Joe Nakano

- KEK FFAG group -

FFAGの開発とその応用について

April 5, 2002

「中間エネルギービームによる物理」 @ RCNP

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Introduction – FFAG Synchrotron

The characteristics of FFAG …

- Fixed Field (cf. Cyclotron)

  FFAG magnetic Field : $\mathbf{B=B_0(r_0/r)^k}$ **k>1**

  Satisfying the cardinal condition, **"zero -chromaticity"**

  - High repetition rate
  - Various acceleration patterns are possible

  large beam current, flexibility, low power consumption

- Alternating Gradient Accelerator

  (cf. Synchrotron)

  strong focusing

- Large Horizontal acceptance

  wide aperture

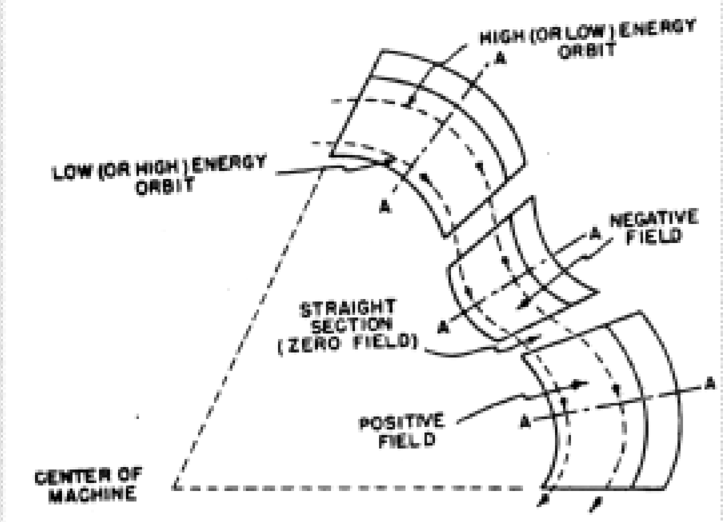


FIG. 2. Plan view of radial-sector magnets.

… Strong focusing accelerator

with high duty factor

Introduction - Applications of FFAG

FFAG's catchphrase…

"High current, High repetition rate and High efficiency"

- *Medical* - Cancer therapy
  - 3dimensional spot scan method
- *Atomic Energy* - Accelerator Driven System
  - High current and efficiency beam, low power consumption and low beam loss
- *Physics* – Accumulator of secondary beam
  - Manipulation of the short-lived secondary beam

    ex.) PRISM, Neutrino-Factory and Unstable Nuclei
- *Environmental Hygienics* – Sterilizer
  - Electron beam or X-ray source for the sanitizing and the sterilizing.

…., etc.

A brief history of FFAG Accelerator – 'PoP FFAG'

~50's FFAG was proposed by Ohkawa, Symon and Kolomensky.

a electron FFAG at MURA project.

"Proton FFAG was difficult."

- Difficulties of designing and manufacturing the large magnet gives the complex magnetic field
- No RF cavity has the large aperture and gives the high gradient field over a wide-frequency

… Great advancement of technologies in 80's ~ 90's

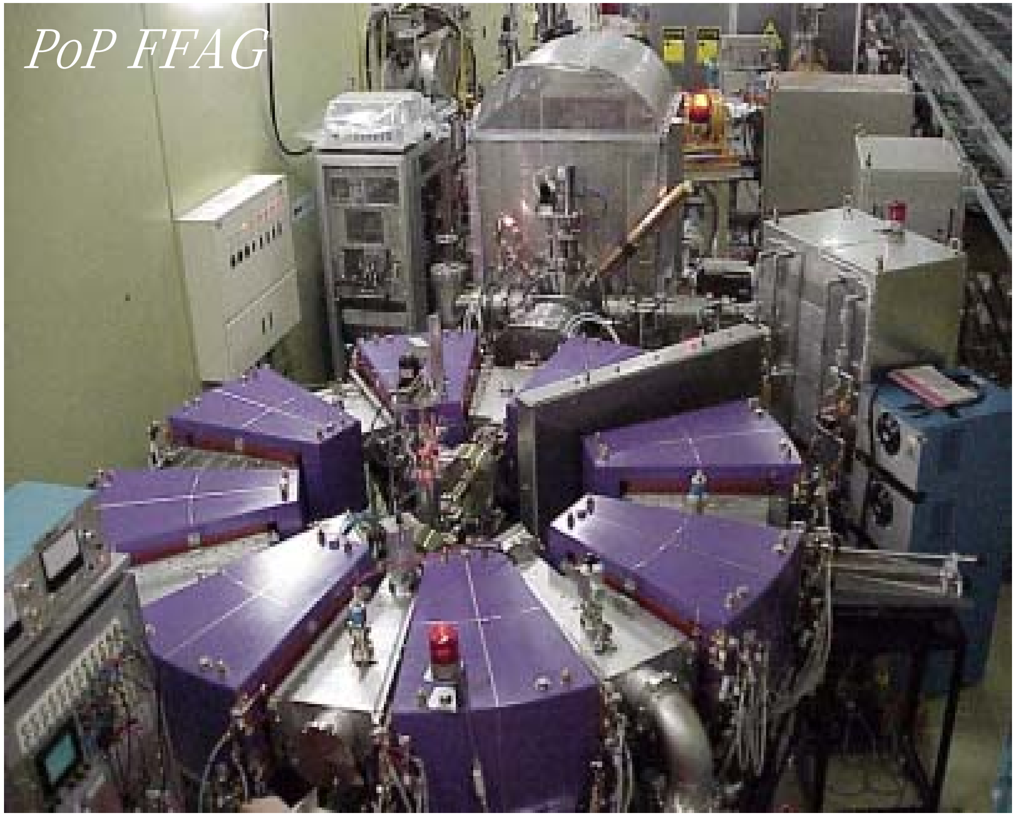
- large CPU power to do the calculation and the simulation easily
- the invention of a Magnetic Alloy for FFAG RF cavity

1998 PoP (proof of principle) FFAG project, to construct the world first proton FFAG, was started.

PoP FFAG - *The first proton FFAG Accelerator in the world*

1. Basic performance
2. Studies of beam dynamics

- Acceptance survey
- Measurement of betatron tune with RF knockout
- A study of resonance crossing with fast acceleration



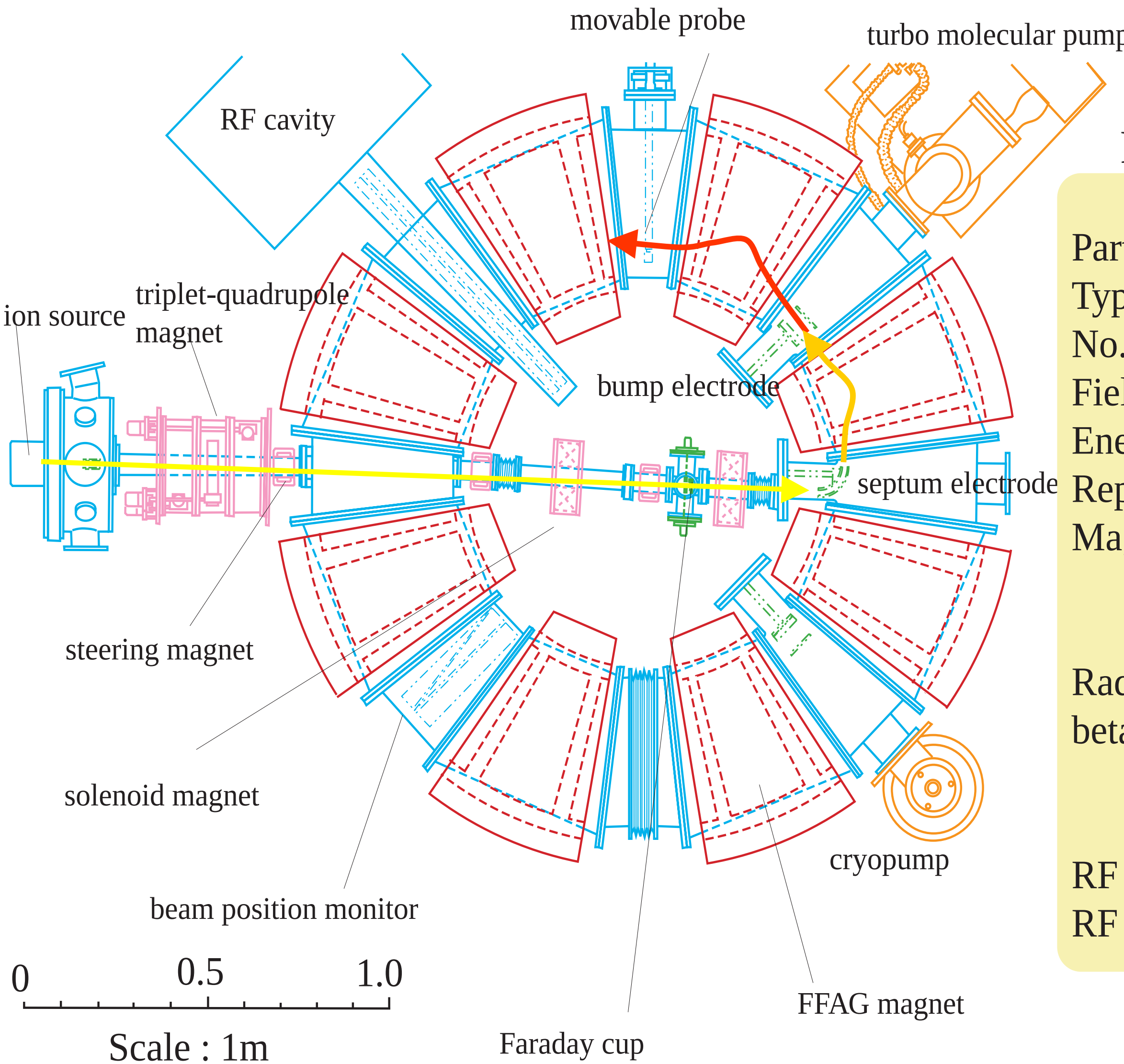
同志社大学　工学部　吉本昌弘

PoP FFAG

T. Adachi, M. Aiba, K. Koba, S. Machida, Y. Mori,
R. Muramatsu, A. Muto, C. Ohomori, I. Sakai,Y. Sato,
M. Sugaya, A. Takagi, R. Ueno, T. Yokoi, M. Yoshii,
M. Yoshimoto,Y. Yuasa and Joe Nakano
- KEK FFAG group -

Top View of PoP-FFAG Accelerator

PoP FFAG



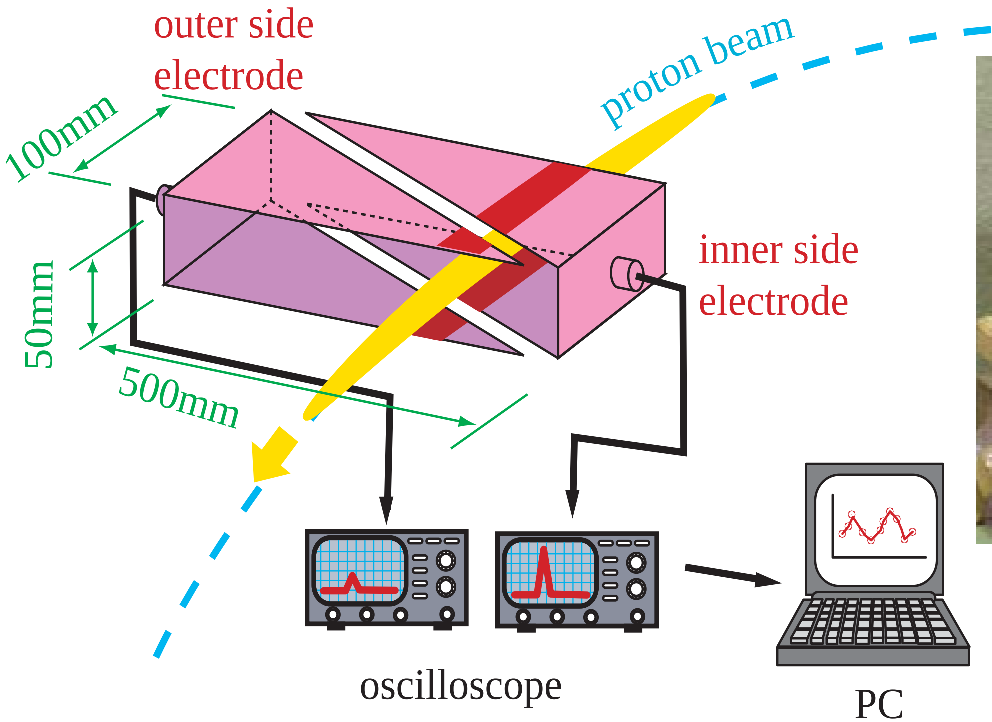
PoP-FFAG parameter table

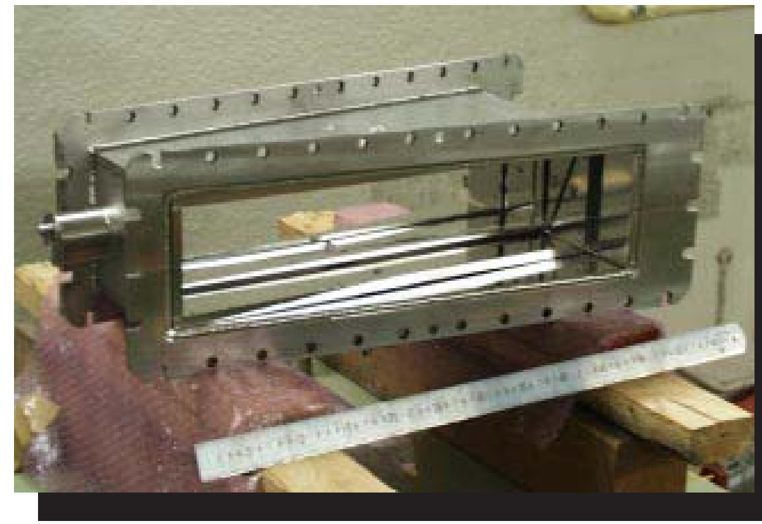
Particle	proton	
Type of magnet	radial sector type	
No.of sector	8	
Field index	k=2.5	
Energy	50keV => 500keV	
Repitition rate	1kHz	
Magnetic field		
	Focus-mag.	0.14 - 0.32 T
	Defocus-mag.	0.04 - 0.13 T
Radial of closed orbit		0.81 - 1.14m
betatron tune		
	horizontal	2.17 - 2.22
	vertical	1.24 - 1.26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

Beam Position Monitor (BPM)

PoP FFAG

horizontal BPM





In FFAG, beam orbit shifts during the acceleration.

=> BPM must have large horizontal aparture.

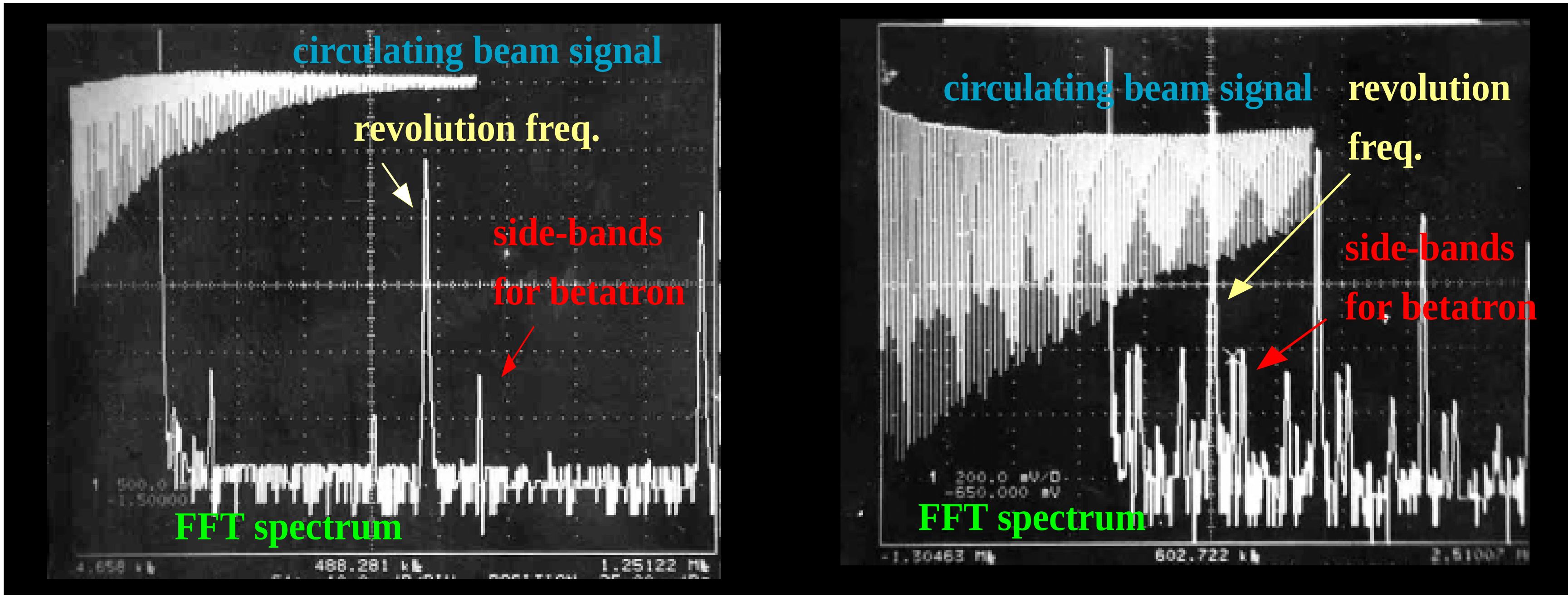
Basic Performance of PoP FFAG

- Betatron tune
- Fast acceleration within 1msec
- Synchrotron oscillation
- Multi turn Injection

Betatron Tune (1)

PoP FFAG

Horizontal beam signal | Vertical beam signal



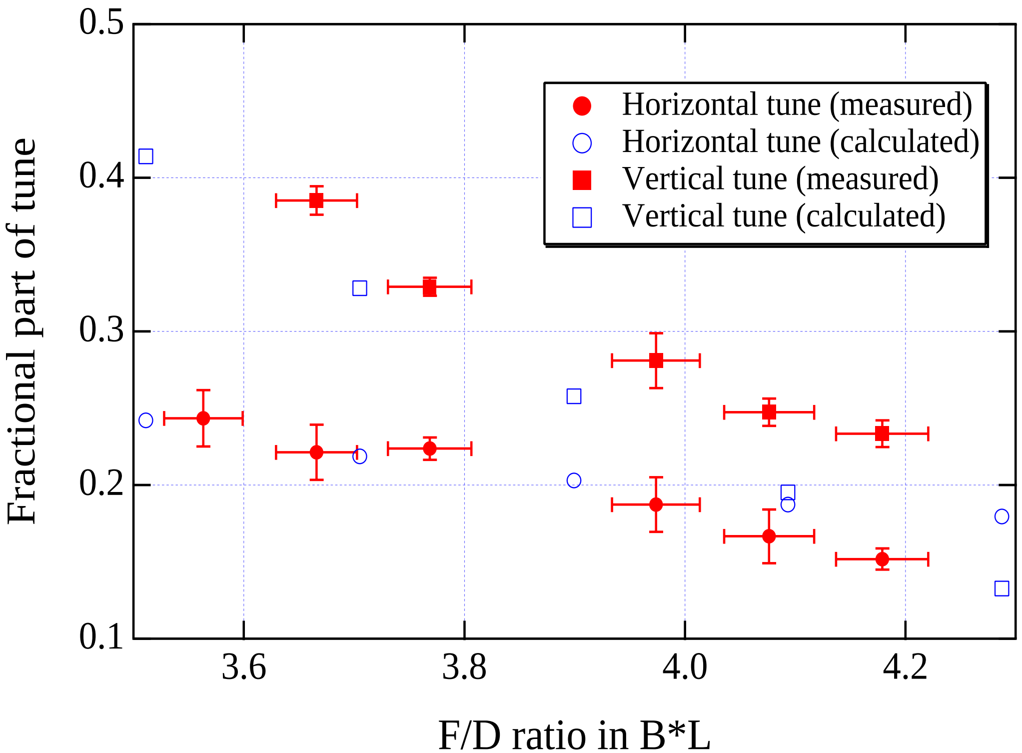
fractional part of betatron tune

$\mu_h = 0.199$ $\mu_v = 0.289$

Betatron Tune (2)

PoP FFAG

betatron tune vs F/D ratio



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

- vertical

  => shift !!

- horizontal

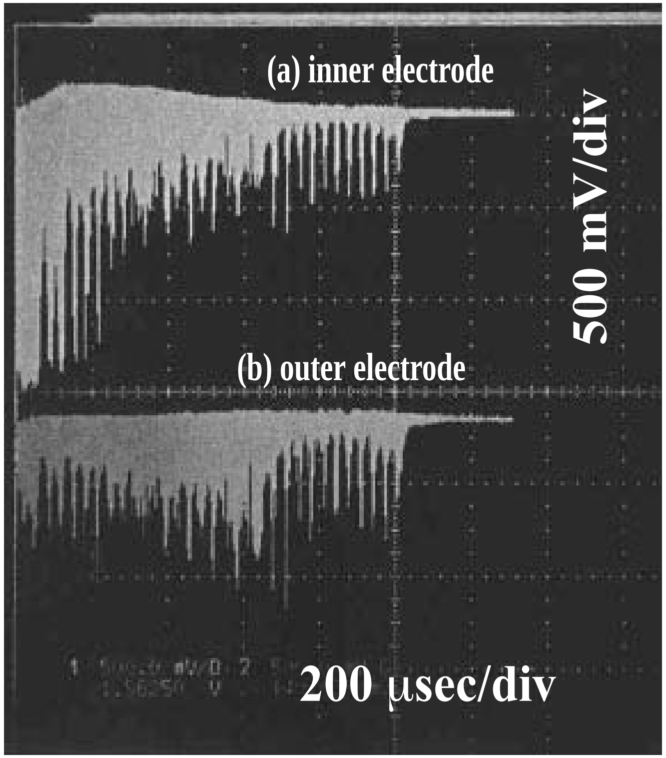
  => almost constant !!

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

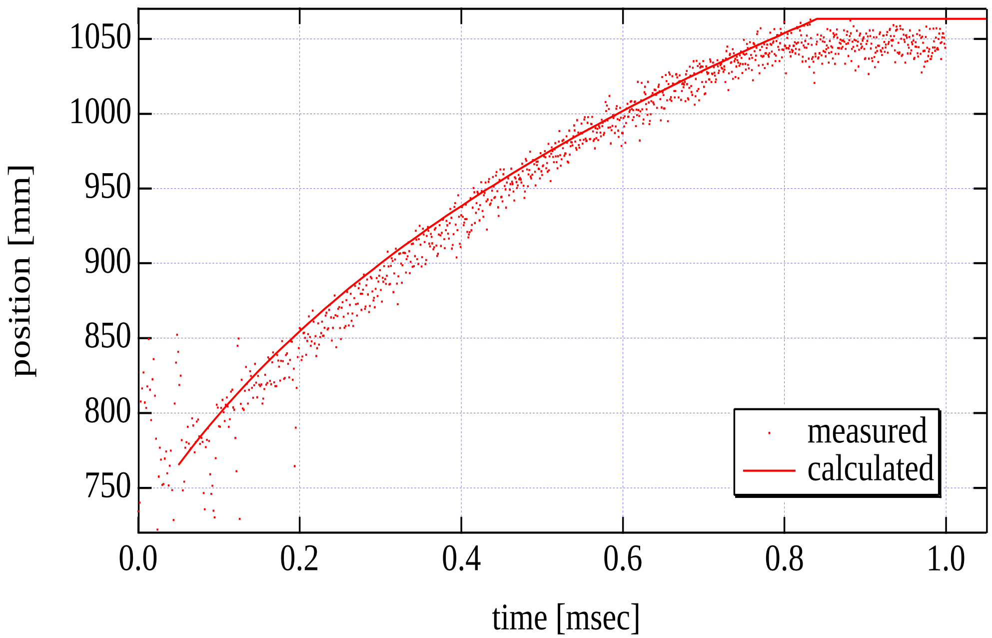
Beam Acceleration

PoP FFAG

BPM signals during the acceleration



beam orbit shift



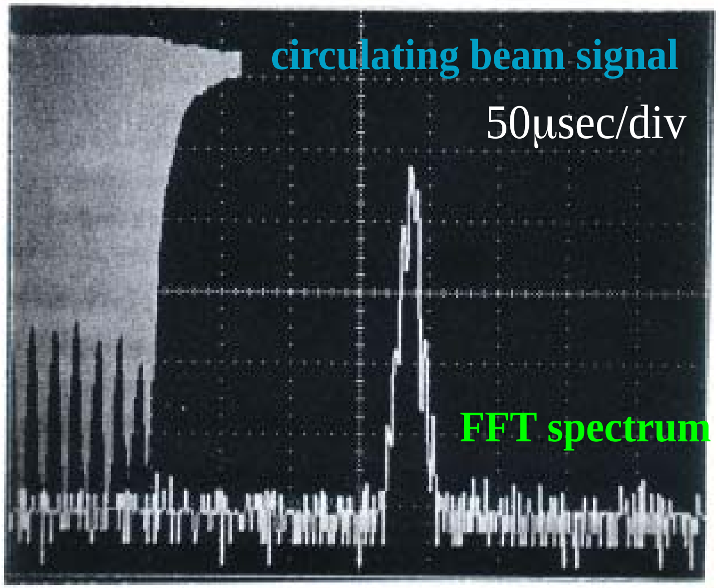
The beam is accelerated from 50keV to 500keV within 1msec.

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

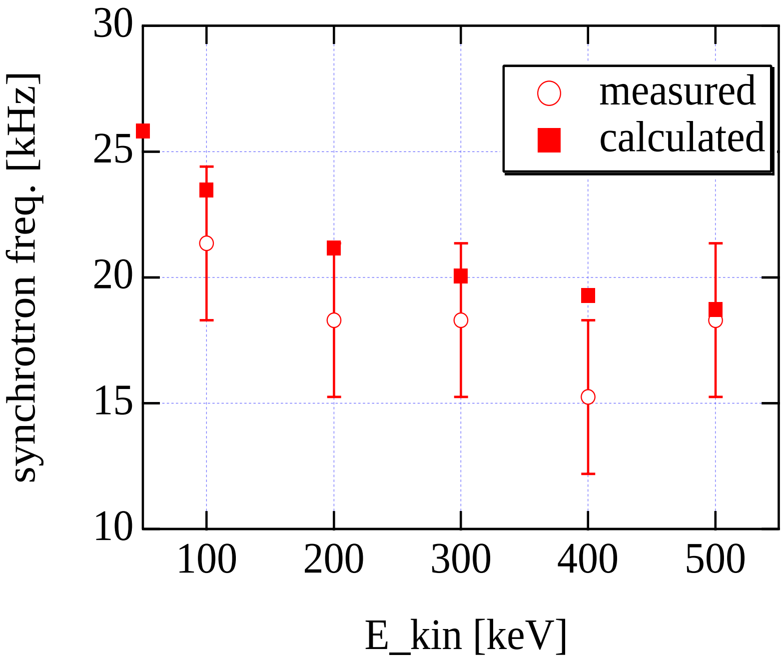
Synchrotron Frequency

PoP FFAG

at 500keV (flat top)



synchrotron freq. vs E_{kin}@flat top



revolution frequency:

1.379MHz

synchrotron frequency:

18.3kHz

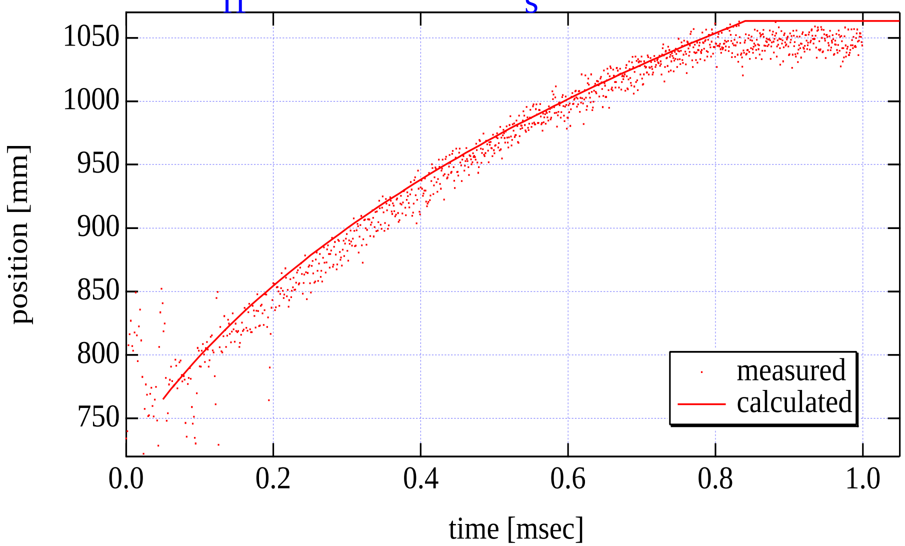
The observed synchrotron frequency agreed with those expected by the beam simulation.

RF pattern

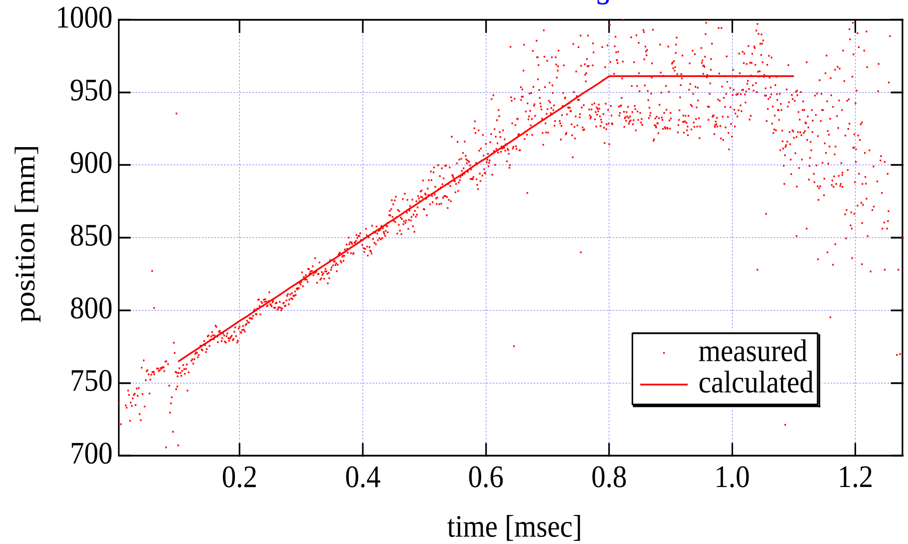
	magnetic field	RF pattern
ordinary synchrotron	changing	with regarding the magnet
FFAG synchrotron	constant	without regarding the magnet

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

V_{rf} = const. $\forall_s$=const.



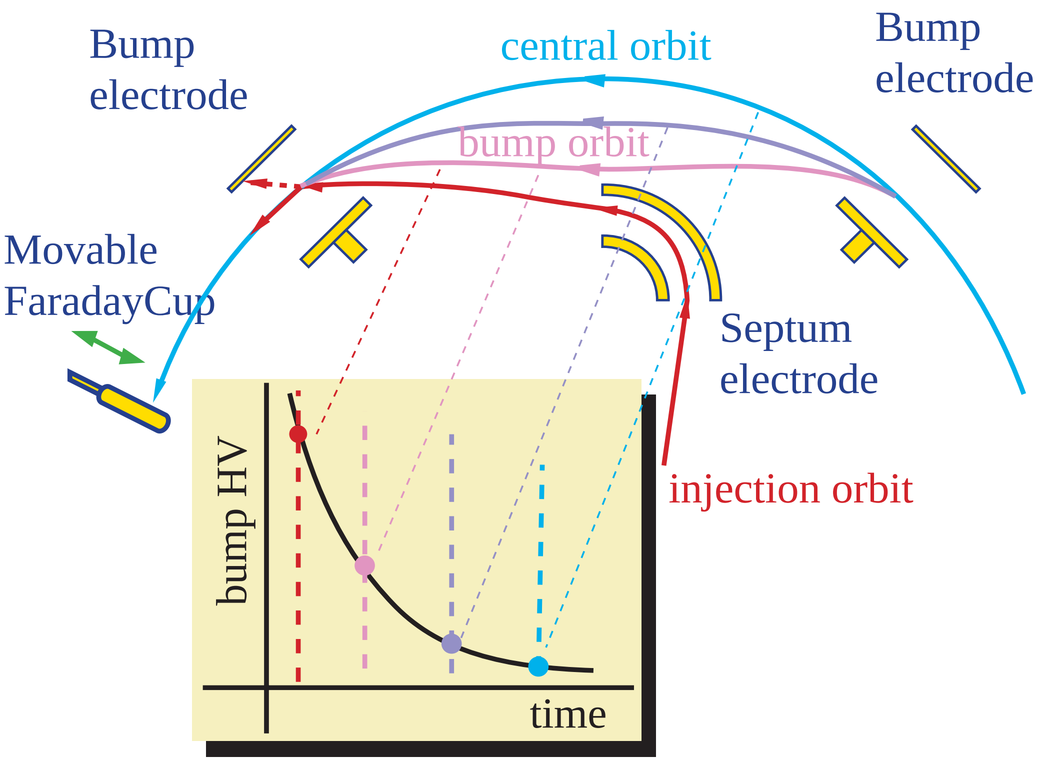
dr/dt = const. $\forall_s$=const.



The various acceleration pattern is possible in PoP-FFAG.

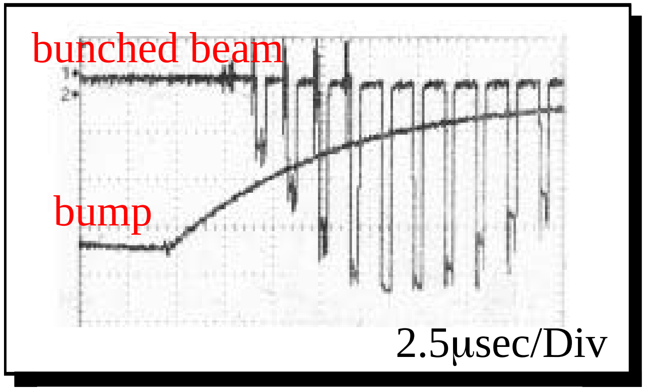
Multi-turn Injection System

PoP FFAG



slow decay time of bump voltage

(decay time >> revolution period



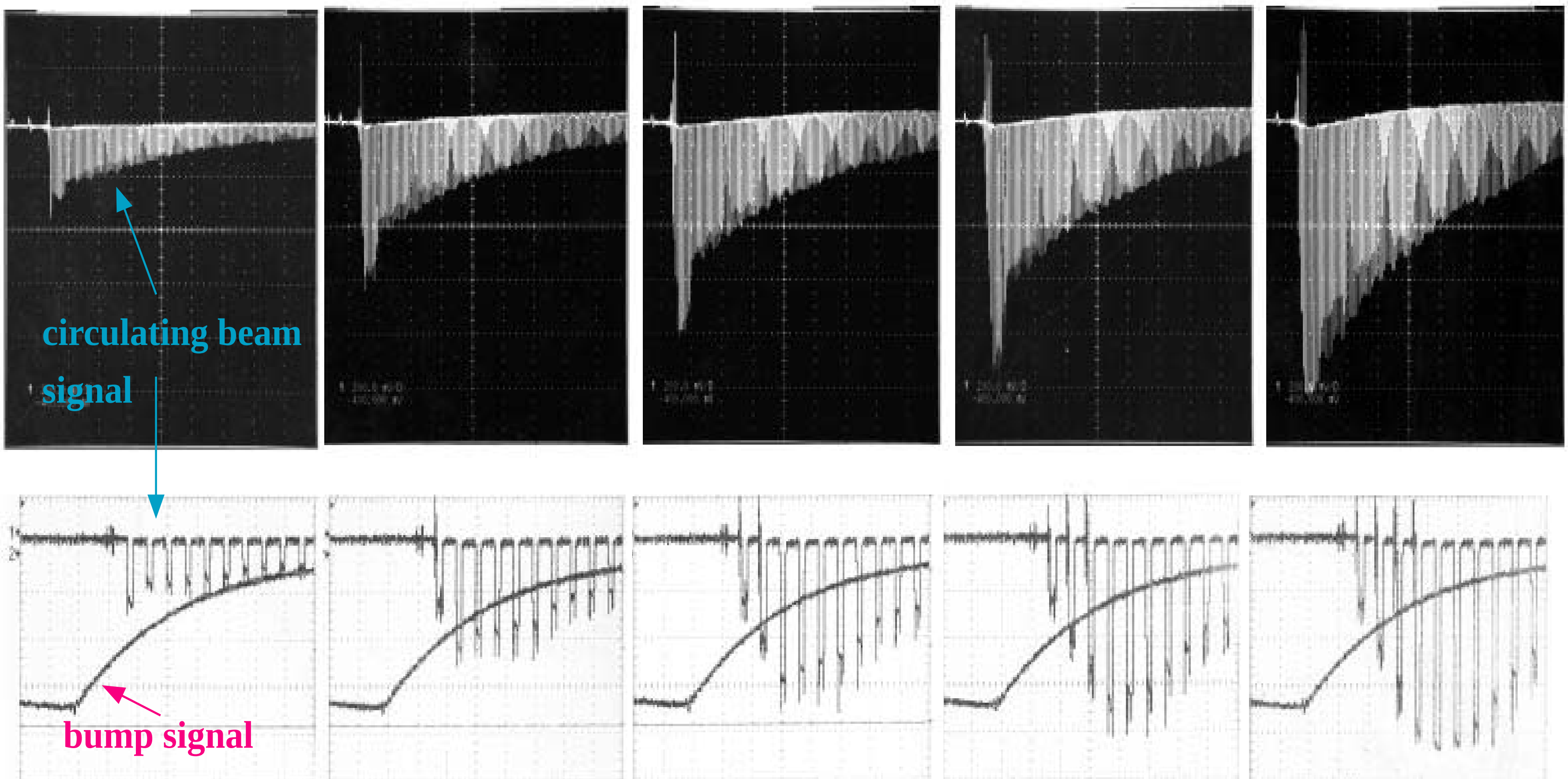
=> multi-turn injection

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

Multi-turn Injection

PoP FFAG

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.

Large horizontal acceptance

Measurement of betatron tune with RF knockout

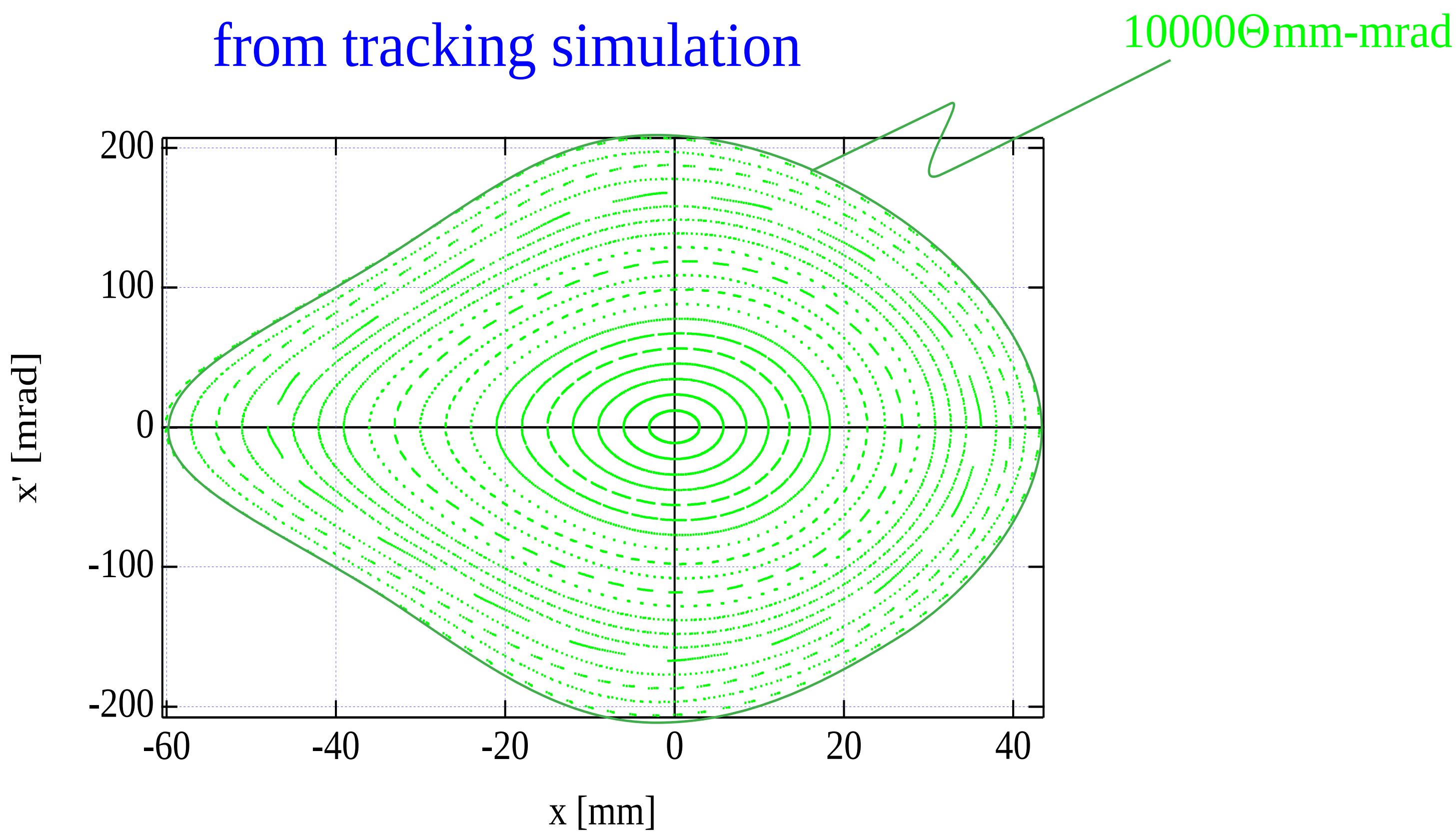
A study of resonance crossing with fast acceleration

Horizontal Acceptance

PoP FFAG

horizontal acceptance @ injection energy

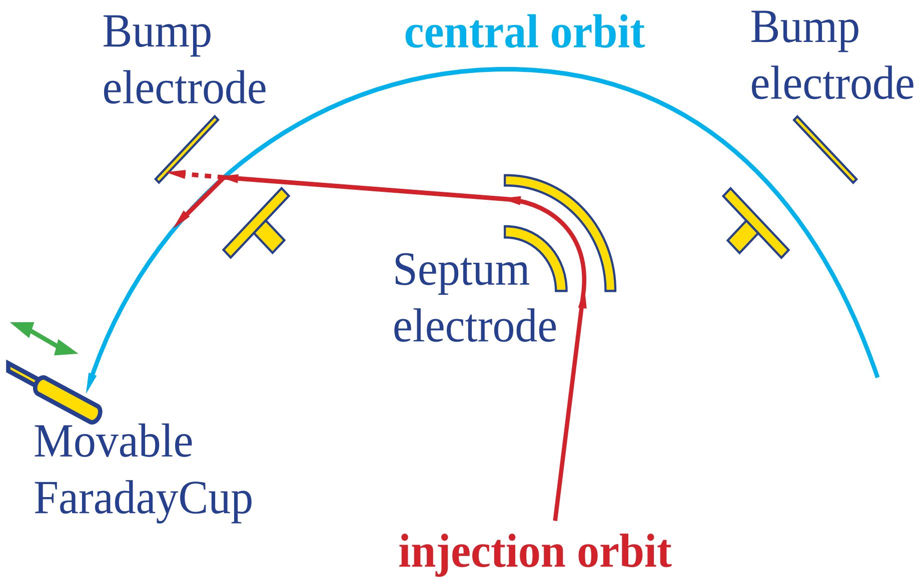
from tracking simulation



FFAG synchrotron has a large horizontal acceptance.

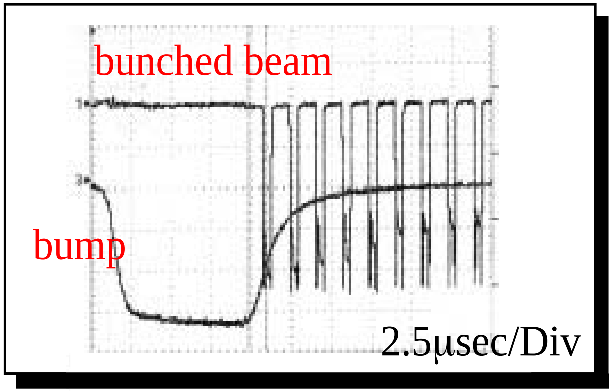
Injection System for Acceptance Survey

PoP FFAG



fast decay time of bump voltage

(decay time ~ revolution period)



=> working as a fast kicker

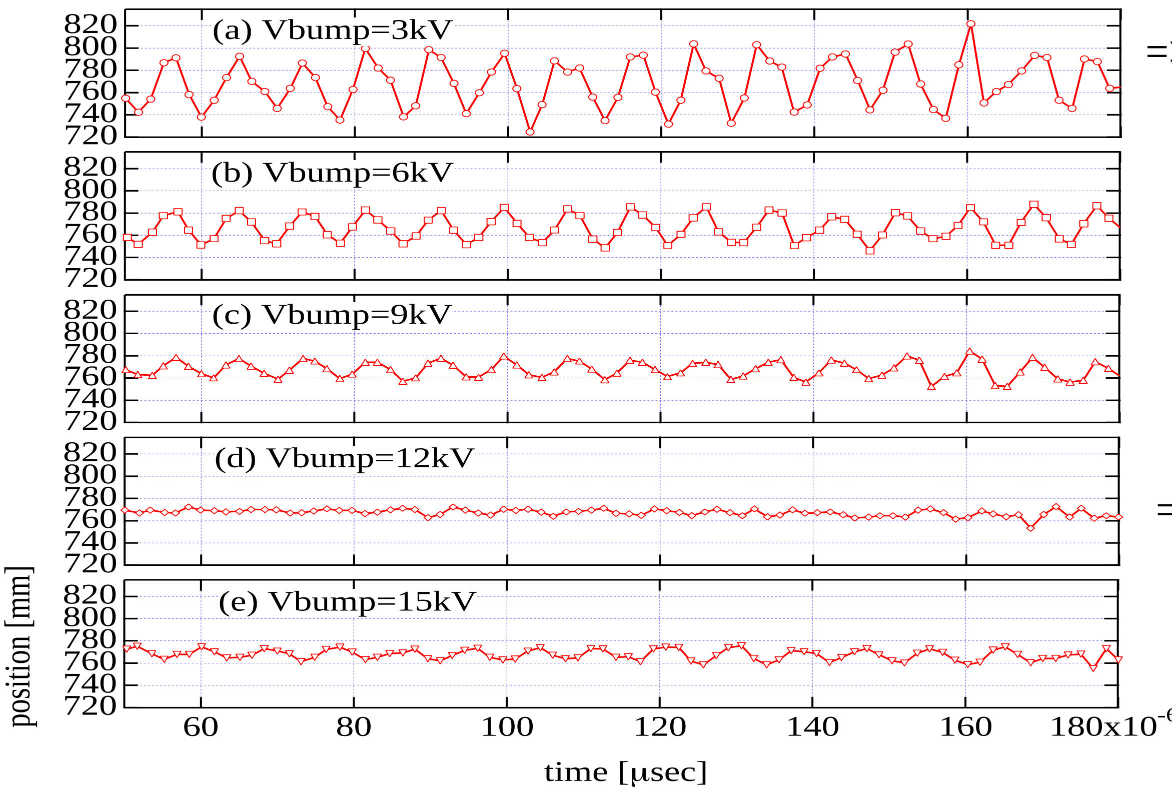
At the fast decay operation, the bump works as a fast kicker .

Horizontal acceptance survey (1)

PoP FFAG

The beam oscillations with various betatrom motion

at the 2kV no signal !!

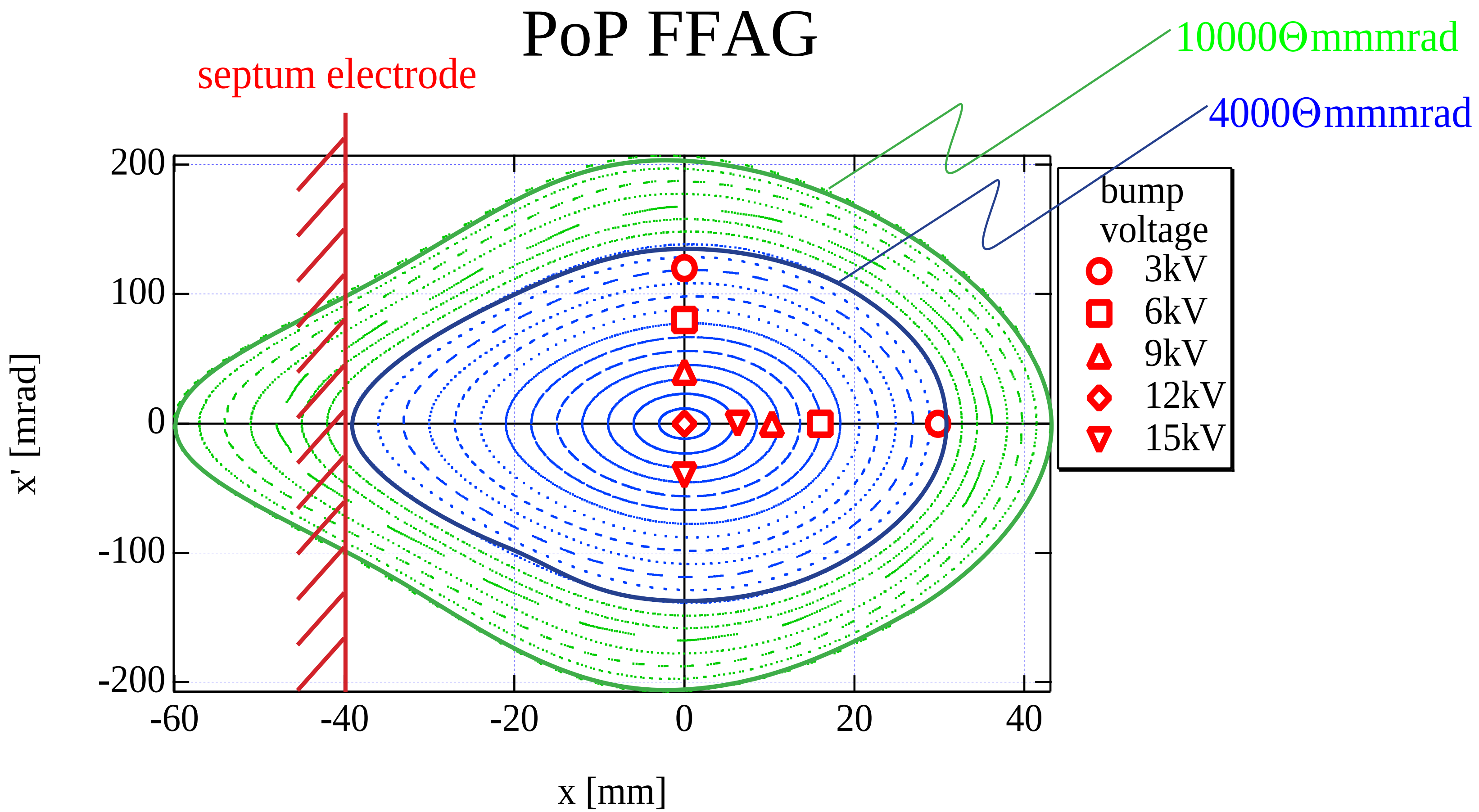


=> at the 3kV
the maximum amplitude

=> at the 12kV
the optimum

(obtained with BPM)

Horizontal acceptance survey (2)



Horizontal acceptance is about 4000Θmm.mrad !

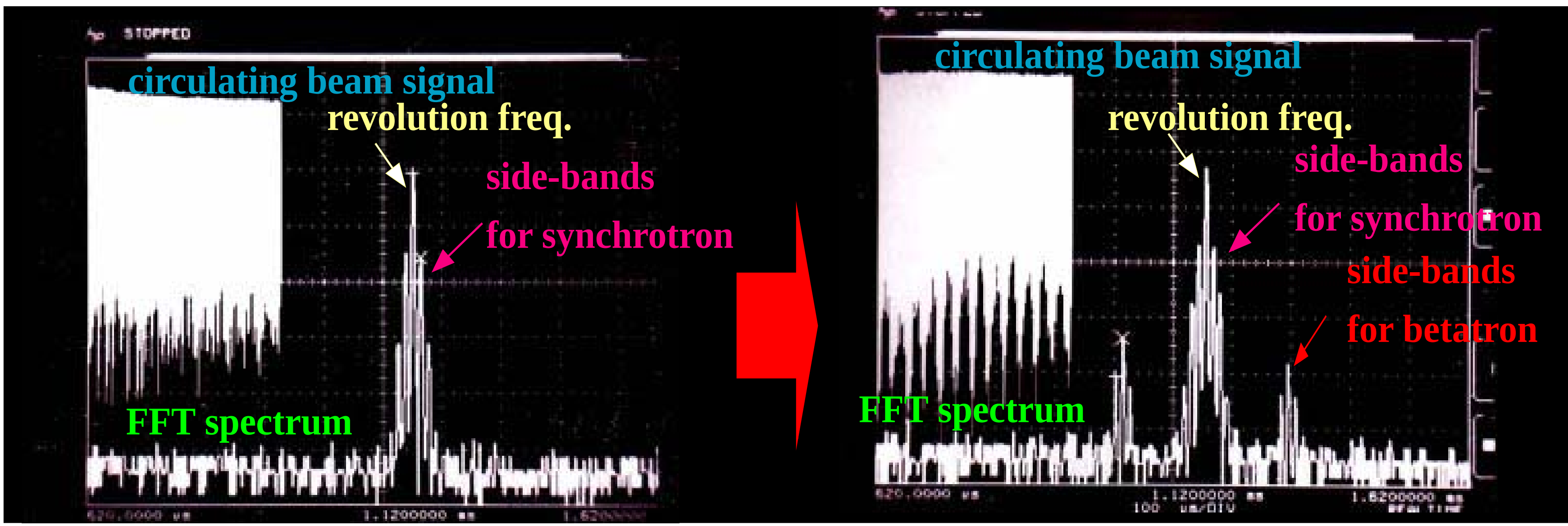
(The limit can be explained by the septum electrode.)

RF Knockout Resonance & Betatron tune

PoP FFAG

RF knockout resonance : $$p\downarrow_h + q\downarrow_V = \pm m \pm \frac{f_{RF}}{f_{rev}}$$ (p,q,m = integer)

250keV flat top | 250keV flat top after RF knockout



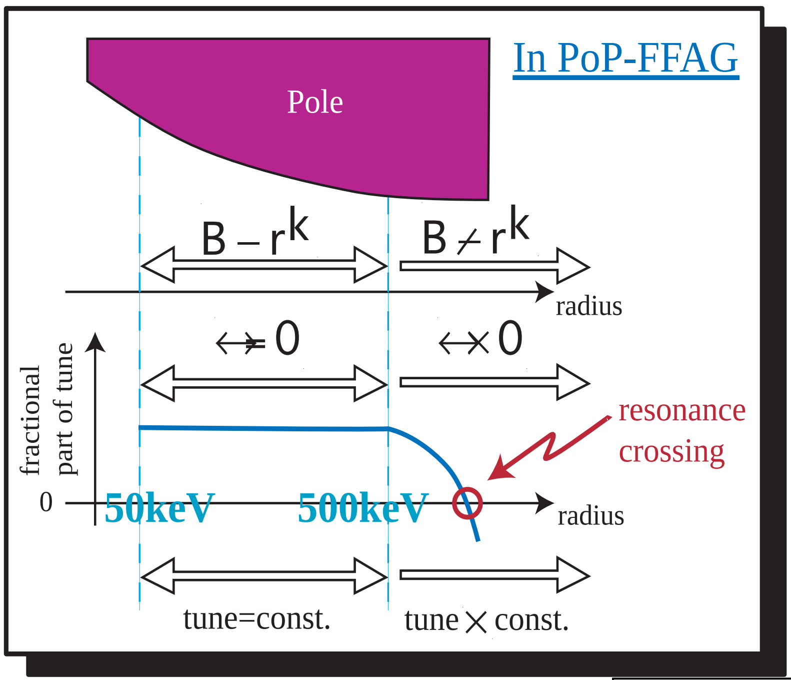
fractional part of betatron tune

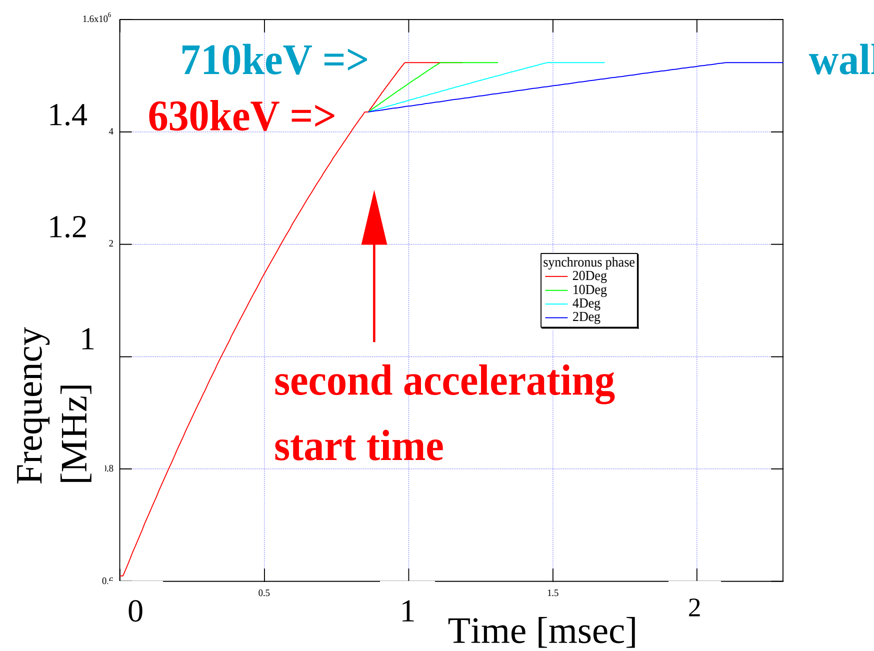
$\downarrow_h$=0.195 (0.199@E_inj)

Resonance & Fast Acceleration (1)

In FFAG synchrotron.......

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





630keV 以降のRF同期位相を変える

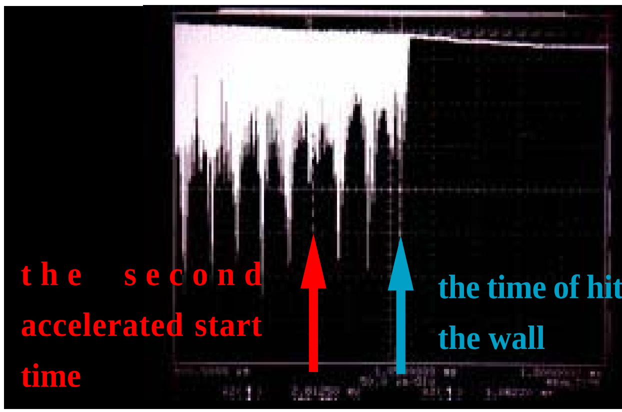
Resonance & Fast Acceleration (2)

PoP FFAG

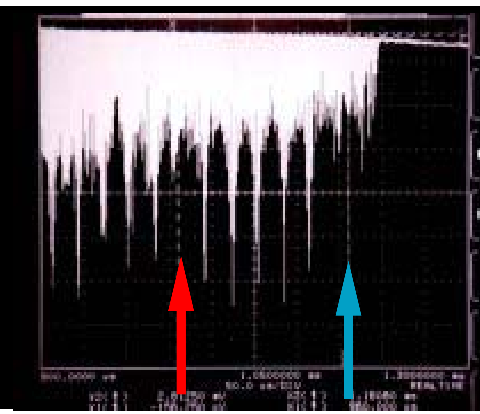
the beam was accelerated from 630keV to 710keV

in various accelerating speed !

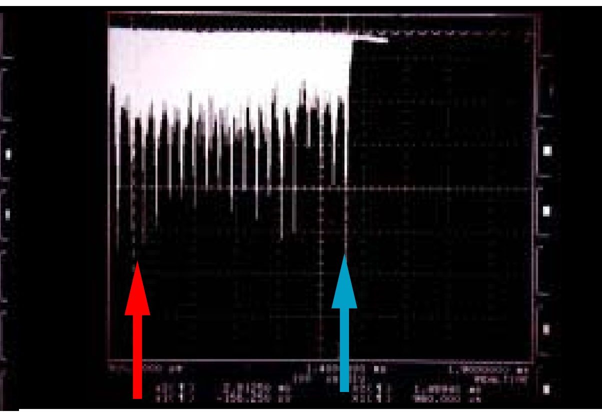
$\forall_s$=20 Deg



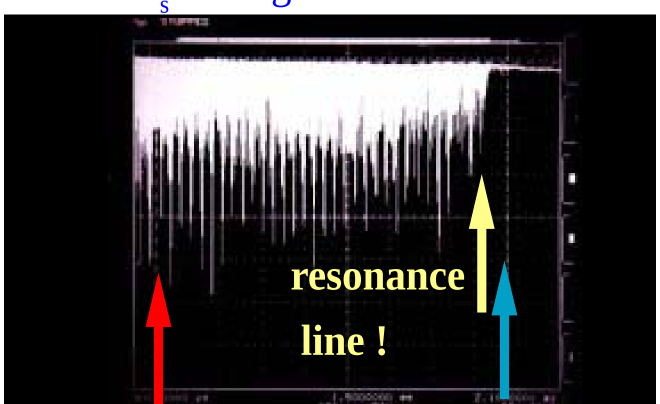
$\forall_s$=10 Deg



$\forall_s$=4 Deg



$\forall_s$=2 Deg

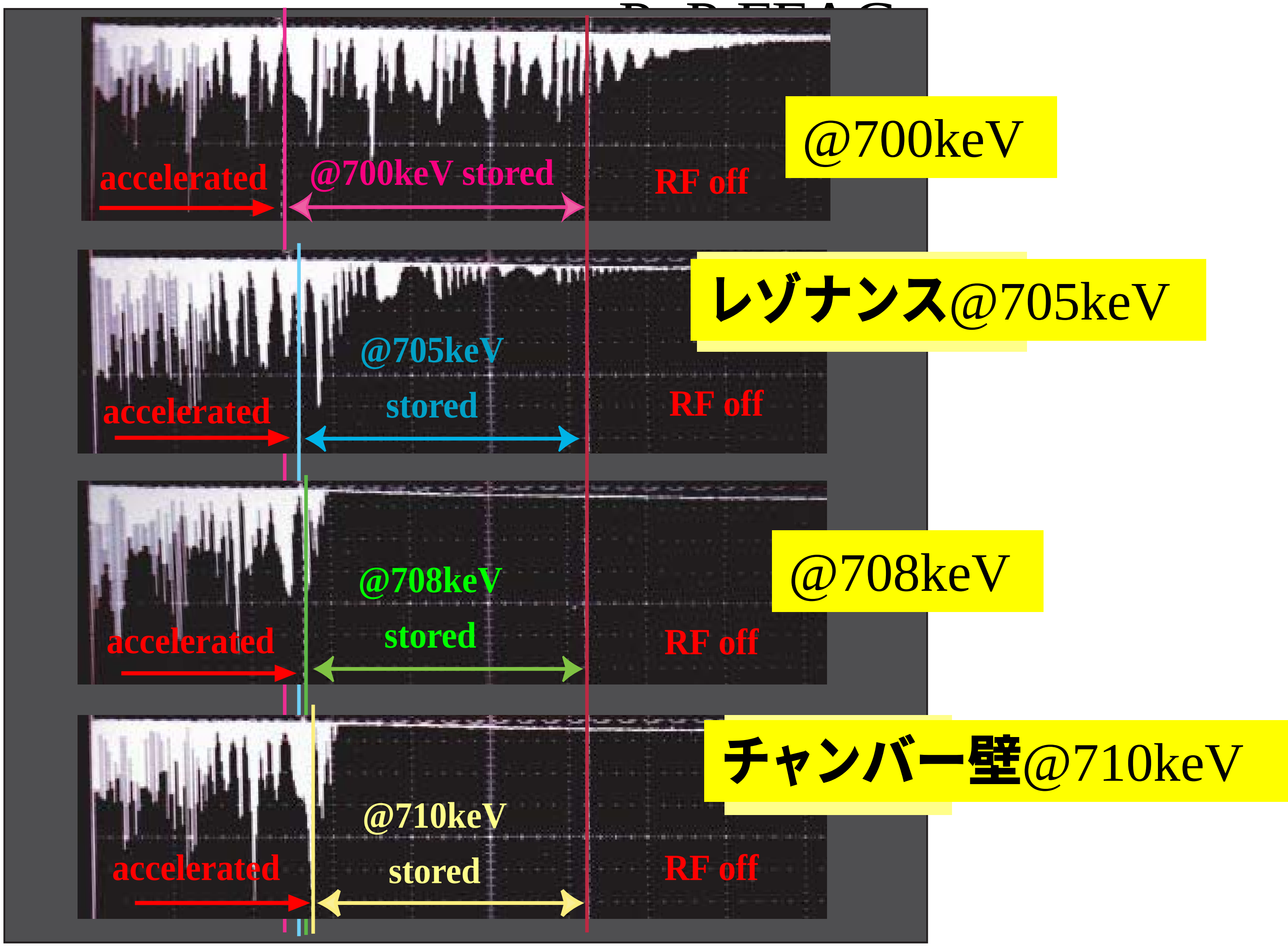


accelerating speed:

slow => doesn’t cross the resonance line

fast => can cross the resonance line

Resonance & Fast Acceleration (3)



Summary

PoP FFAG

*the measurements of the machine parameters:

- The PoP-FFAG works as designed.
- The proton can be accelerated within 1msec.
- It was ascertaned 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 4000Θmm-mrad.
- Betatron tunes almost didn’t change between 50keV and 250keV.
- The beam was accelerated even if the betatron tune crosses the resonance.