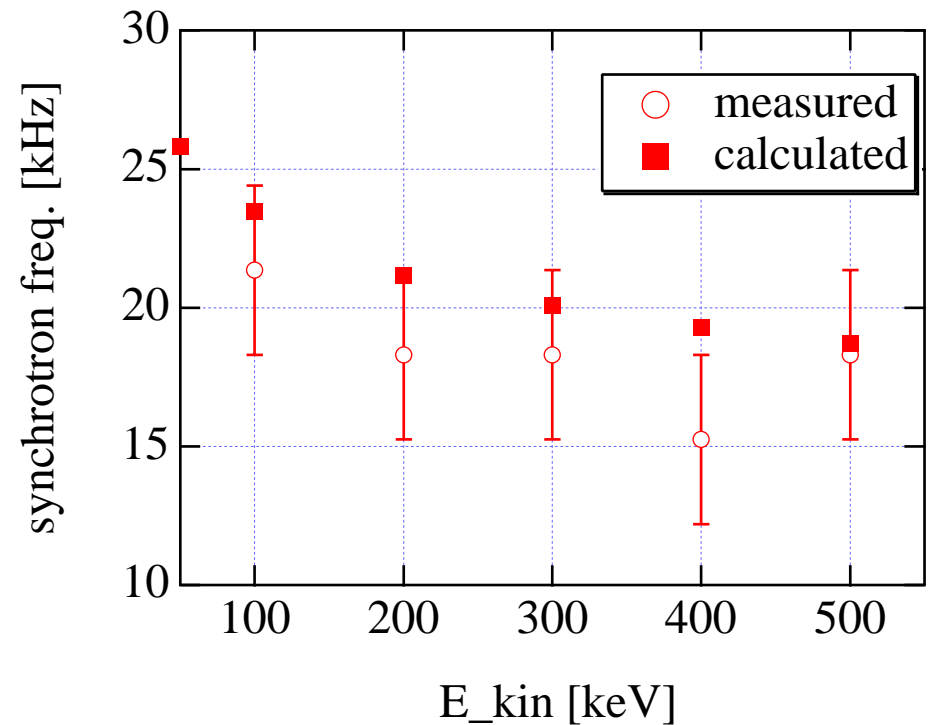
=> The beam orbit shifts from 765mm to 1050mm.

Synchrotron Frequency

at 500keV (flat top)



synchrotron freq. vs E_{kin} @flat top



revolution frequency:

1.379MHz

synchrotron frequency:

18.3kHz

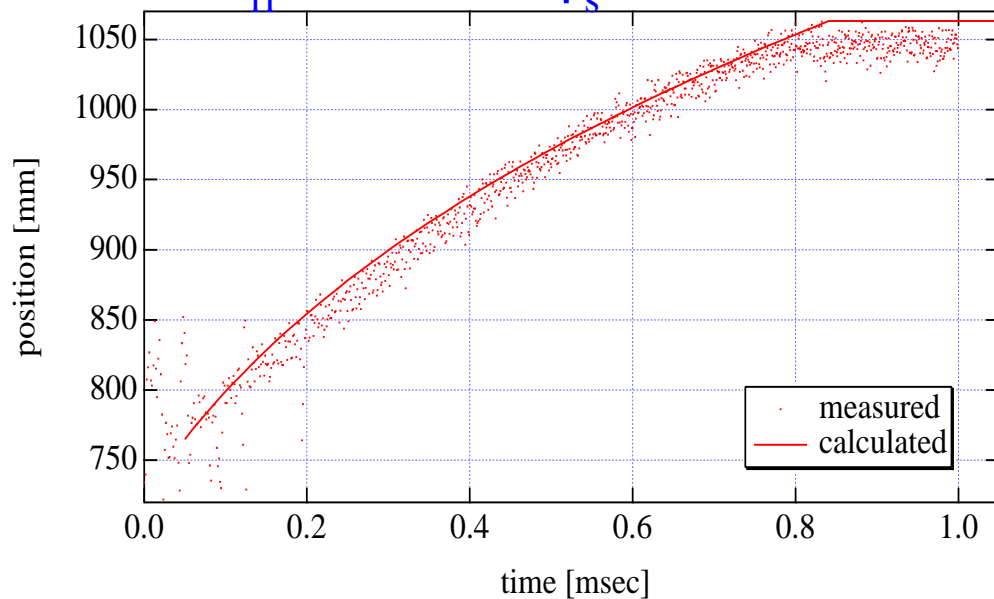
The observed synchrotron frequency agreed with those expected by the beam simulation.

RF pattern

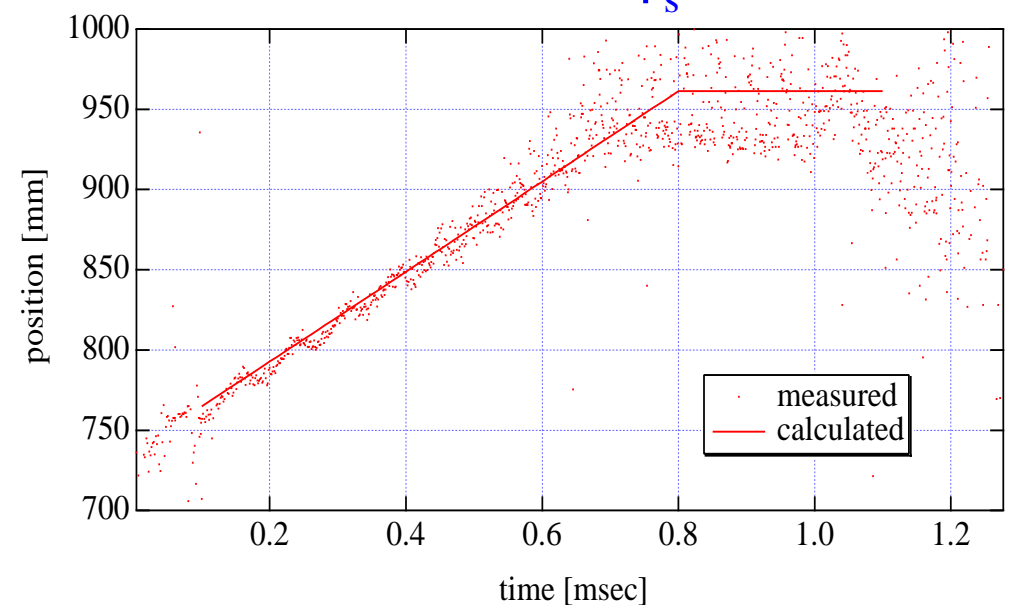
	magnetic field	RF pattern
ordinary synchrotron	changing	with regarding the magnet
FFAG synchrotron	constant	without regarding the magnet

=> RF pattern can be flexibly designed in FFAG synchrotron !

$$V_{rf} = \text{const.} \quad \phi_s = \text{const.}$$

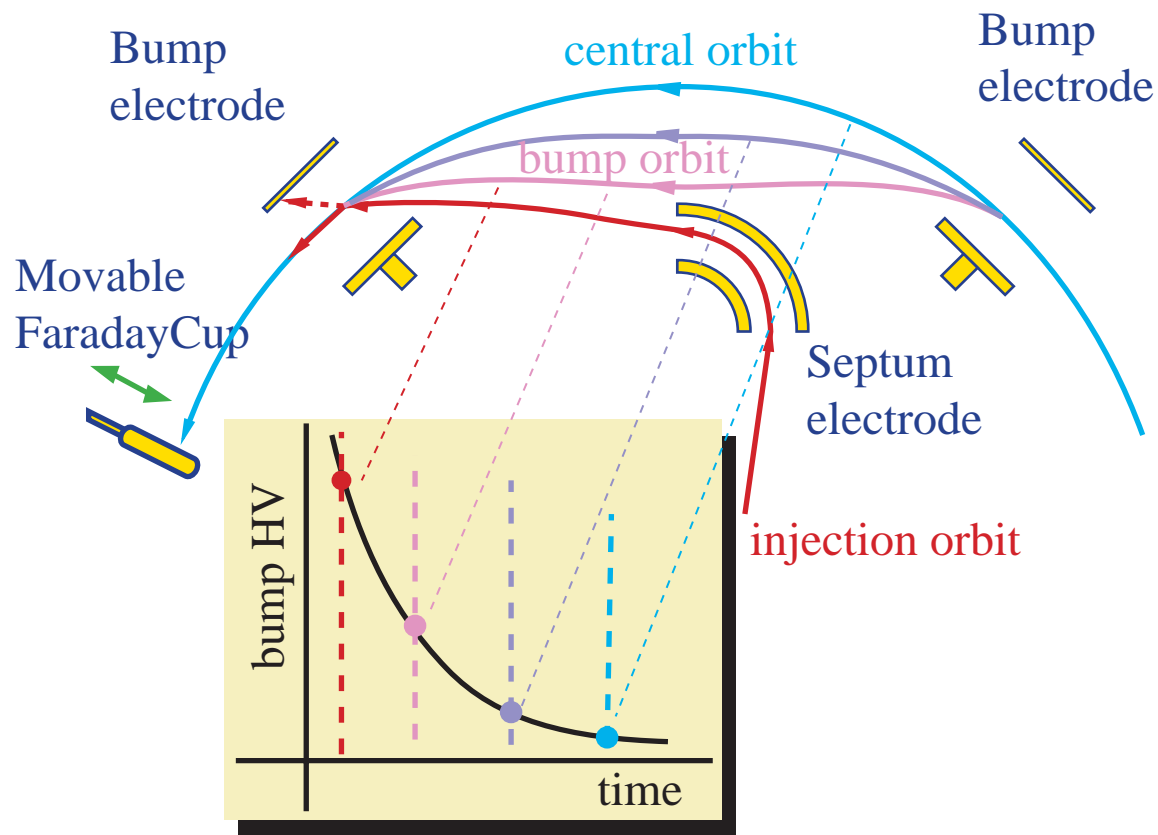


$$dr/dt = \text{const.} \quad \phi_s = \text{const.}$$

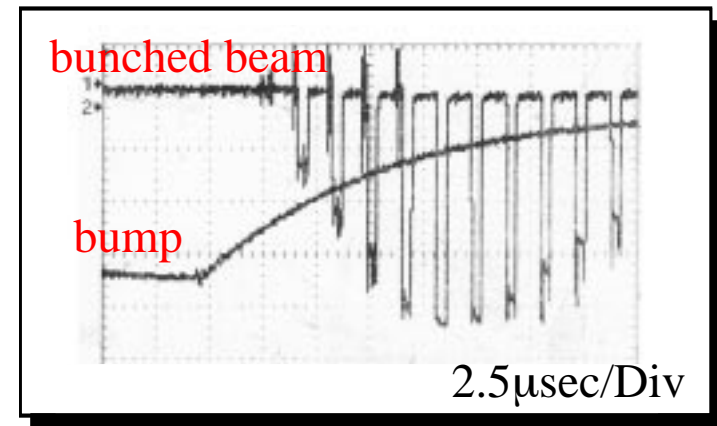


The various acceleration pattern is possible in PoP-FFAG.

Multi-turn Injection System



slow decay time of bump voltage
(decay time \gg revolution period)



=> multi-turn injection

The slow decay operation makes the multi-turn injection in possible.

Multi-turn Injection

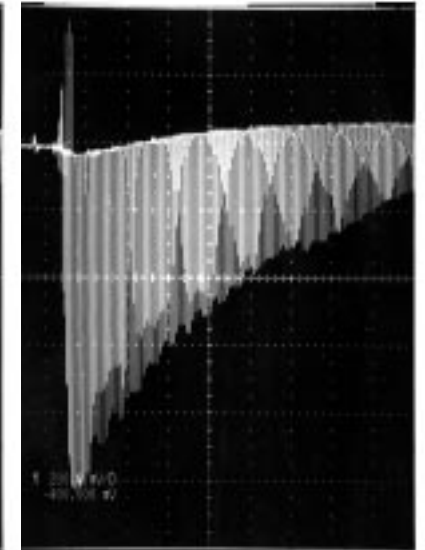
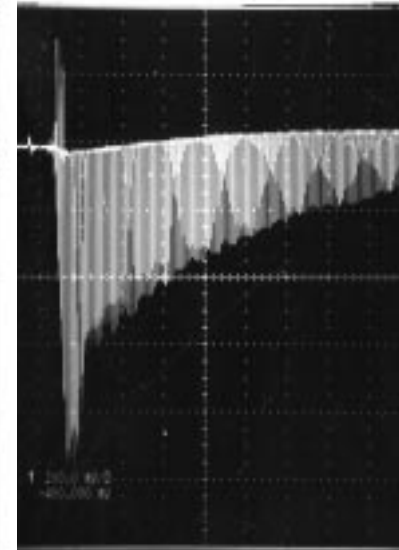
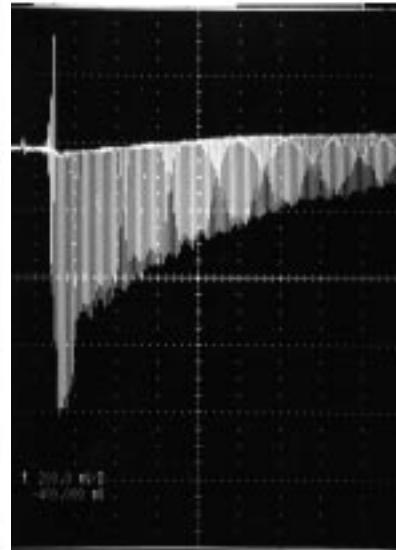
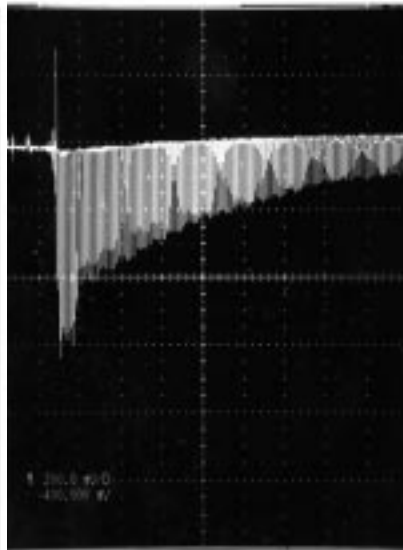
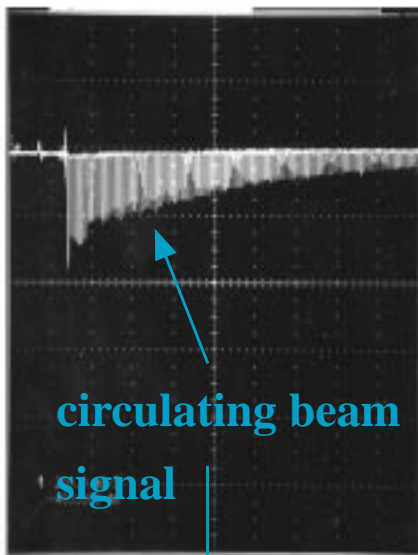
1bunch inj.

2bunches inj.

3bunches inj

4bunches inj.

5bunches inj

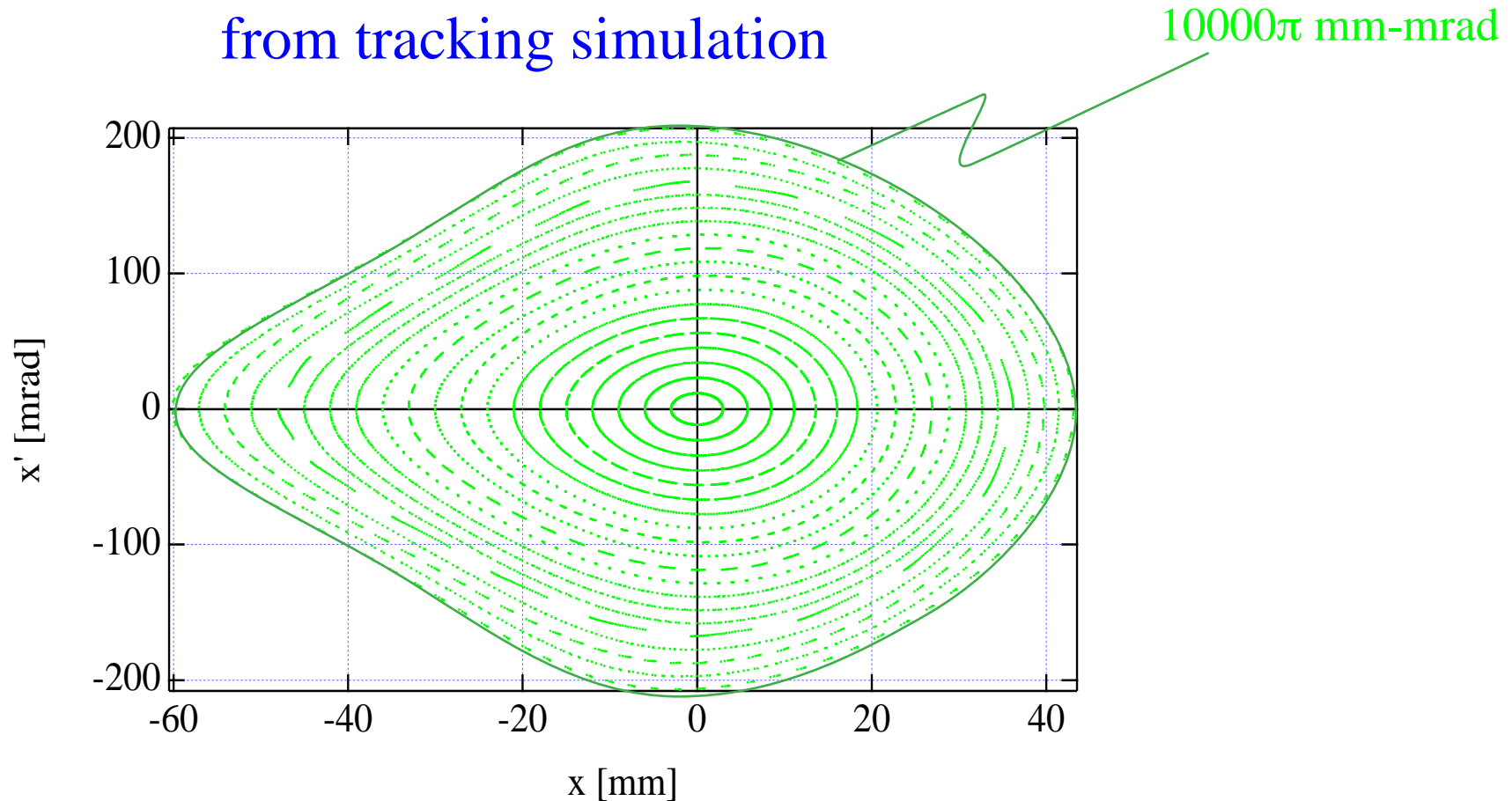


The beam intensity can be increased with multi-turn injection.

The Studies of the beam dynamics in the PoP-FFAG.

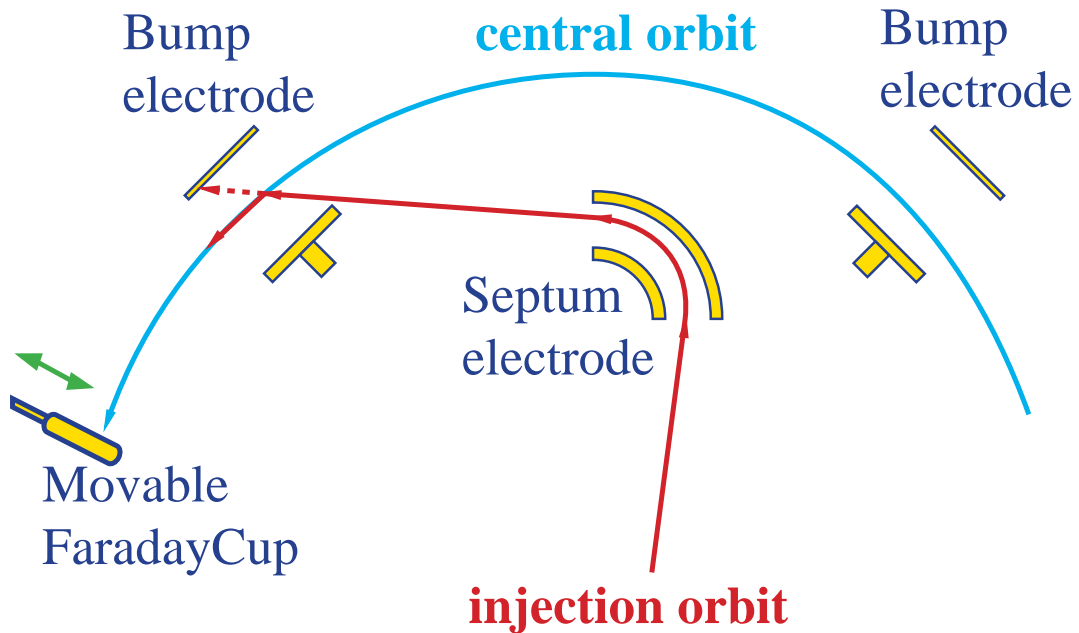
Horizontal Acceptance

horizontal acceptance @ injection energy
from tracking simulation

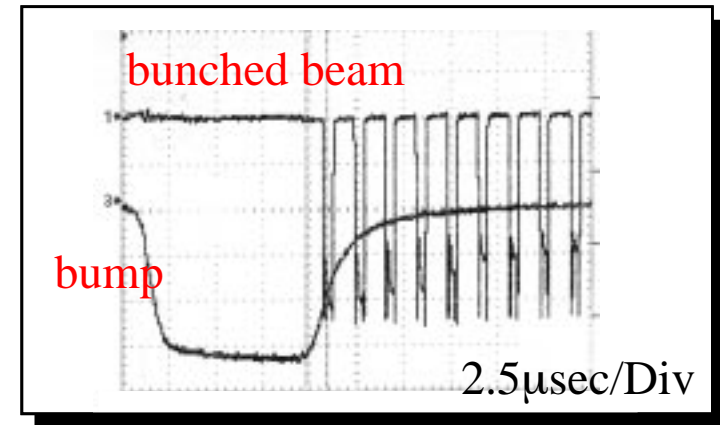


FFAG synchrotron has a large horizontal acceptance.

Injection System for Acceptance Survey



fast decay time of bump voltage
(decay time \sim revolution period)



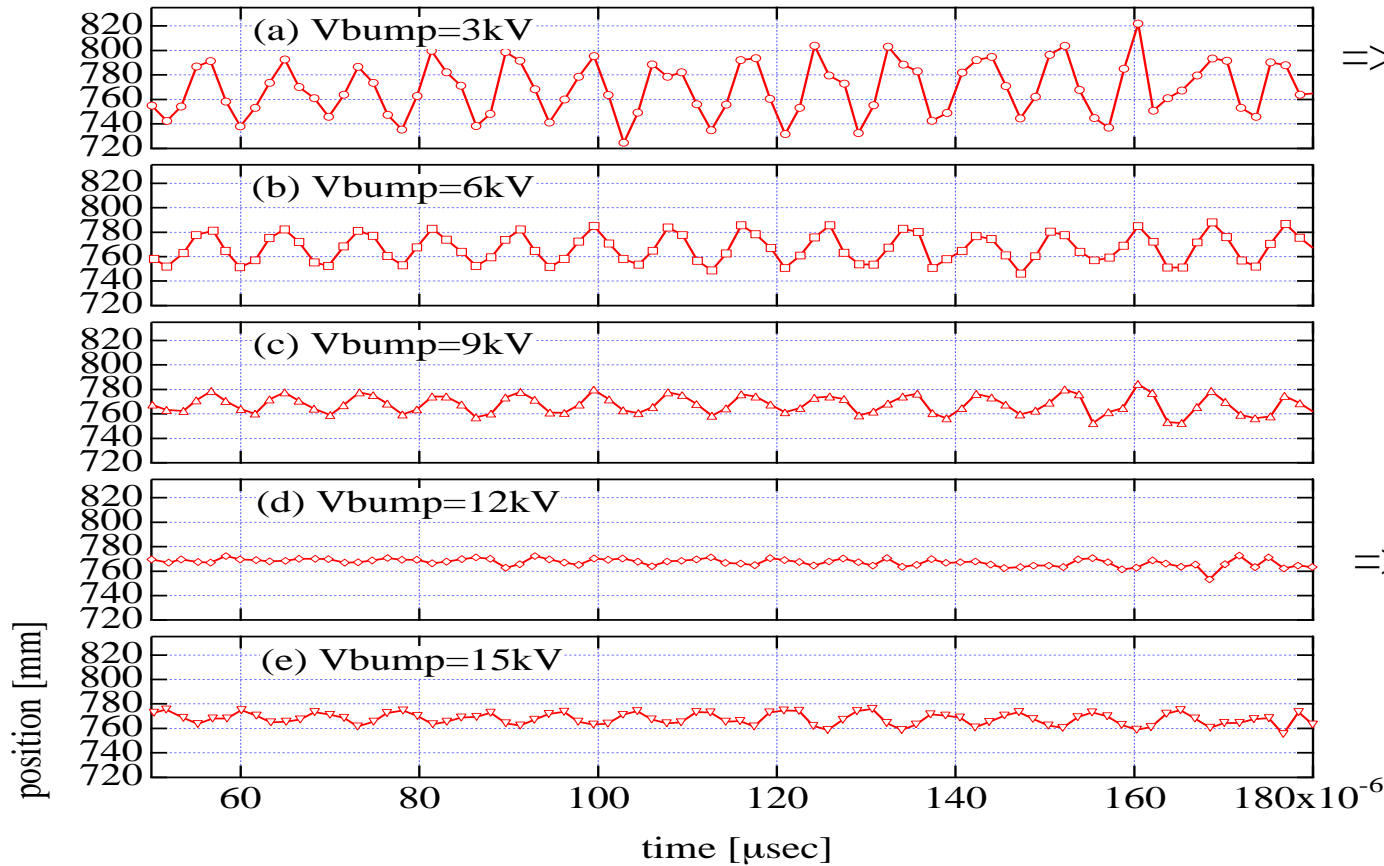
\Rightarrow working as a fast kicker

At the fast decay operation, the bump works as a fast kicker .

Horizontal acceptance survey (1)

The beam oscillations with various betatron motion

at the 2kV no signal !!

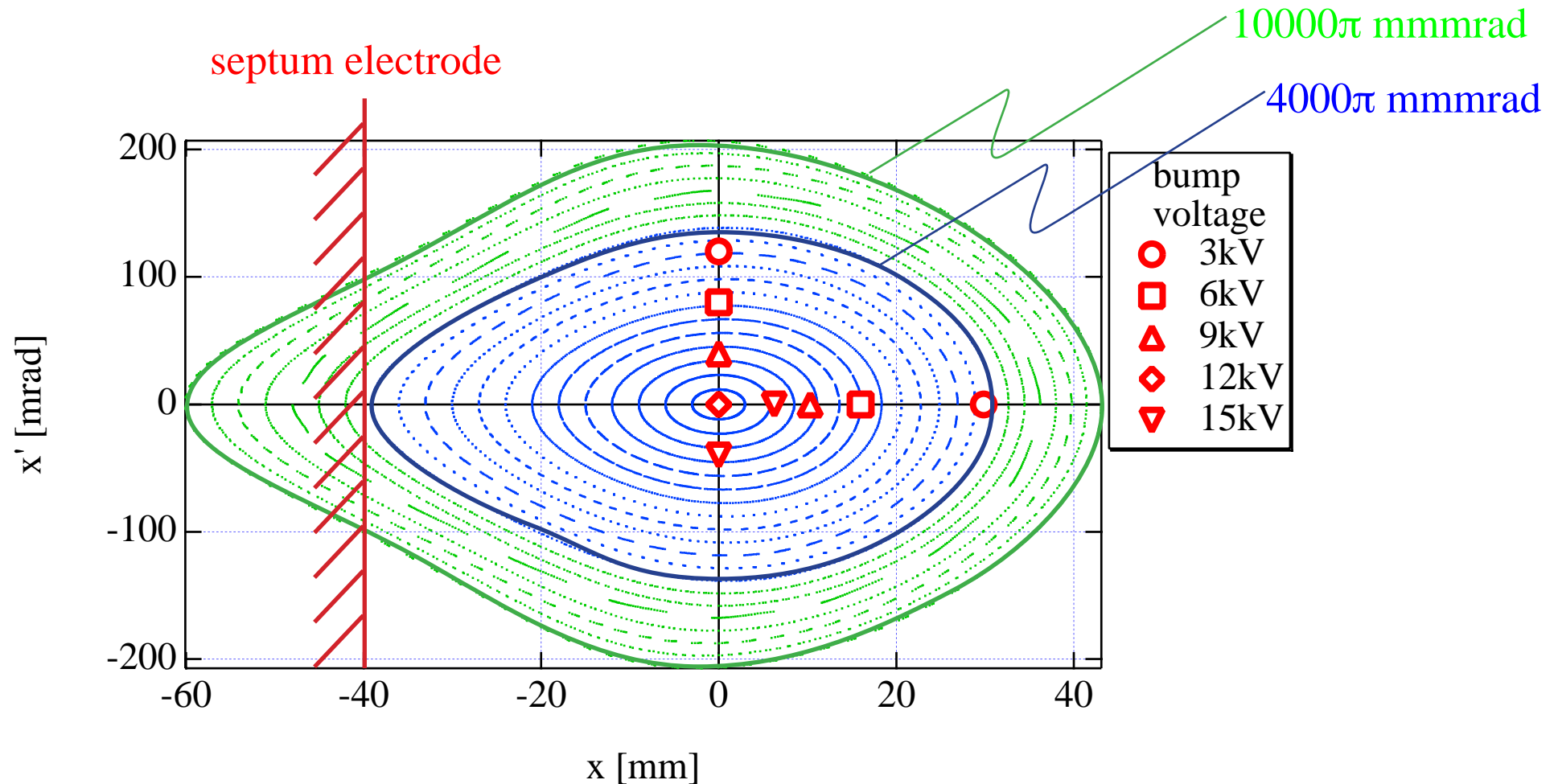


=> at the 3kV
the maximum amplitude

=> at the 12kV
the optimum

(obtained with BPM)

Horizontal acceptance survey (2)



Horizontal acceptance is about 4000π mm.mrad !
(The limit can be explained by the septum electrode.)

RF Knockout Resonance & Betatron tune

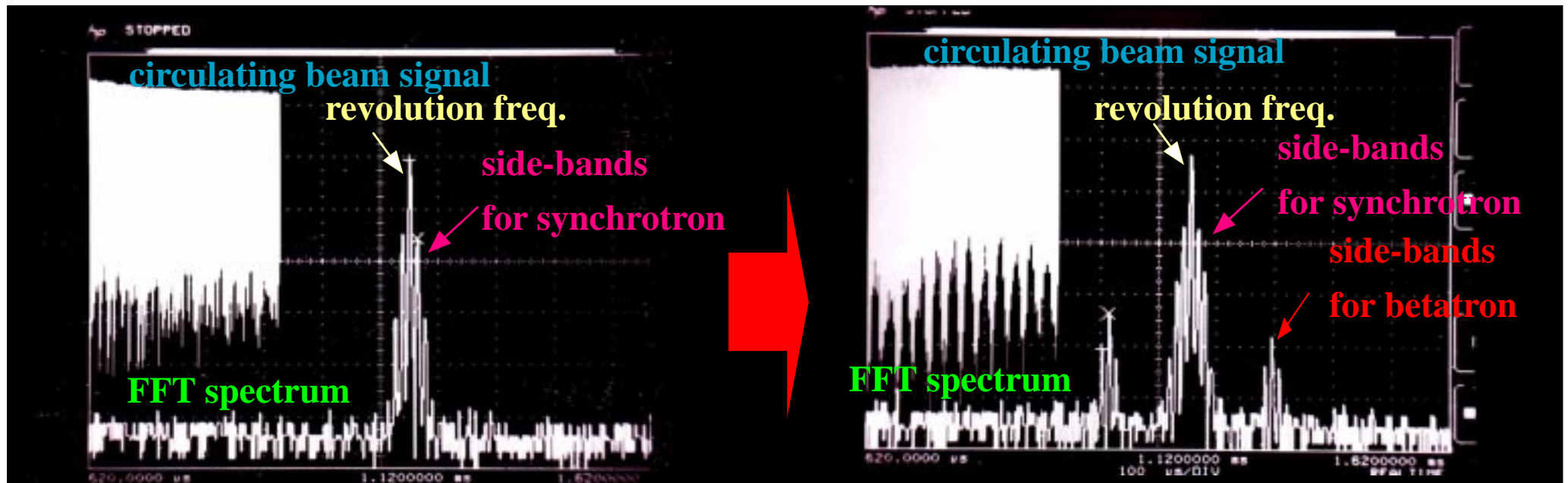
RF knockout resonance :

$$pv_h + qv_v = \pm m \pm \frac{f_{RF}}{f_{rev}}$$

($p, q, m = \text{integer}$)

250keV flat top

250keV flat top after RF knockout



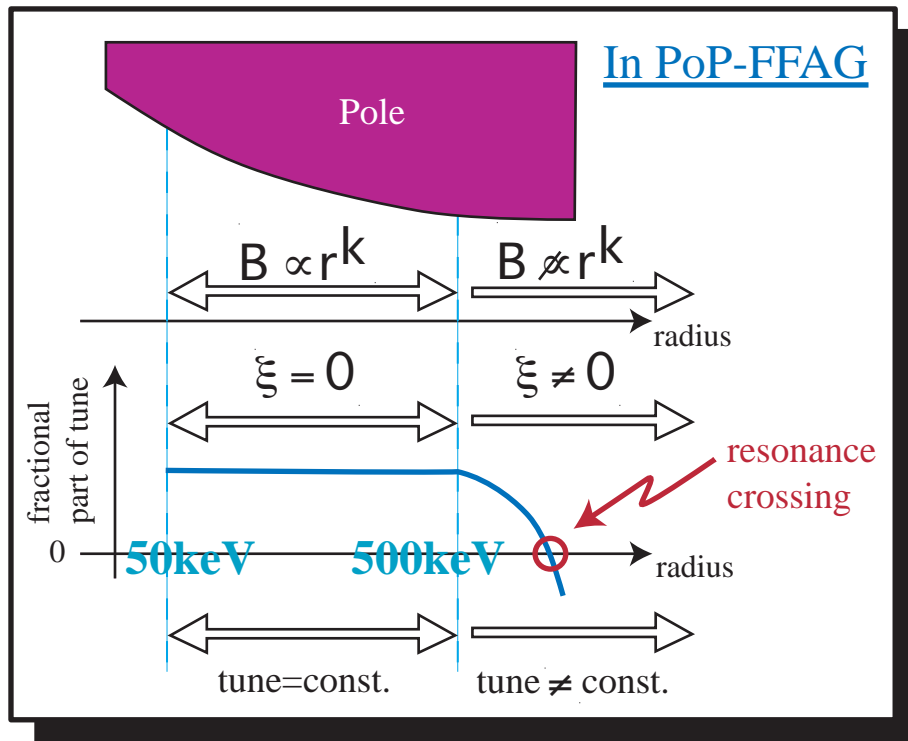
fractional part of betatron tune

$$\nu_h = 0.195 \quad (0.199 @ E_{inj})$$

Resonance crossing & Fast Acceleration (1)

In FFAG synchrotron.....

the fast acceleration \Rightarrow the beam can be accelerated
even if the betatron tune crosses the
resonance line during the acceleration !



accelerating speed can be changed !

Resonance crossing & Fast Acceleration (2)

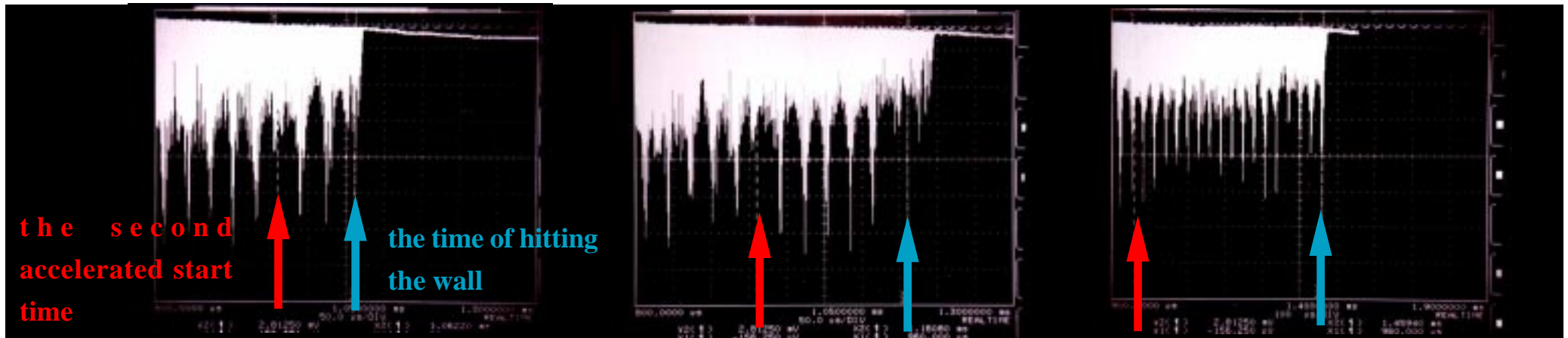
the beam was accelerated from 630keV to 710keV

in various accelerating speed !

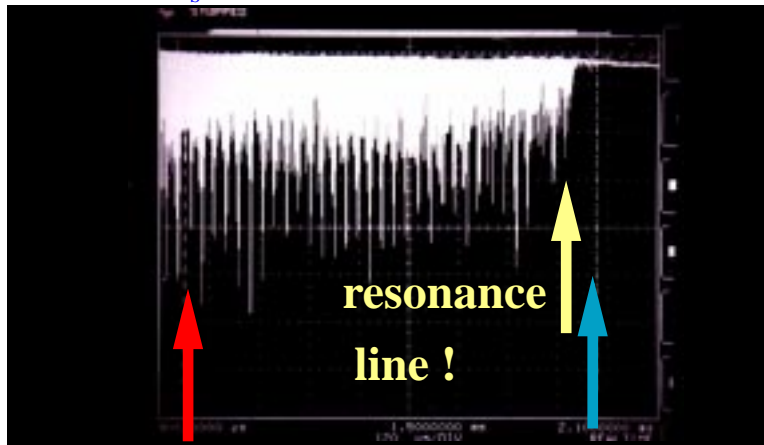
$\phi_s=20$ Deg

$\phi_s=10$ Deg

$\phi_s=4$ Deg



$\phi_s=2$ Deg

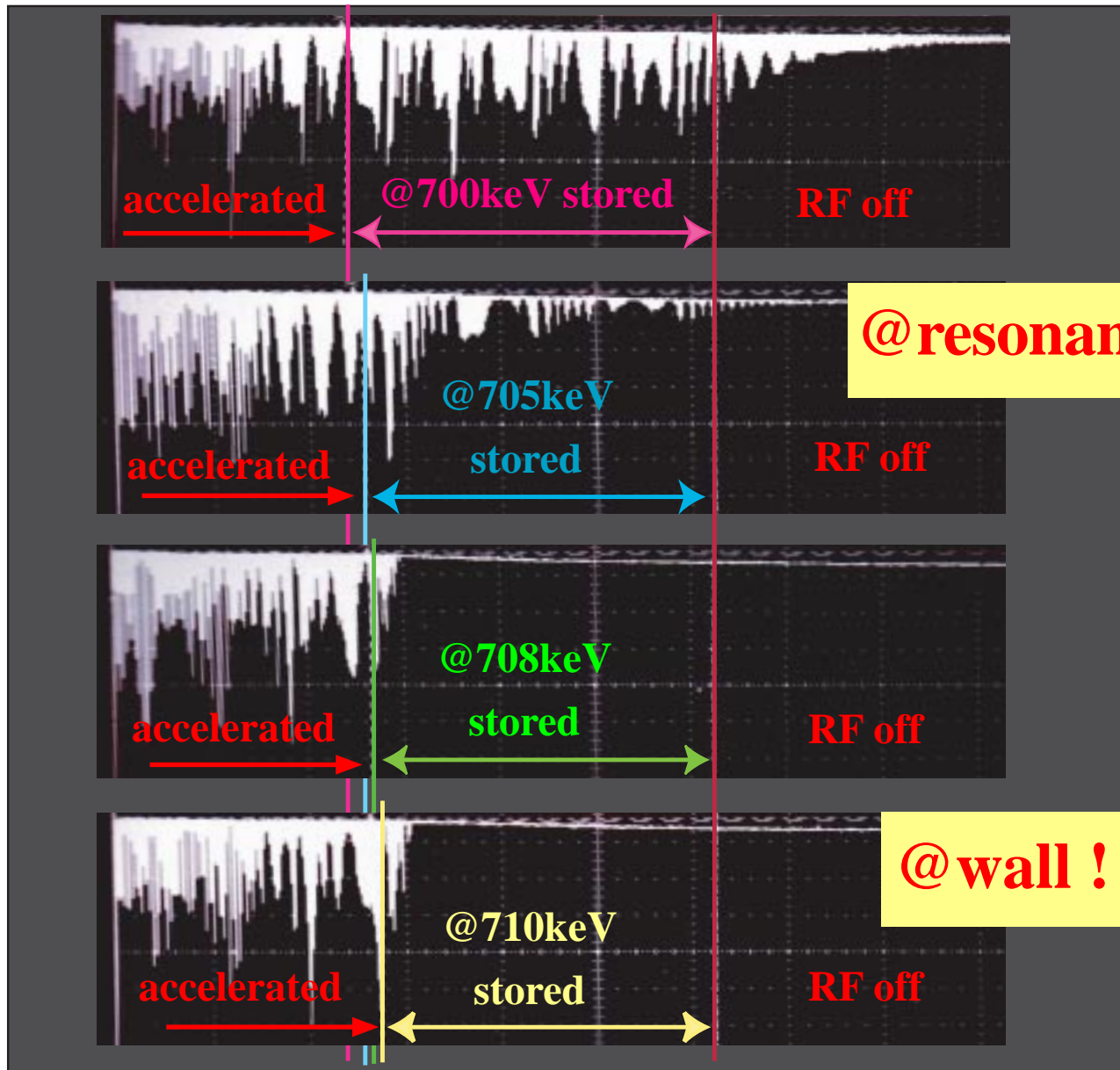


accelerating speed:

slow => doesn't cross the resonance line

fast => can cross the resonance line

Resonance crossing & Fast Acceleration (3)



fast acceleration
up to around the resonance!

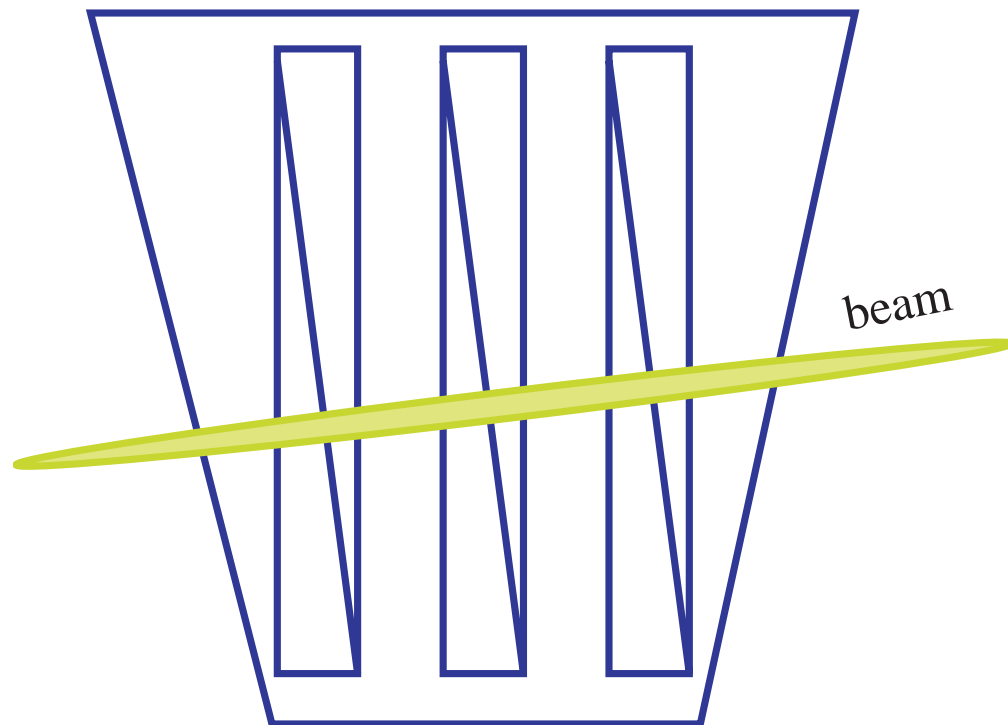
@resonance !

@wall !

Future Plan

Now we are planning in PoP-FFAG development new monitor in order to measure the shape of horizontal acceptance.

new BPM



- *three horizontal BPMs are installed
- *it is possible to measure the position and the beam angle at the same time turn by turn
- *plotting these positions and angles in the phase space, we obtained the beam trajectory in the phase space

Summary

*the measurements of the machine parameters:

- The PoP-FFAG works as designed.
- The proton can be accelerated within 1msec.
- It was ascertained that
tune is adjustable as a function of F/D ratio,
various acceleration pattern is possible,
and the beam intensity increased with multi-turn injection.

*the studies of the beam dynamics:

- Horizontal acceptance at injection energy is at least 4000π mm-mrad.
- Betatron tunes almost didn't change between 50keV and 250keV.
- The beam was accelerated even if the betatron tune crosses the resonance.