ASTOR as an injector of FFAG

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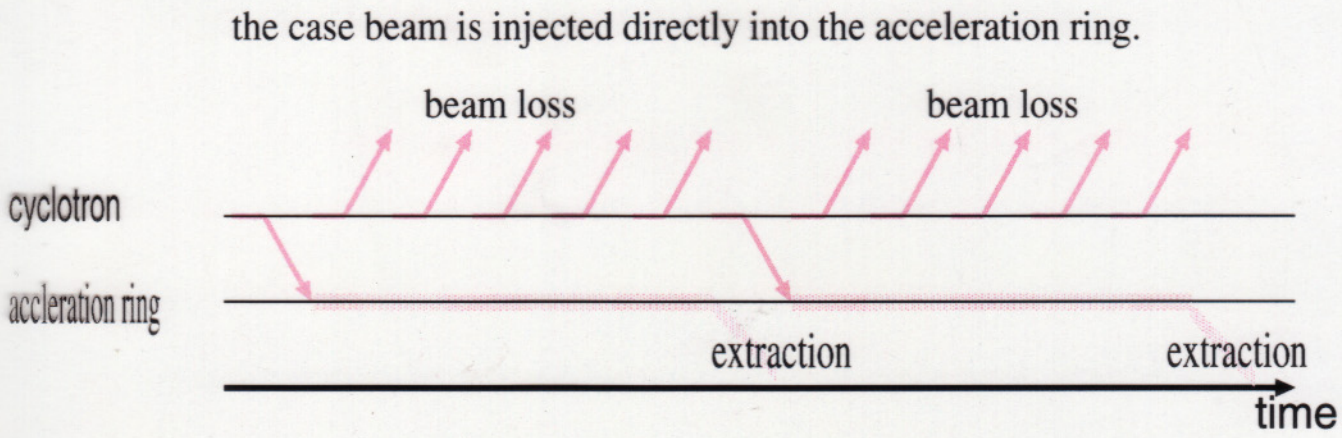
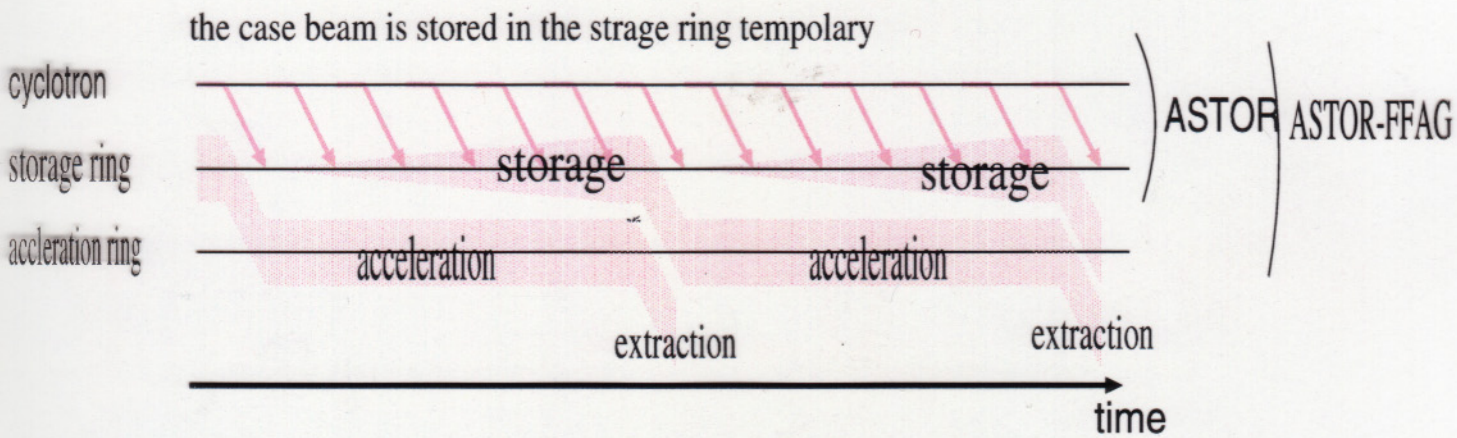
The injection efficiency of cyclotron

It is planned that a 10 MeV cyclotron is used as the injector of 150 MeV FFAG in KEK FFAG Group.

About the 99.8 percent of the beam extracted from the cyclotron is lost without acceleration.



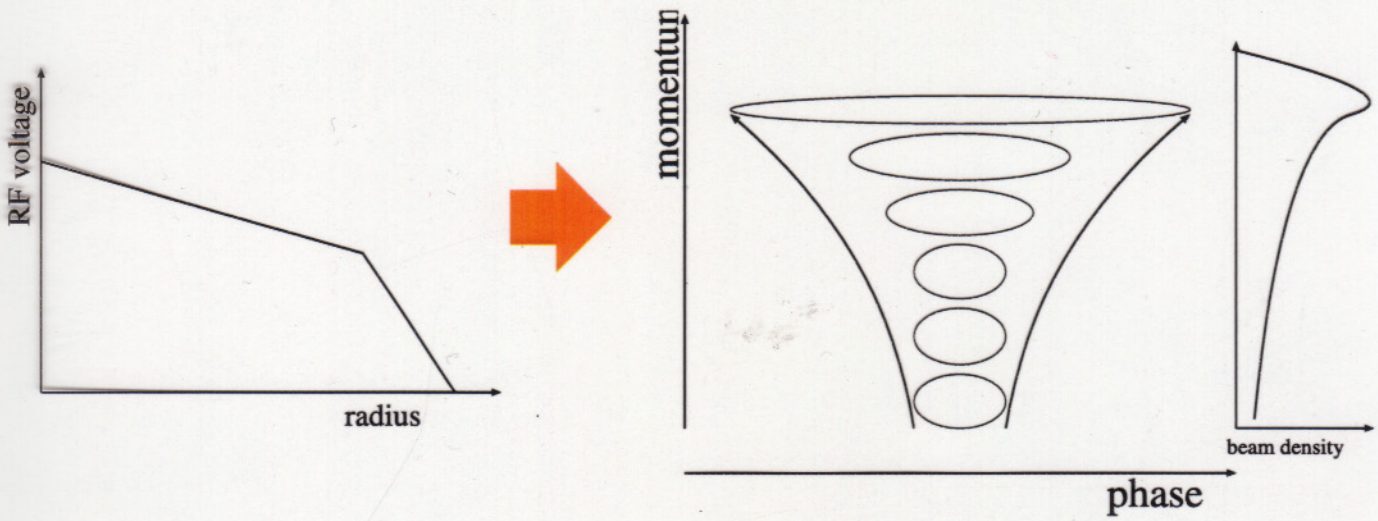
The efficiency is improved with stacking the coasting beam temporarily and bunching the beam.



Combination of cyclotron and storage ring

ASTOR(an Acceleration and STOrage Ring) which combines the acceleration and storage effect in one isochronous cyclotron was proposed in '70s.

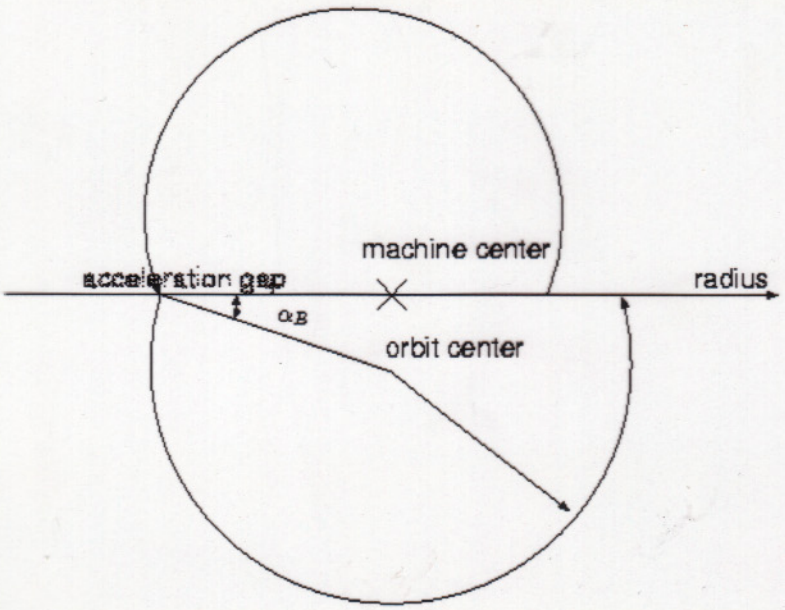
The storing process can be accomplished with phase expansion effect. The beam is stored violating the isochronism intentionally and making a high beam density area.



This effect needs a radial dependent RF voltage.

The mechanism of the phase expansion

The RF voltage which has radial dependence make magnetic field whose phase is delayed π radian from the RF voltage.



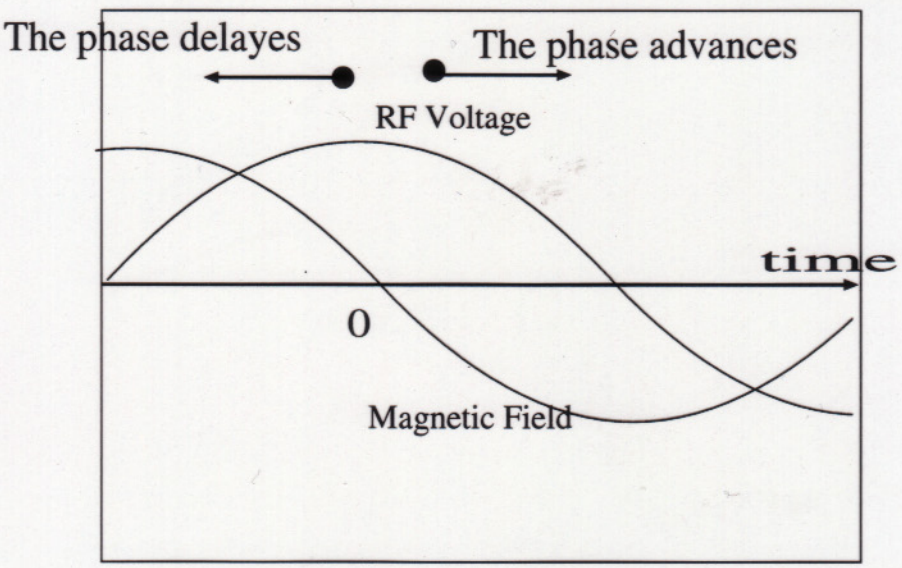
$$\Delta E = E(R)\cos\phi$$

$$\rightarrow \quad \dot{b} = rot\mathcal{E}$$

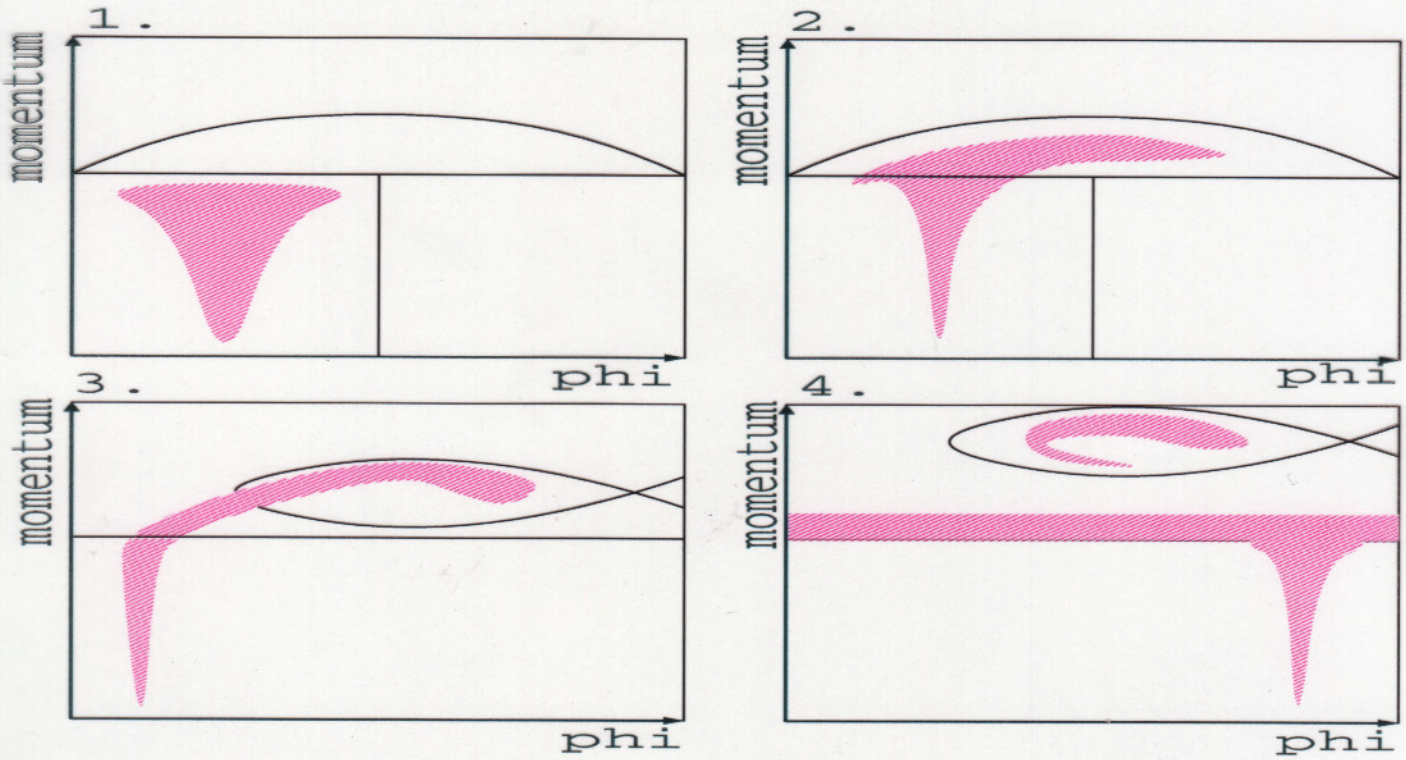
$$\rightarrow \quad b_z = -\frac{\mathcal{E}'}{\omega_{rf}}\sin\phi$$

Magnetif Field

The beam is kicked by this magnetic field and the orbit length changes and the phase expansion occurs.



beam handling between ASTOR and FFAG



beam capture at the FFAG region

1. Storage Stage: the beam is stored with radial dependent RF at the ASTOR region.
2. Acceleration Stage: The stored beam is accelerated to the FFAG region with radial independent RF.
3. Beam Capture Stage: The beam is captured with radial independent RF before the beam falls down into the deceleration phase.
4. Acceleration Stage: The beam acceleration of the captured beam.

In this scheme it is assumed that only the particles in the acceleration phase can be captured.

knobs to improve injection efficiency 1.

The parameters to improve injection efficiency

- the gradient of the RF voltage of radius direction.
- the k value around the conjunction area of ASTOR and FFAG.
- the RF phase to pass over the beam from ASTOR to FFAG.

How can the injection efficiency be improved?

- Increase the stored beam changing the gradient of RF Voltage.
- Increase the time storing the beam compared to acceleration time in FFAG.
- Improve the efficiency to pass over the beam from ASTOR to FFAG.

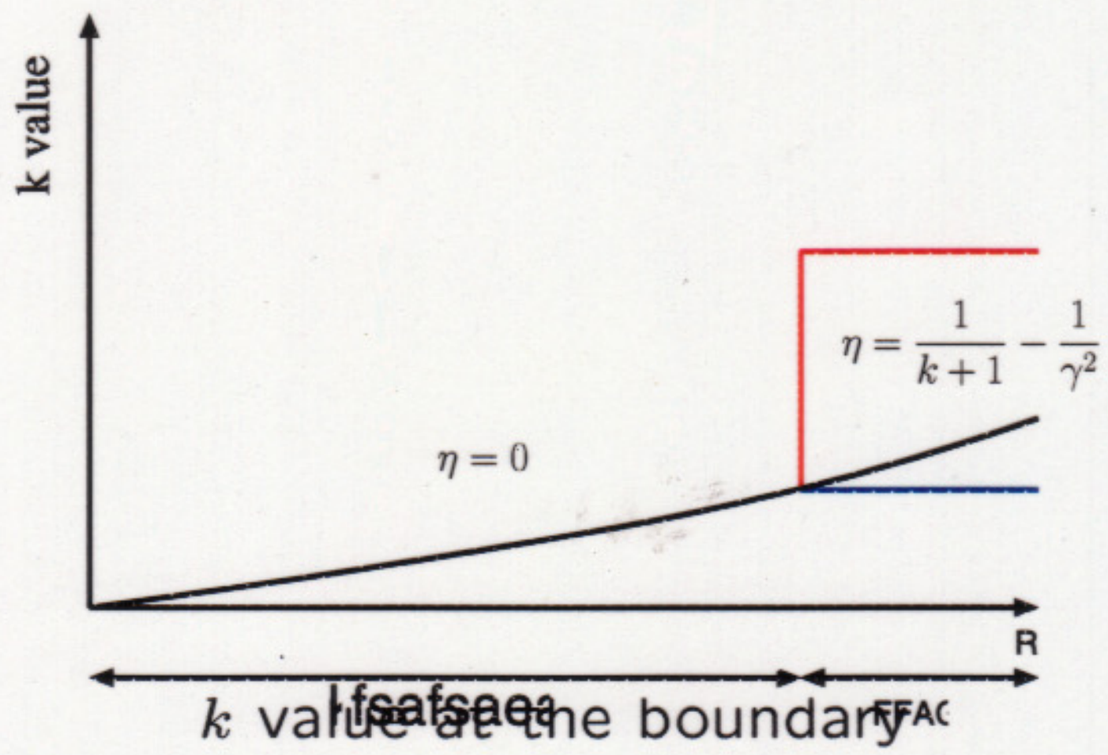
knobs to improve injection efficiency 2.

The synchrotron frequency is

$$Q_s = \omega_s \sqrt{-\frac{h n_e V \eta \cos\phi_s}{2\pi E_s}}$$

η	:	slipage factor
ω_s	:	RF frequency
V	:	RF Voltage
h	:	harmonic number
n_e	:	charge number
ϕ_s	:	synchronous phase
E_s	:	synchronous energy

In the cyclotron, the slipage factor is zero.



In case k connected continuously at the boundary , synchrotron frequency is too small to bunch the beam quickly at the boundary. k must be changed discontinuously at the boundary.

ASTOR-FFAG longitudinal simulation

Longitudinal simulation of the ASTOR-FFAG is simulated changing the two beam handling parameters at the boundary.

1. RF voltage of the ASTOR
2. The RF phase to pass over the beam.

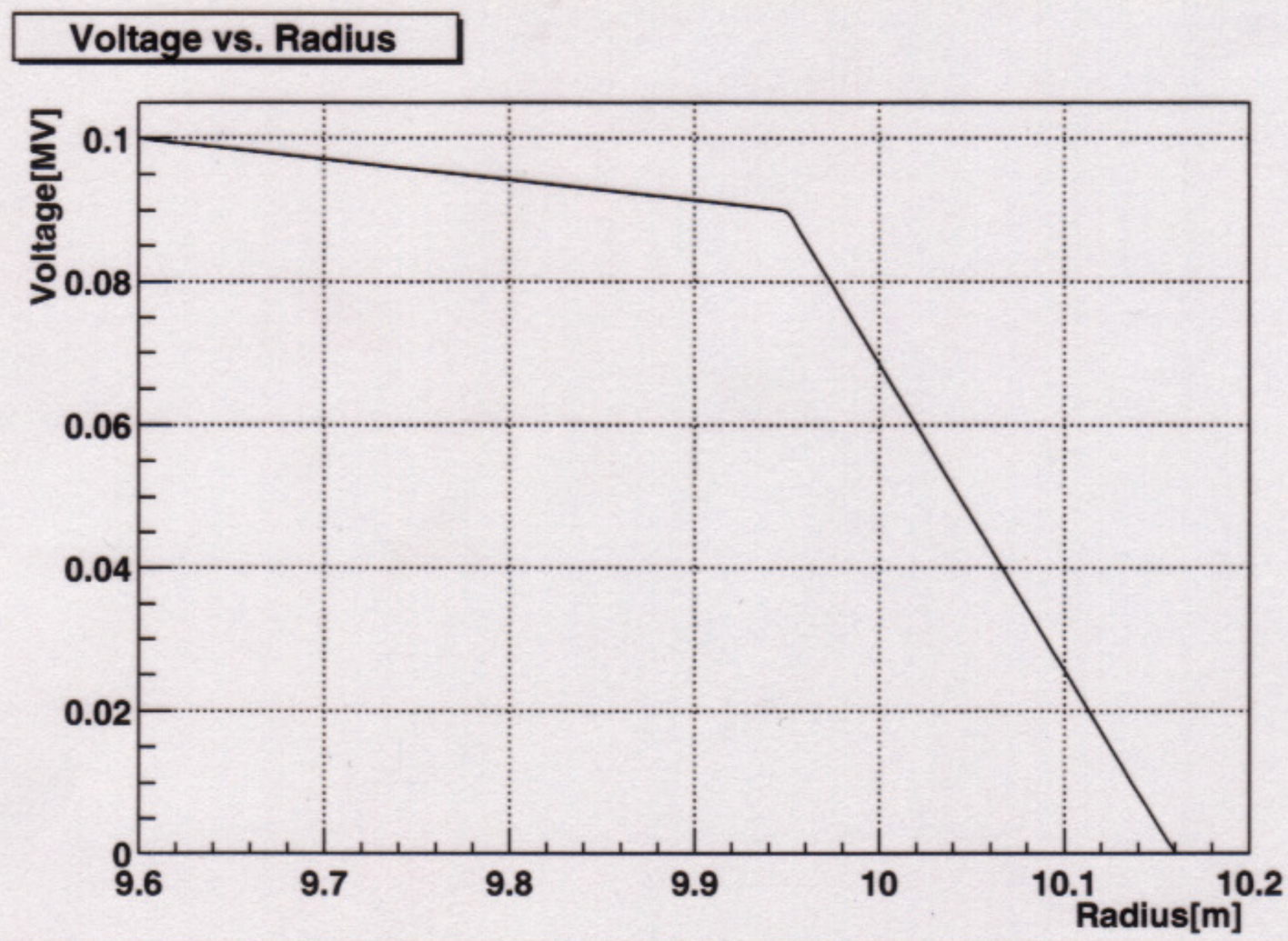
ring parameters

particle	proton
energy	$250 - 340 MeV$
center magnetic field	$0.2T$
radius	$10m$
cyclotron frequency	$3.05MHz$

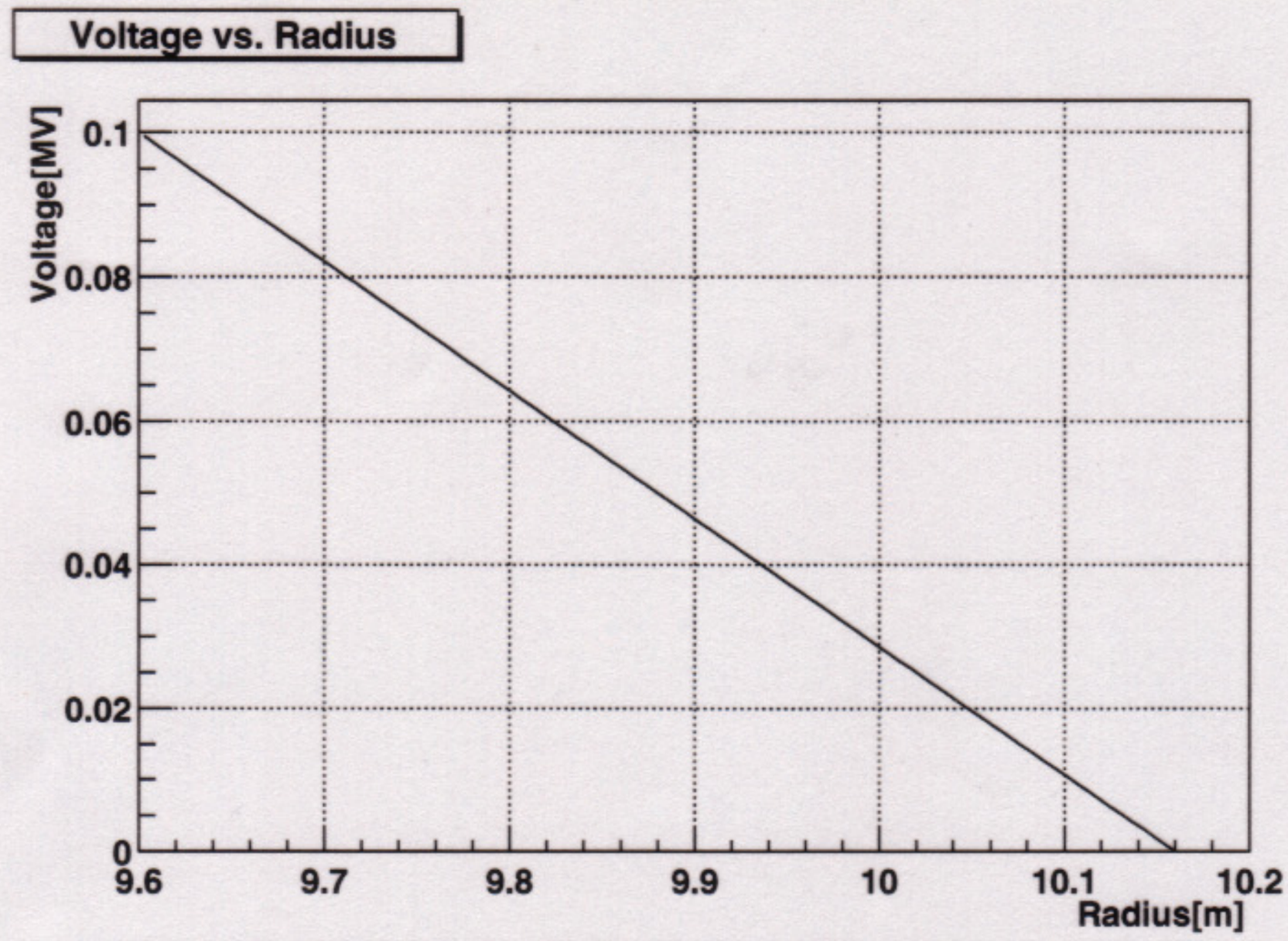
The ASTOR and FFAG is connected at $10.16m$ and the k value change from 0.6 to 2.5 at the boundary.

the amount of stored beam and radial dependence of the RF voltage

RF voltage patterns

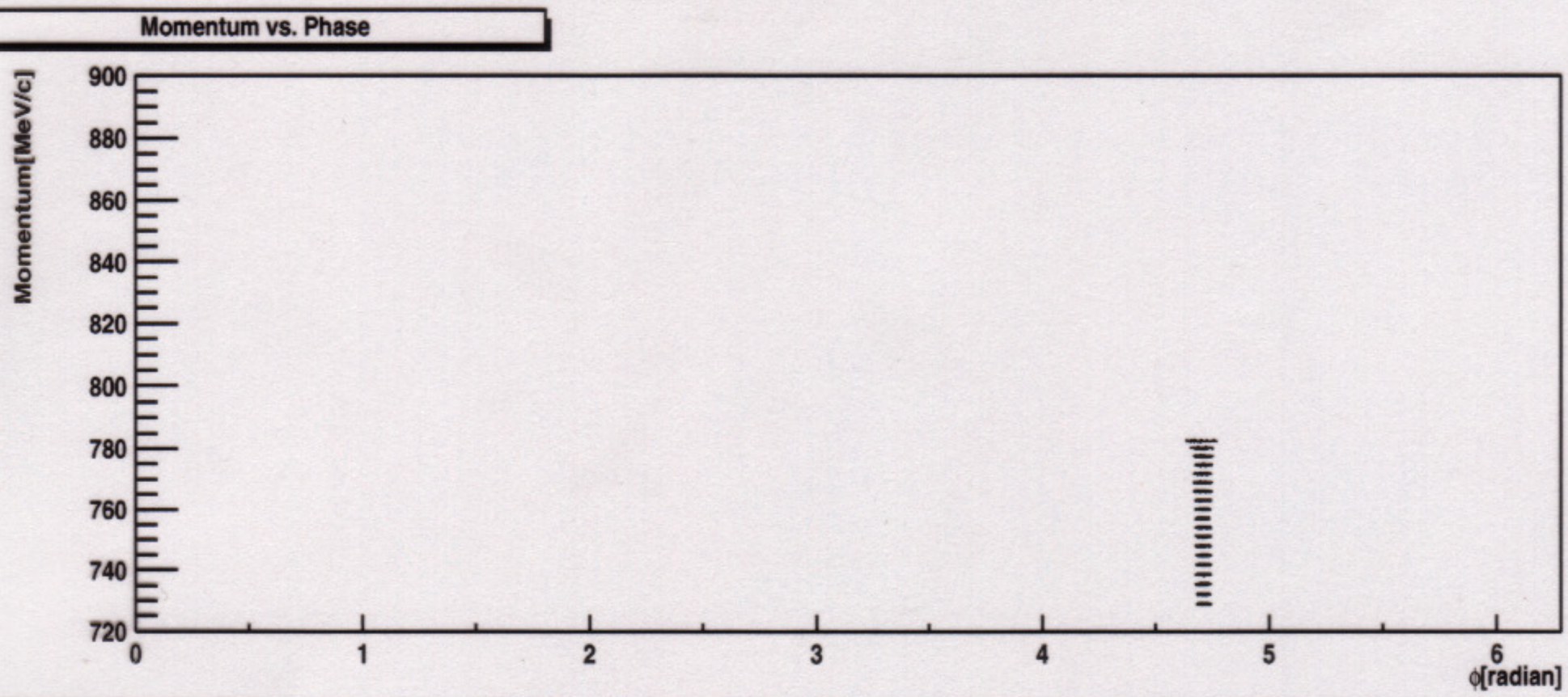


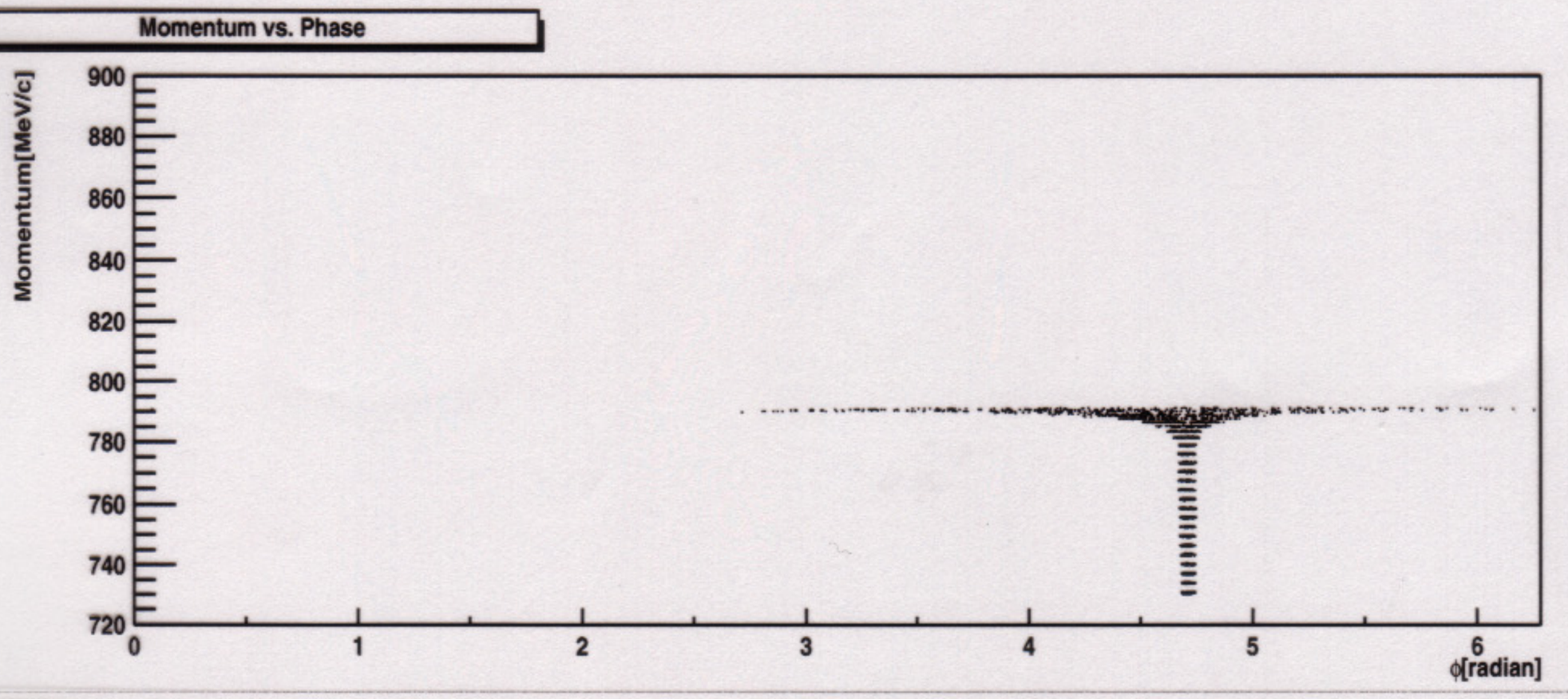
pattern 1



pattern 2

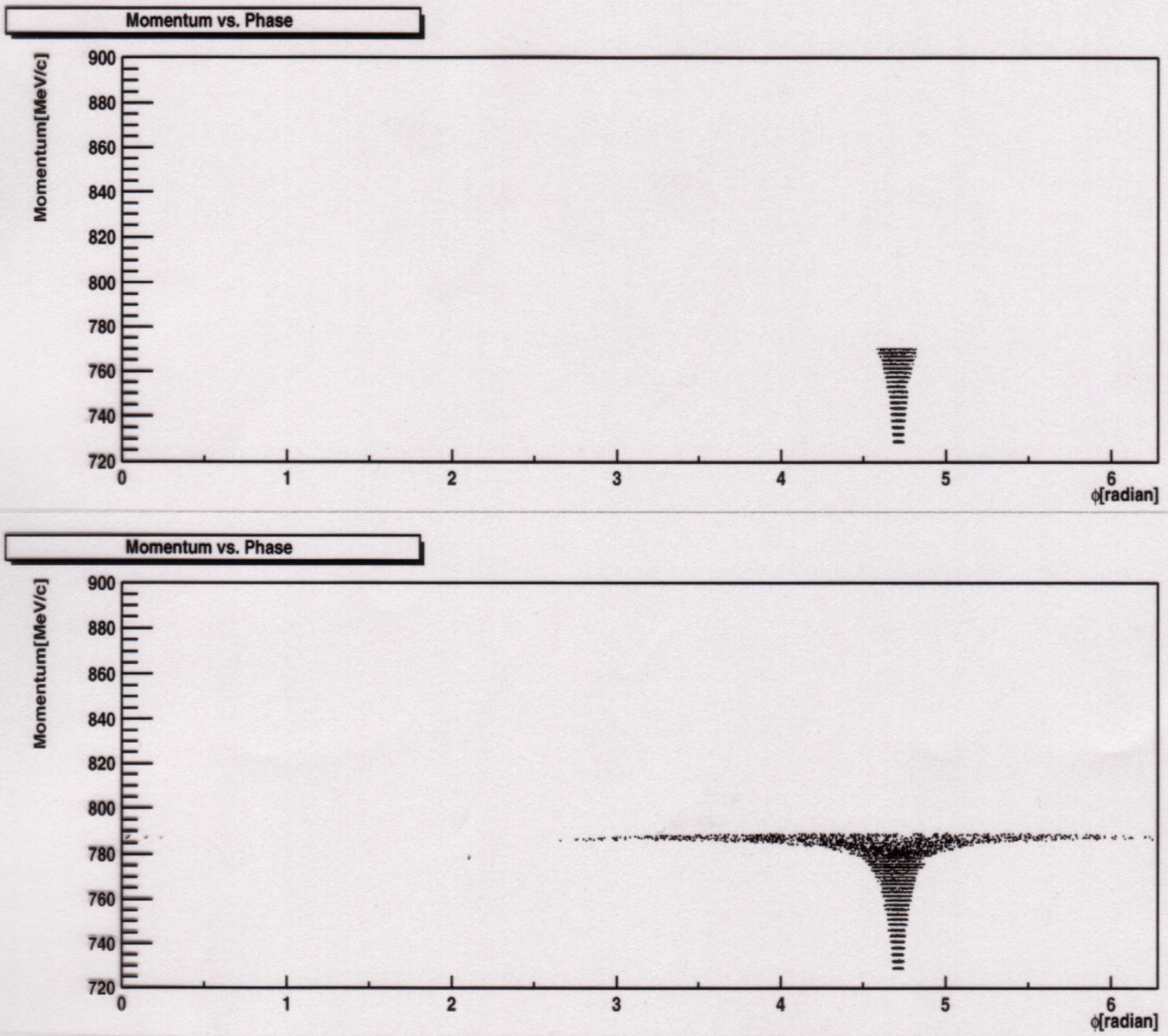
particle distribution in phase space(pattern 1)



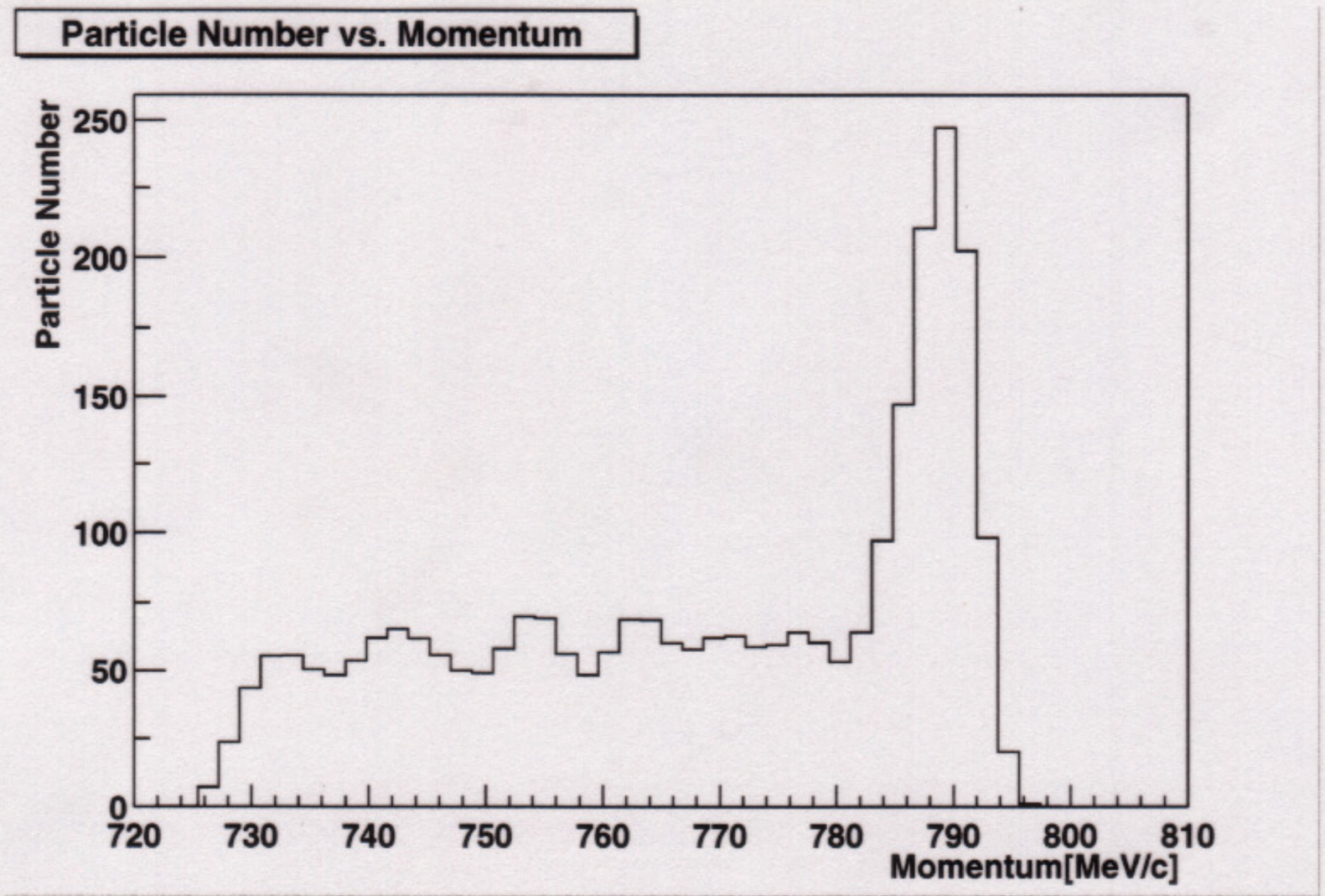


after 118μsec (360 cycles) and 180μsec(550 cycle)

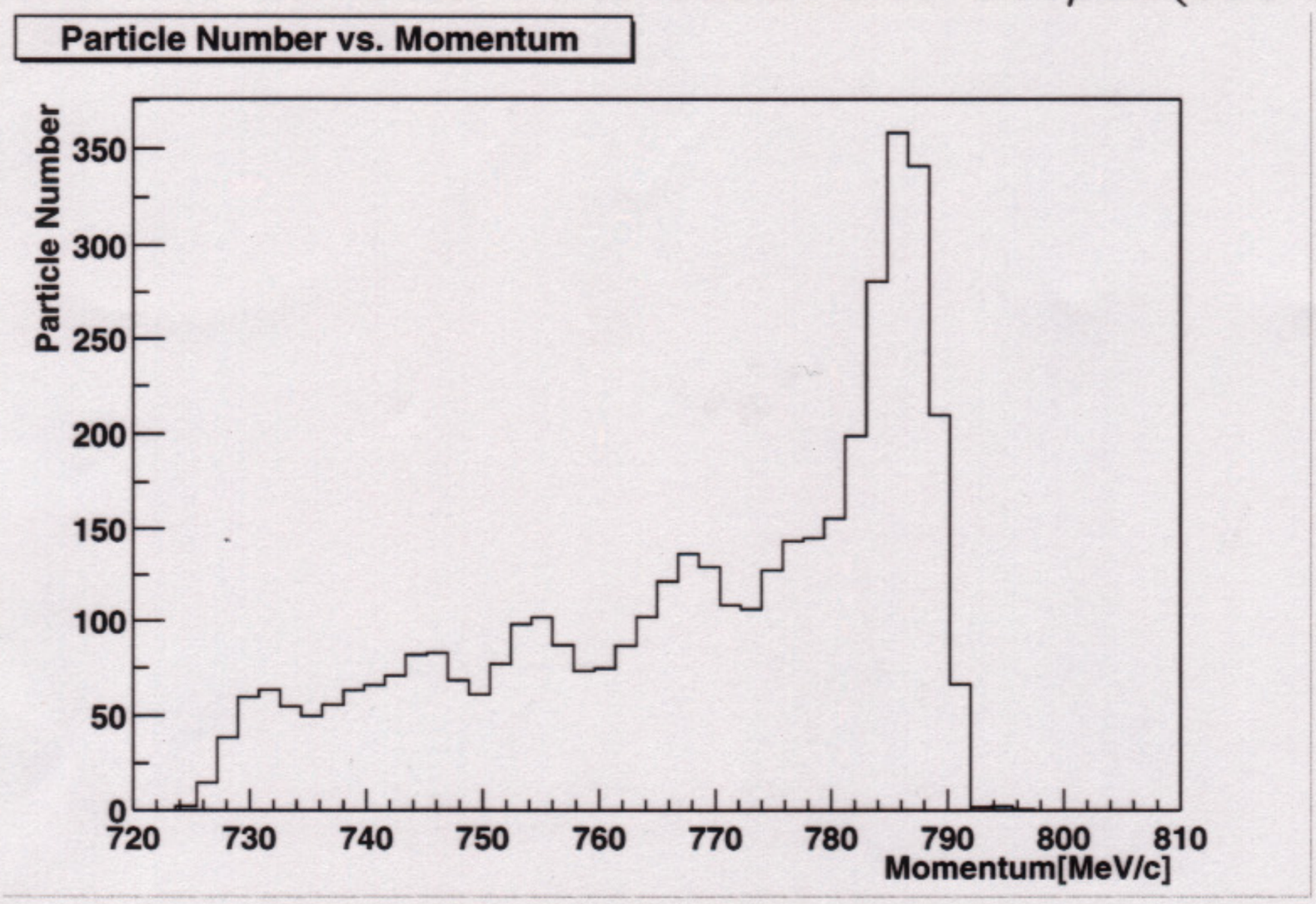
particle distribution in phase space(pattern 2)



118μsec (360 cycles) and 262μsec (800 cycle)



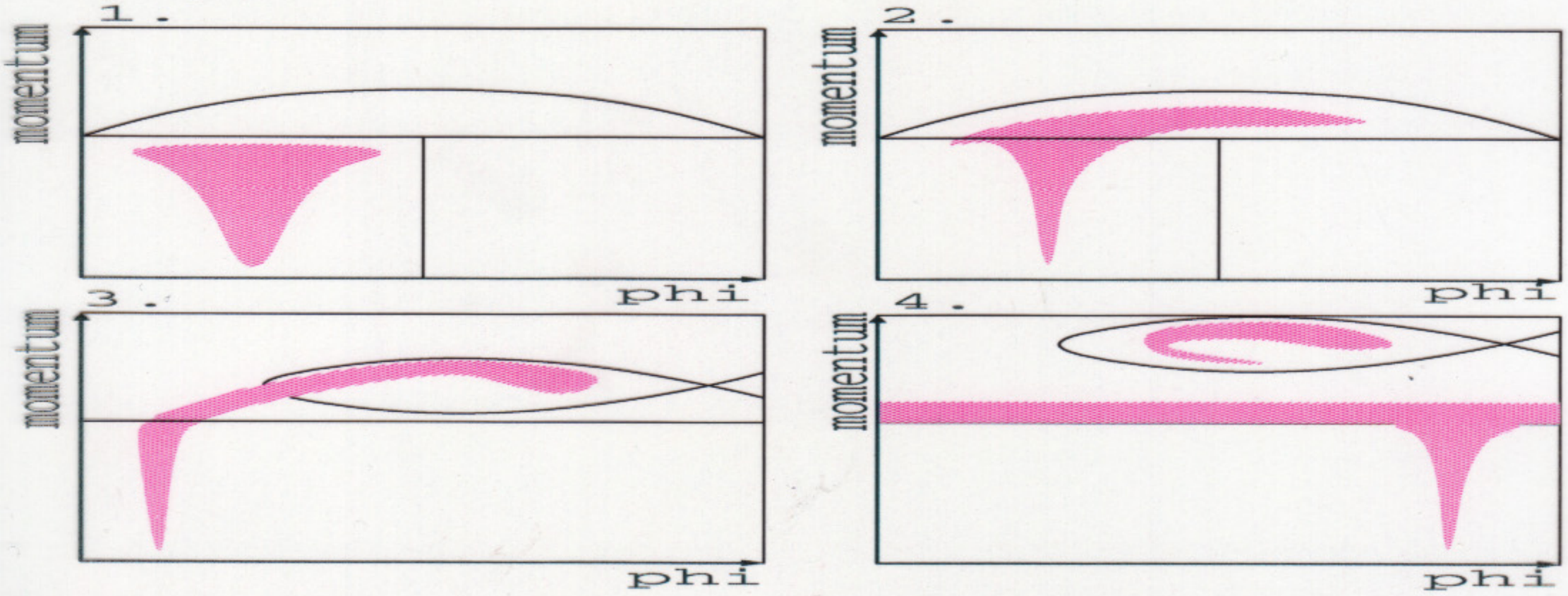
pattern 1: the momentum distribution after 180μsec(550 cycle)



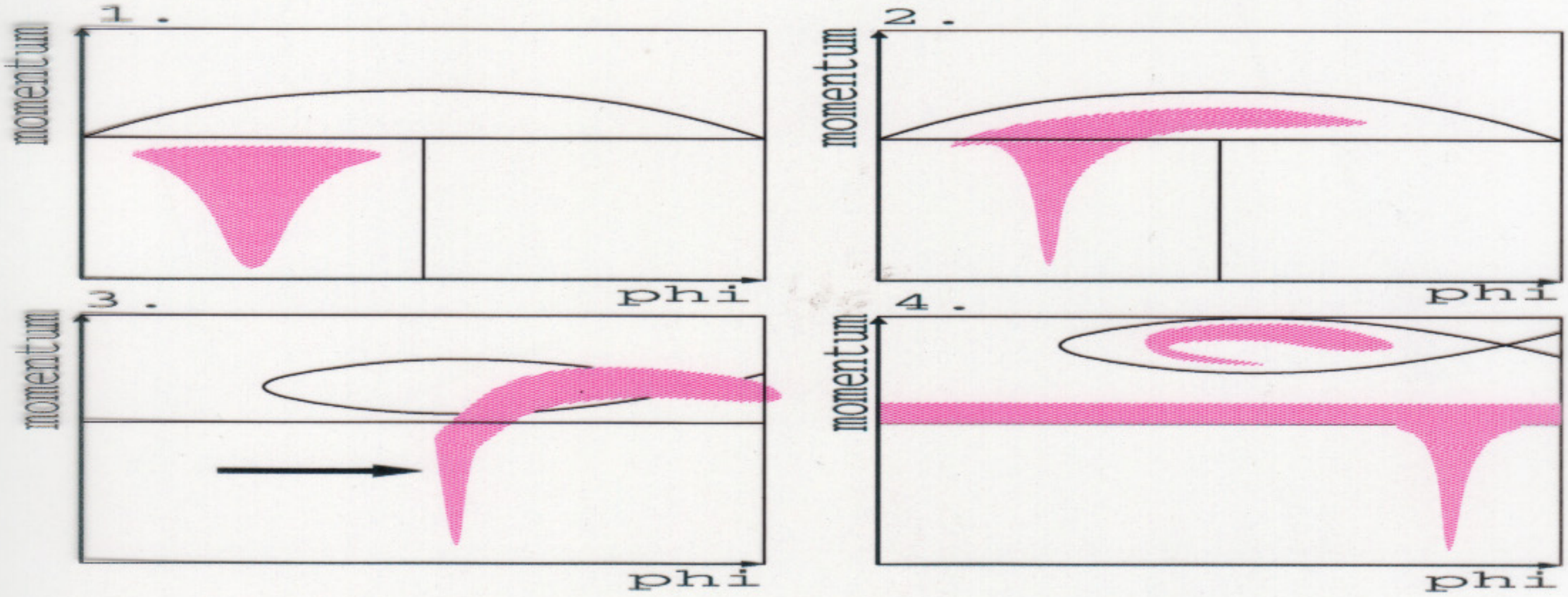
pattern 1: the momentum distribution after 262μsec(800 cycle)

RF phase to pass over the beam from ASTOR to FFAG.

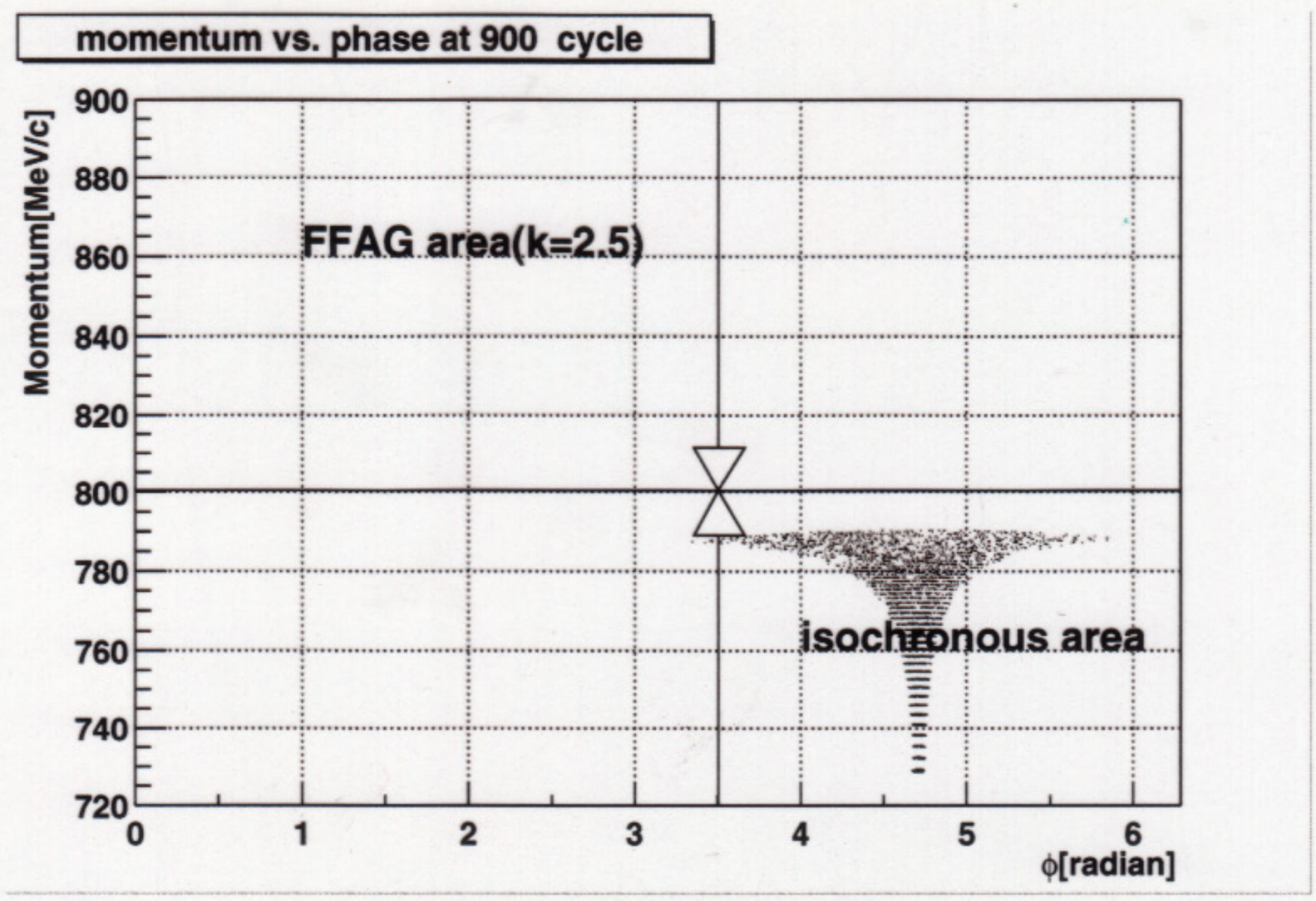
Case 1. The RF phase of acceleration is same as the RF phase of ASTOR.



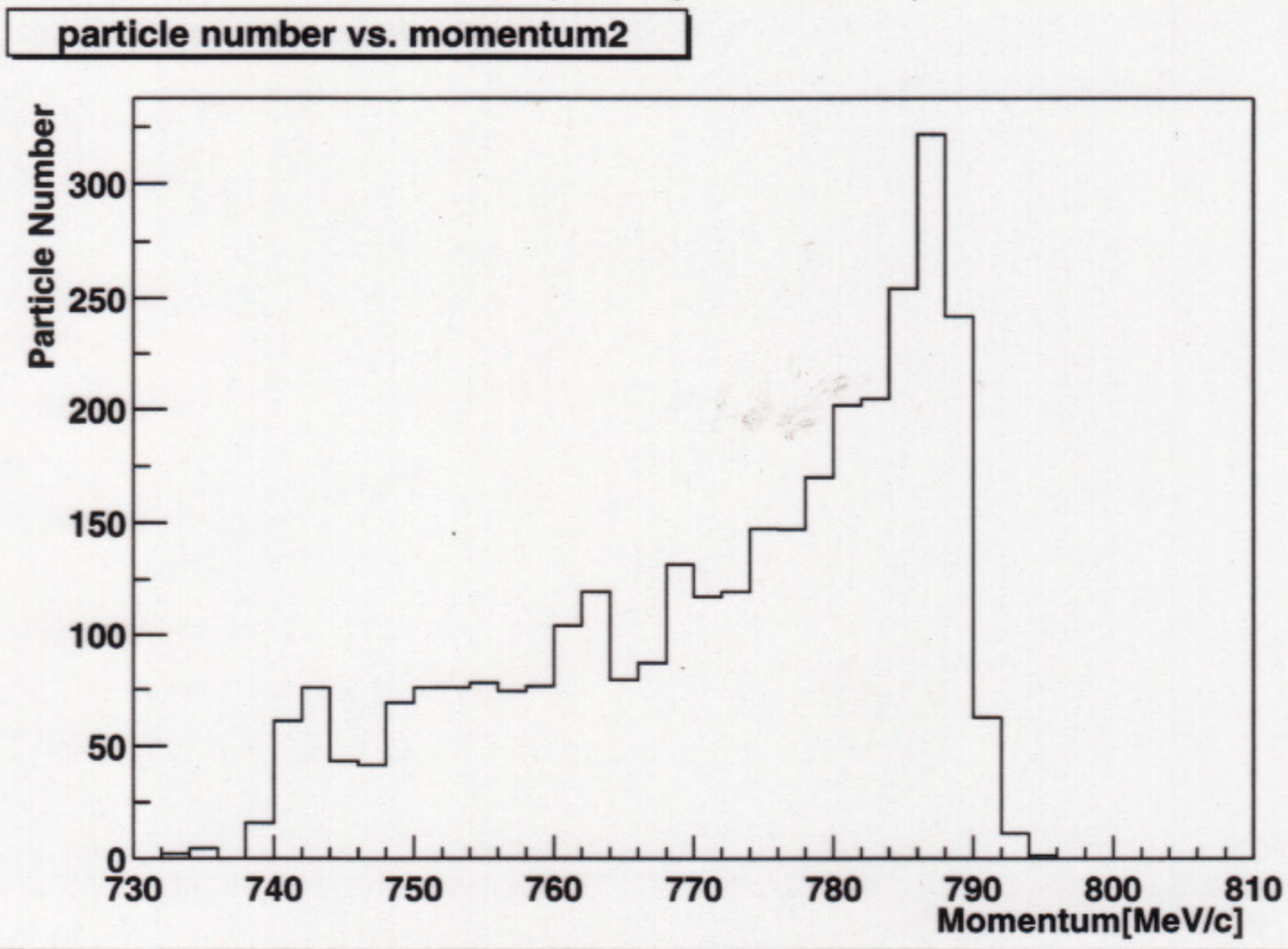
Case 2. The RF phase of acceleration is shifted $\pi/2 radian$ from the RF phase of ASTOR.



the particle distribution after storage

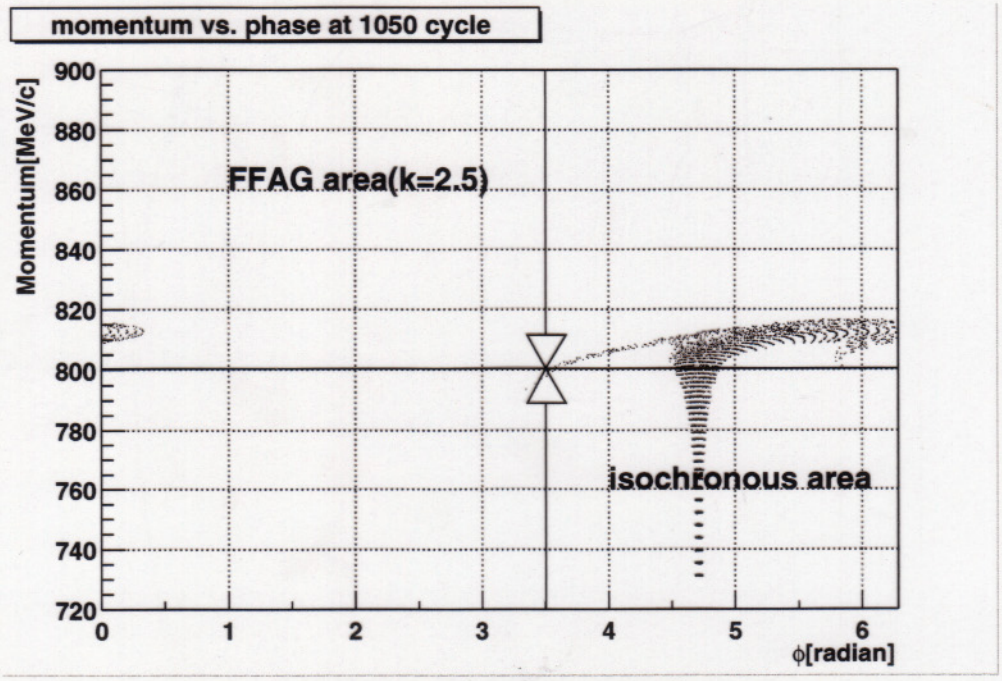


295μsec(900cycle)

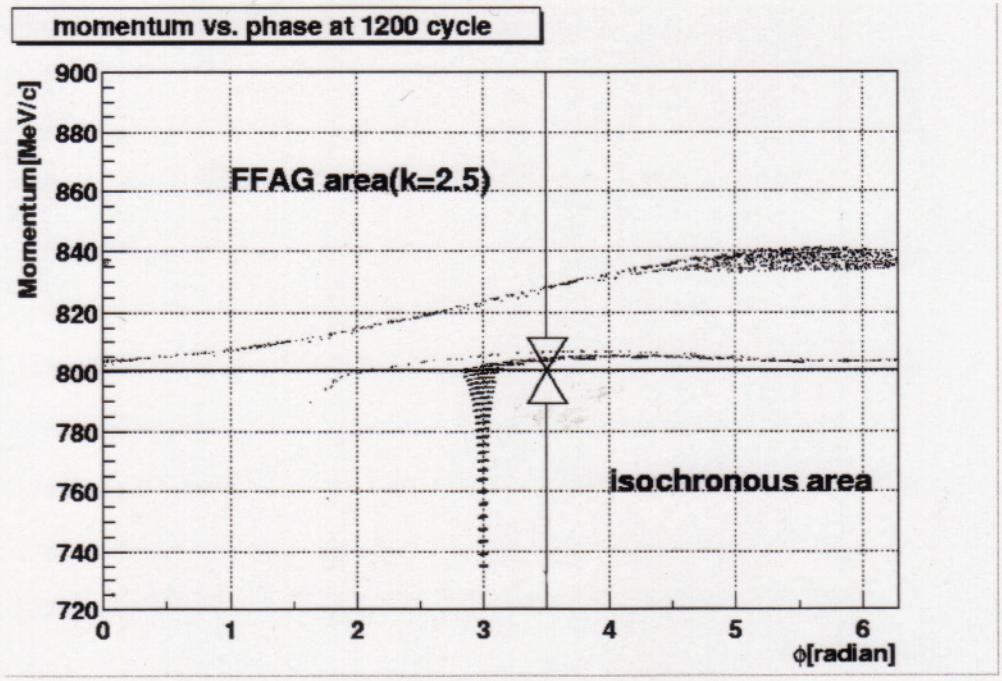


295μsec(900cycle)

Case 1

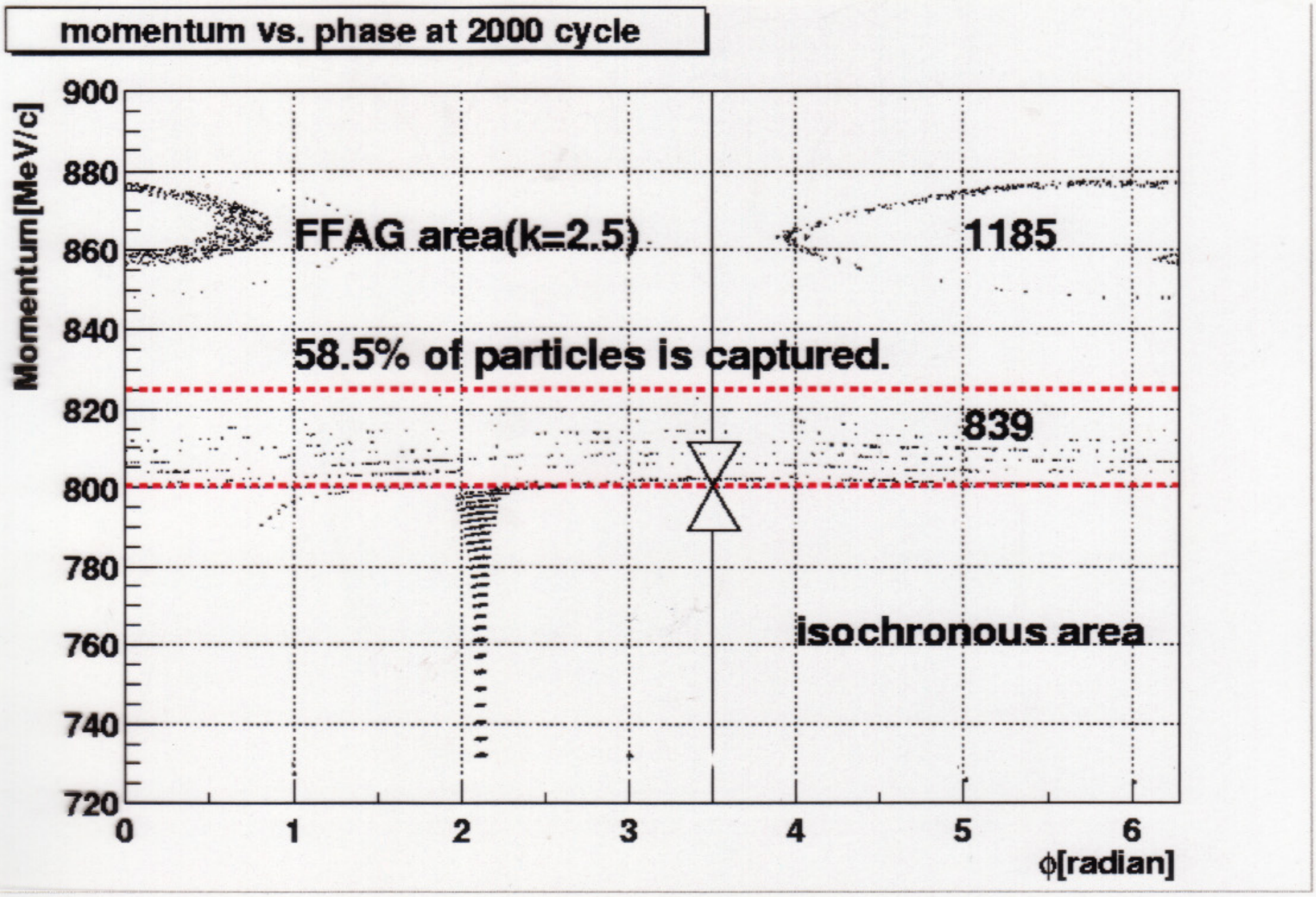


344μsec(1050 cycle)



393μsec(1200cycle)

These two graphs show the capturing process phase 2 and phase 3.



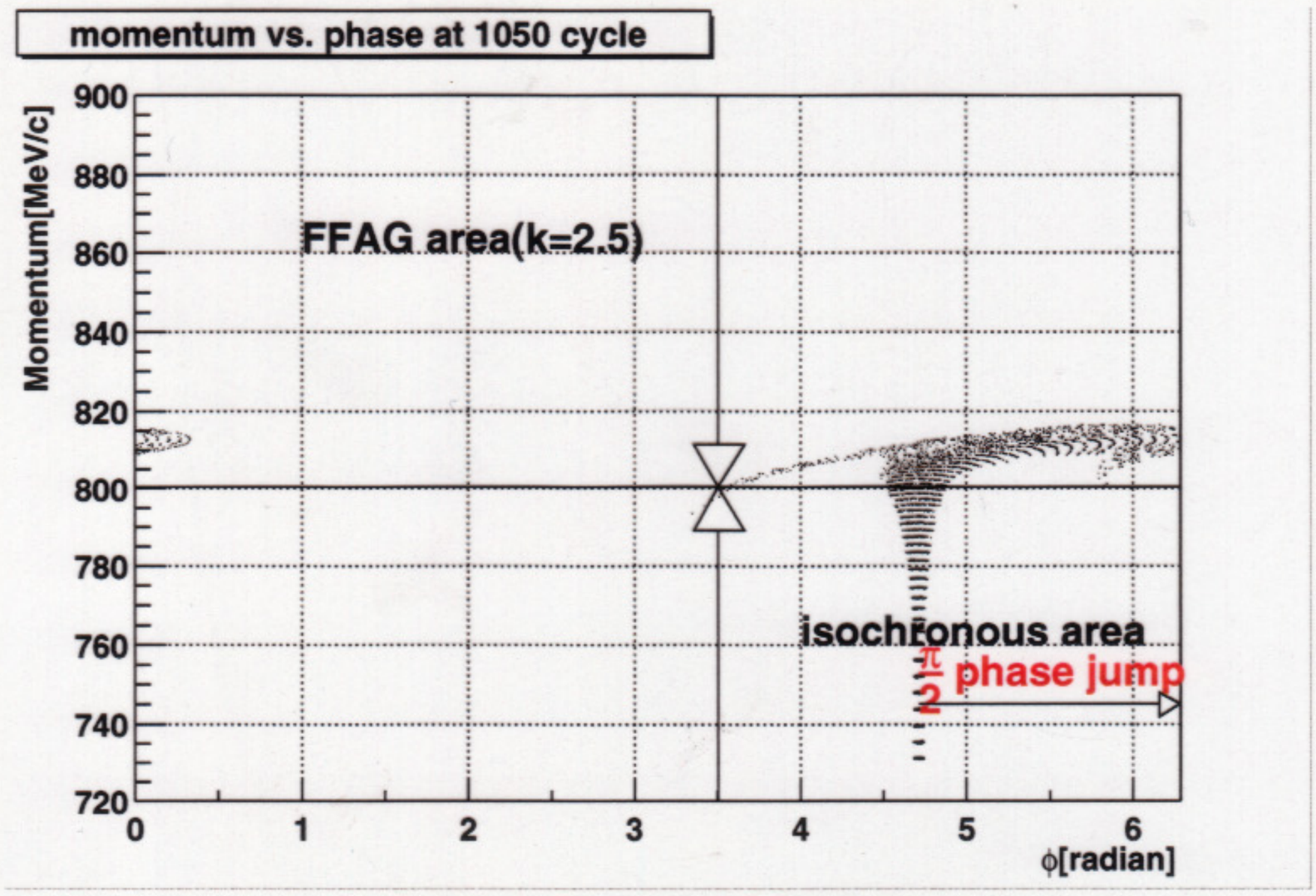
656μsec(2000cycle)

This is the result of Case 1.

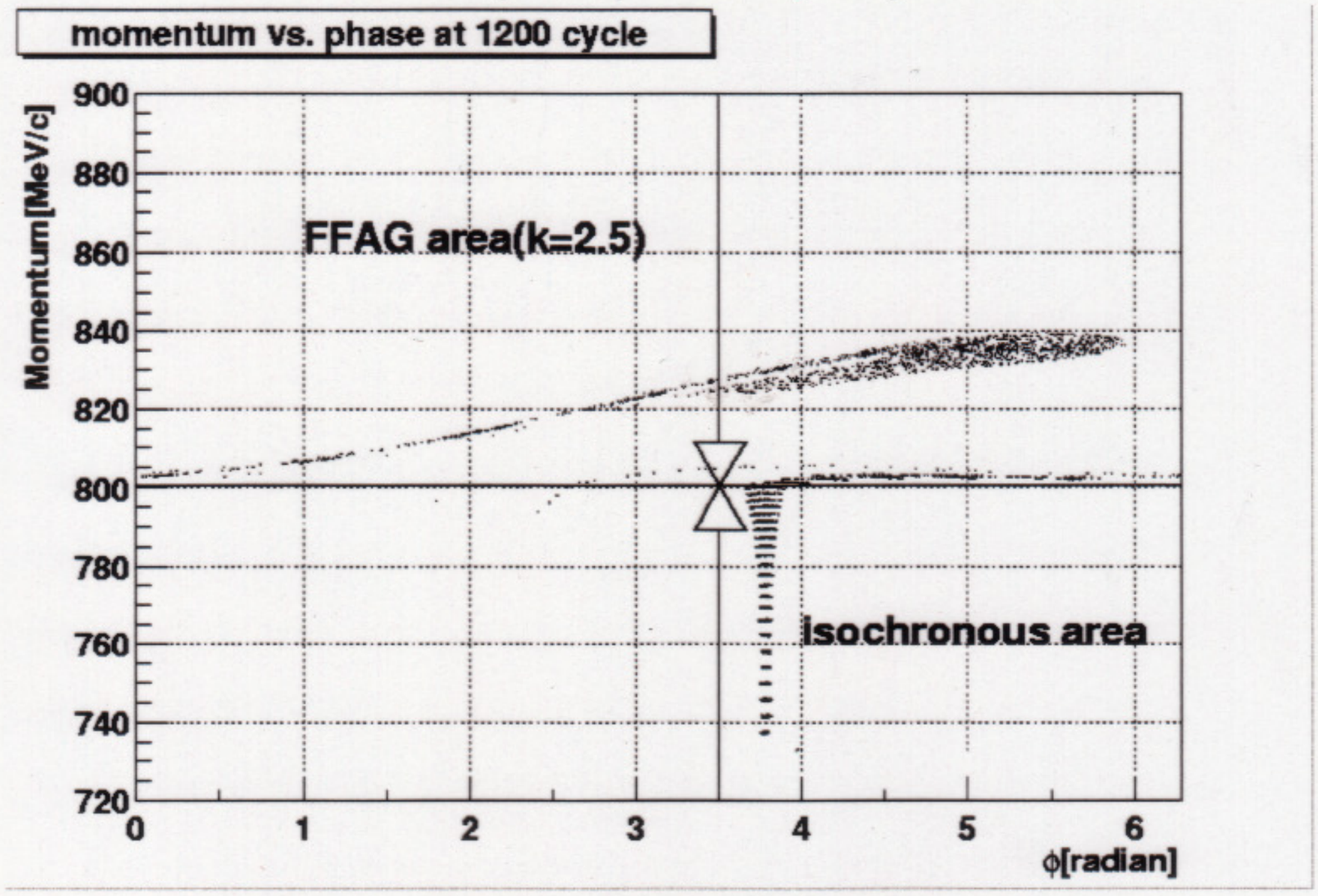
58.5% of particles are captured.

The particles rest in the ASTOR area is not disarranged, so it is possible to accelerate the particle again.

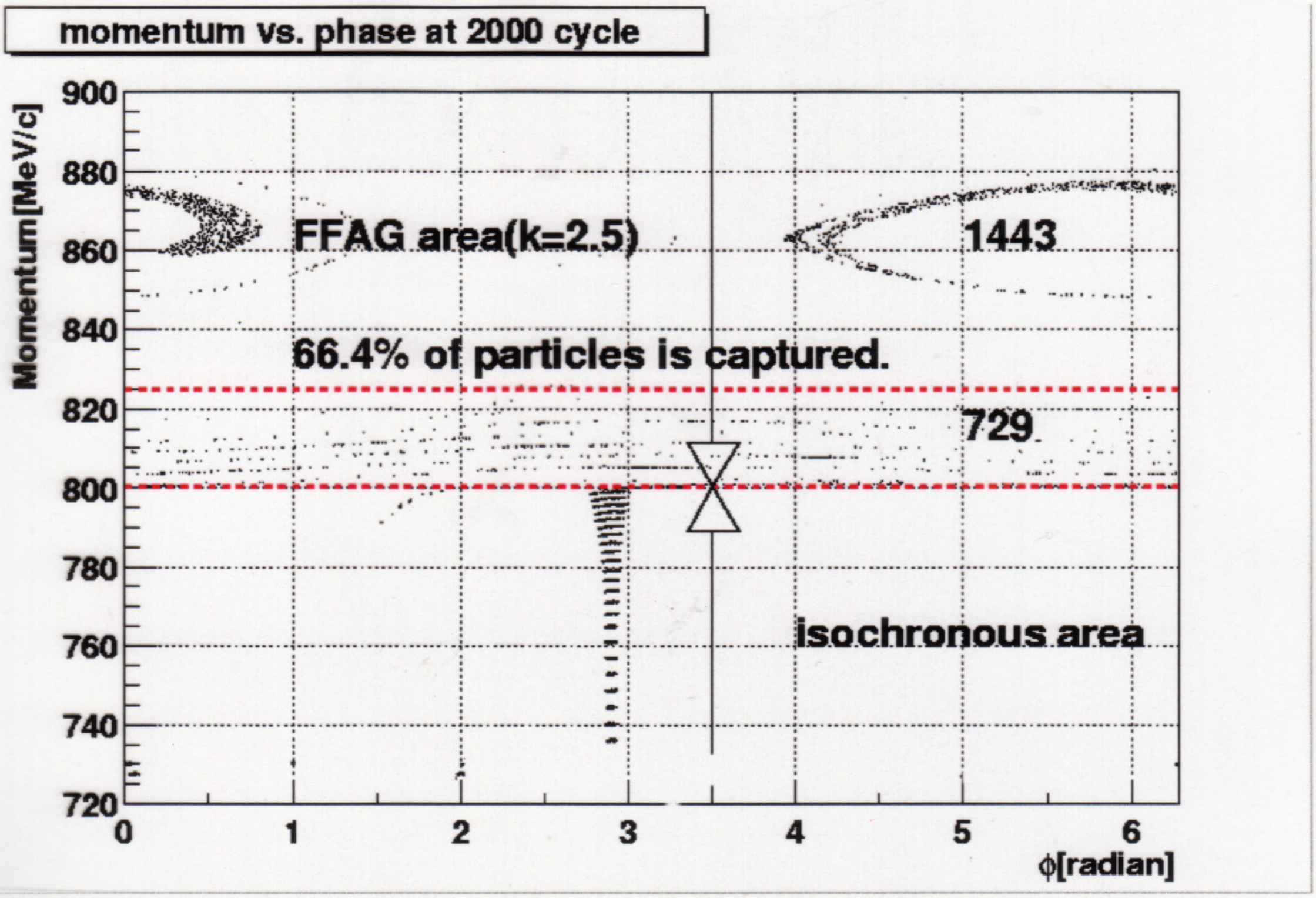
Case 2



$344\mu sec$(1050 cycle)



$393\mu sec$(1200cycle)



656μsec(2000cycle)

This is the result of Case 2.

The captured amount of the particle is improved from 58.5%.

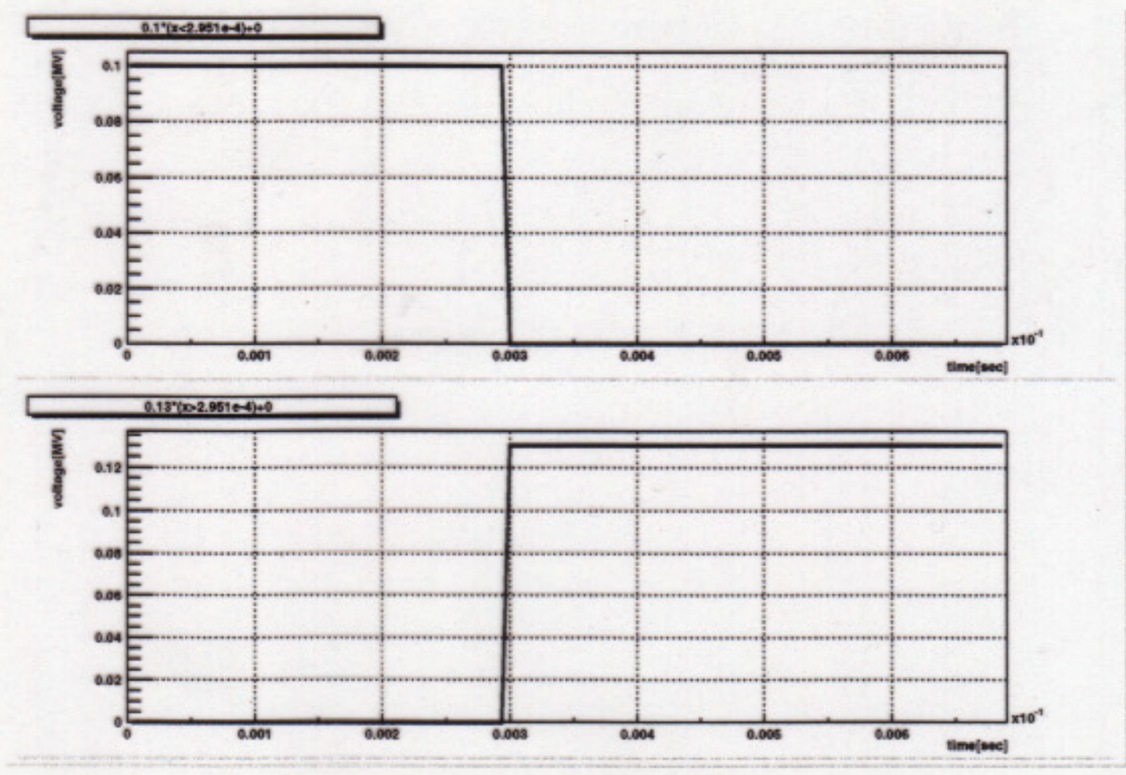
Summary

- The injection efficiency is improved to 64%. This is about 100 times larger than that of ordinary way.
- Tuning of the radial dependence improve the efficiency of the
- When the beam is passed over the boundary, the efficiency is improved when the RF phase is shifted $\pi/2 radian$.

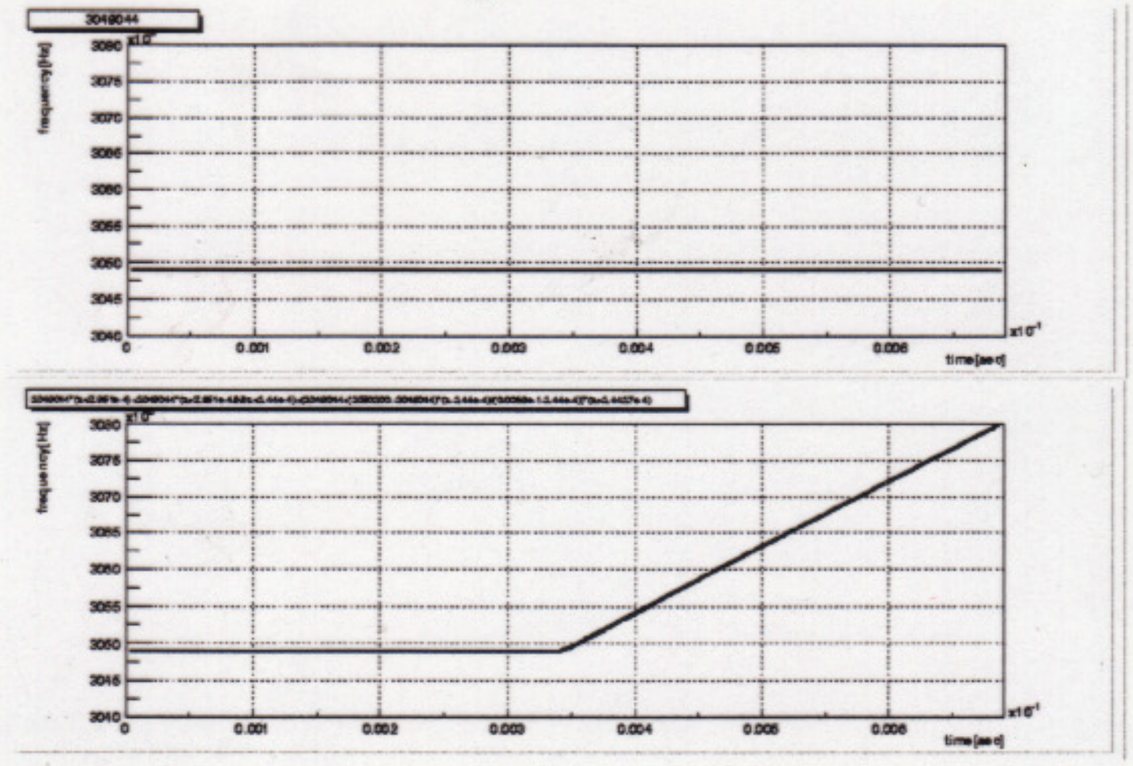
The R&D items to realize ASTOR-FFAG

- The Design Of The Magnet: The magnet connects the isochronous magnetic field and the ffag magnetic field.
- The Study Of The Beam Stability: The betatron tune jumps at the boundary, so the resonance jump must be needed.
- RF Design: The radial dependent RF voltage.

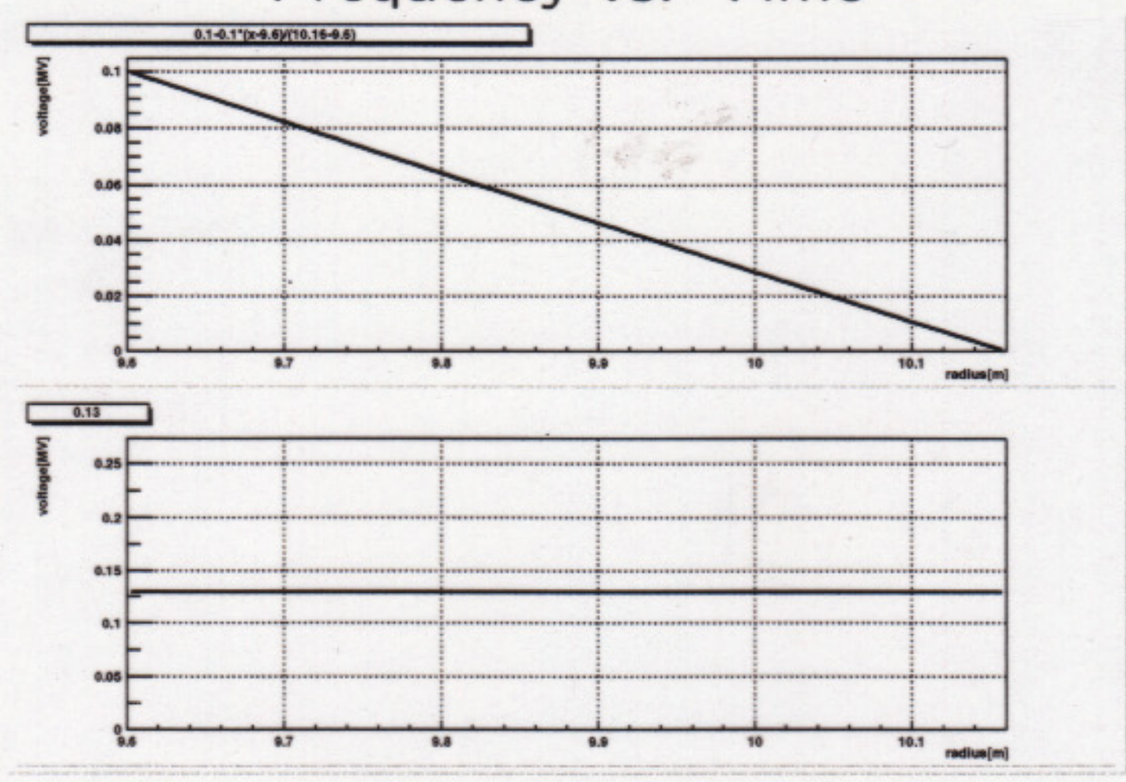
ASTOR-FFAG RF parameters



Voltage vs. Time



Frequency vs. Time



Voltage vs. Radius