EXPERIMENTAL STUDY TOWARDS HIGH BEAM POWER FFAG

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Kyoto university
research reactor institute

TOC

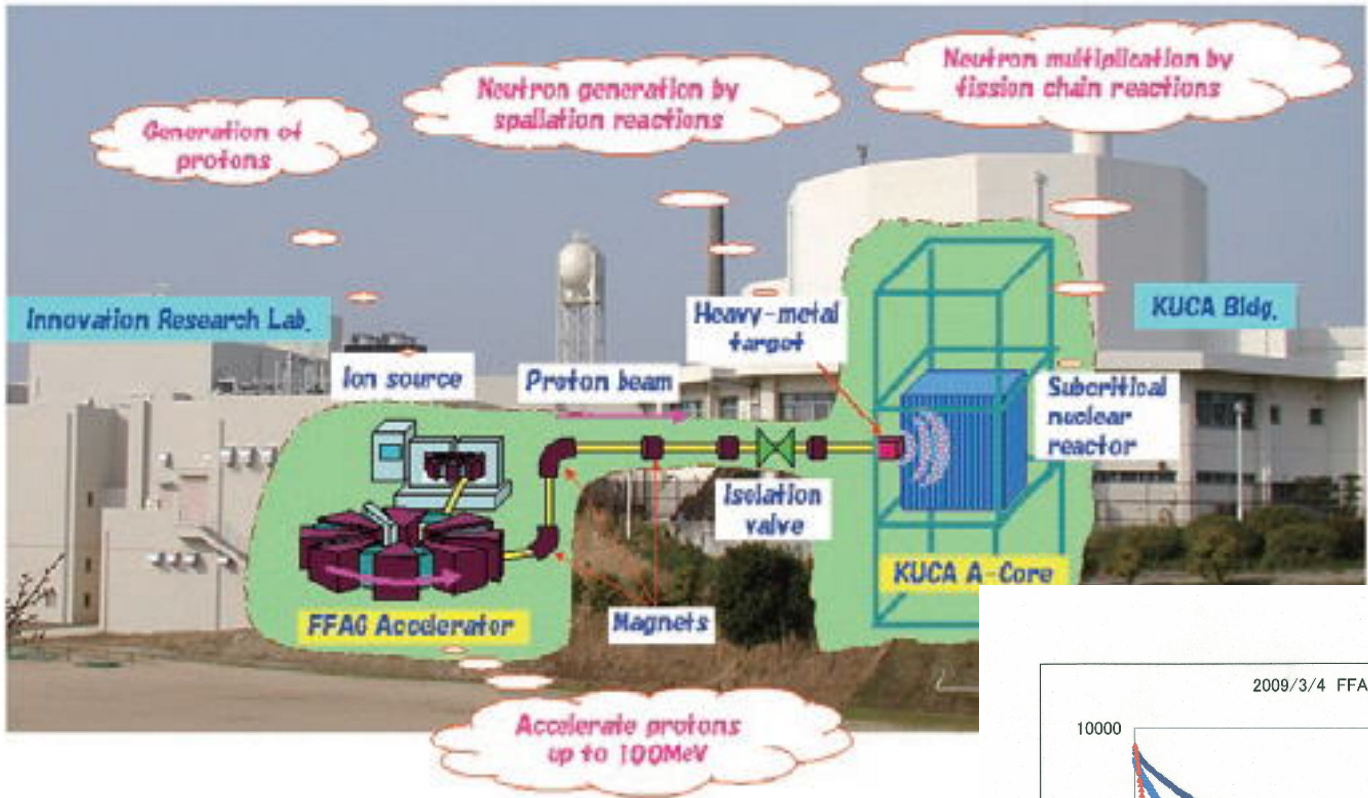
Kyoto university research reactor institute

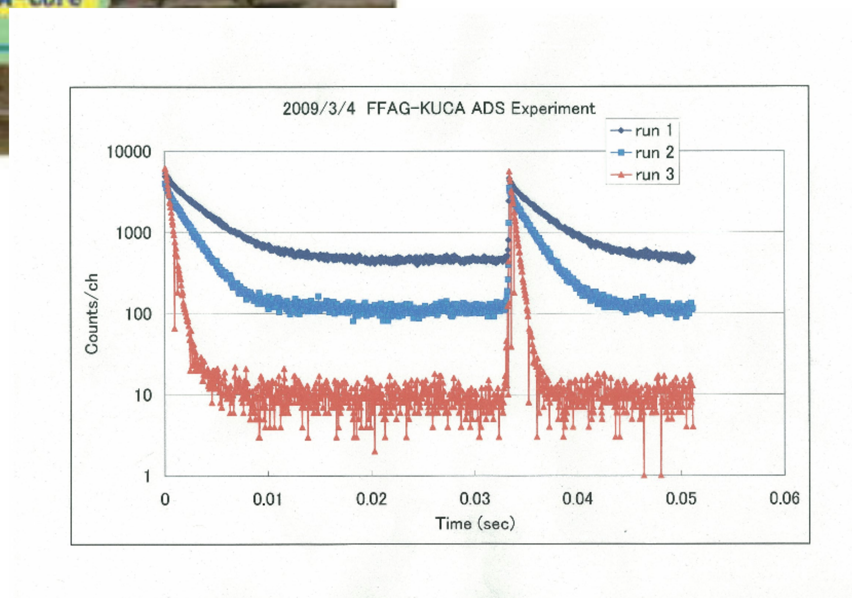
Osaka, Japan

- Kyoto university Research Reactor
- Hot Laboratory
- Kyoto University Critical Assembly
- Thermal-Hydraulic Test Loop
- Electron Linear Accelerator
- Tracer Laboratory
- Co-60 gamma-Ray Irradiation Facility
- Radioactive Waste Management Facility
- Radiation Monitoring System
- Innovation Research Laboratory
- Atom Science Building

ADS Study at KURRI

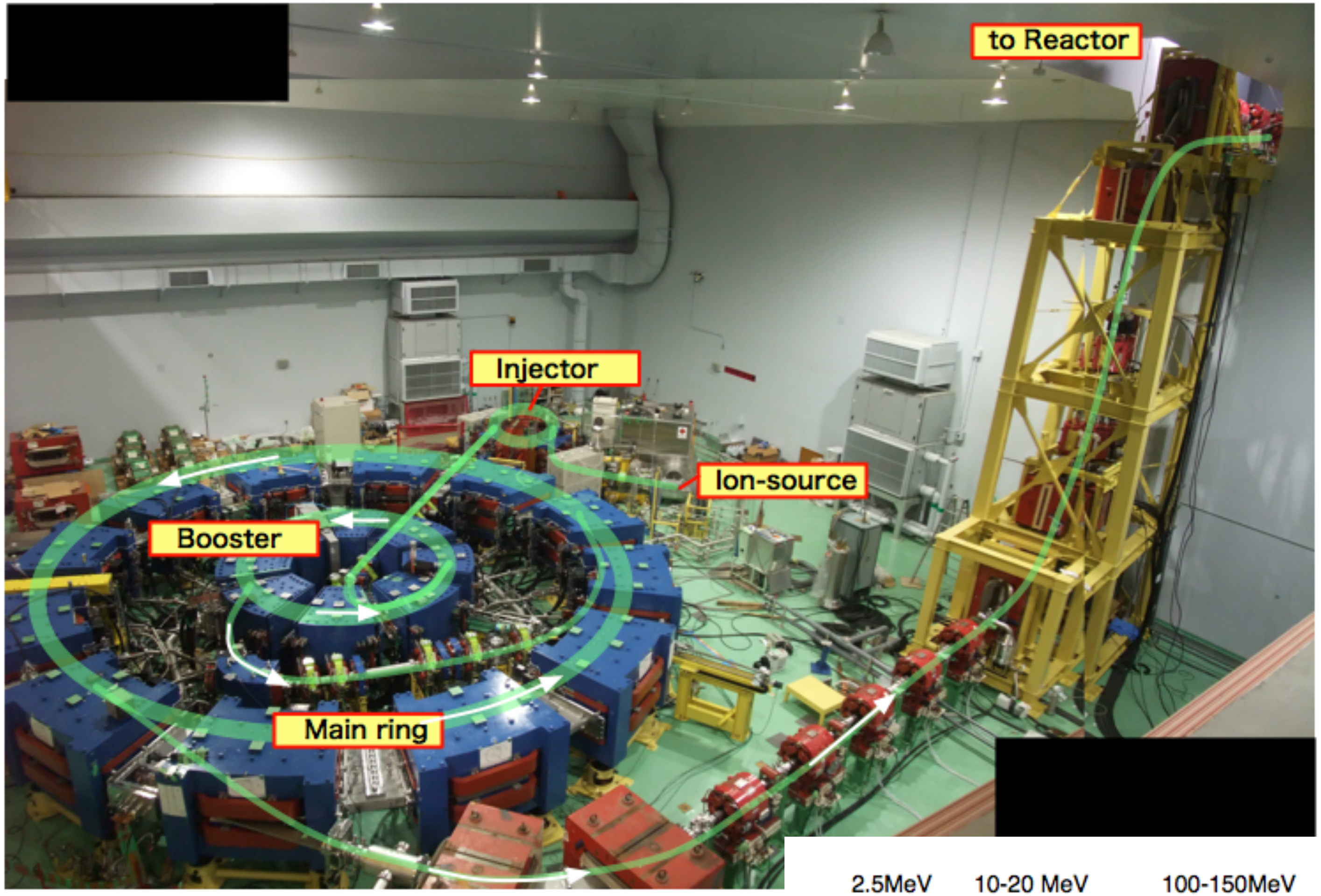
(accelerator driven subcritical system)

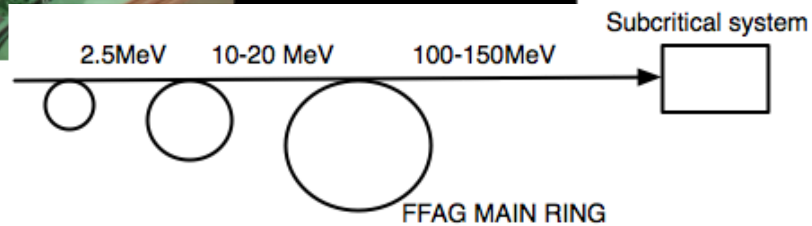




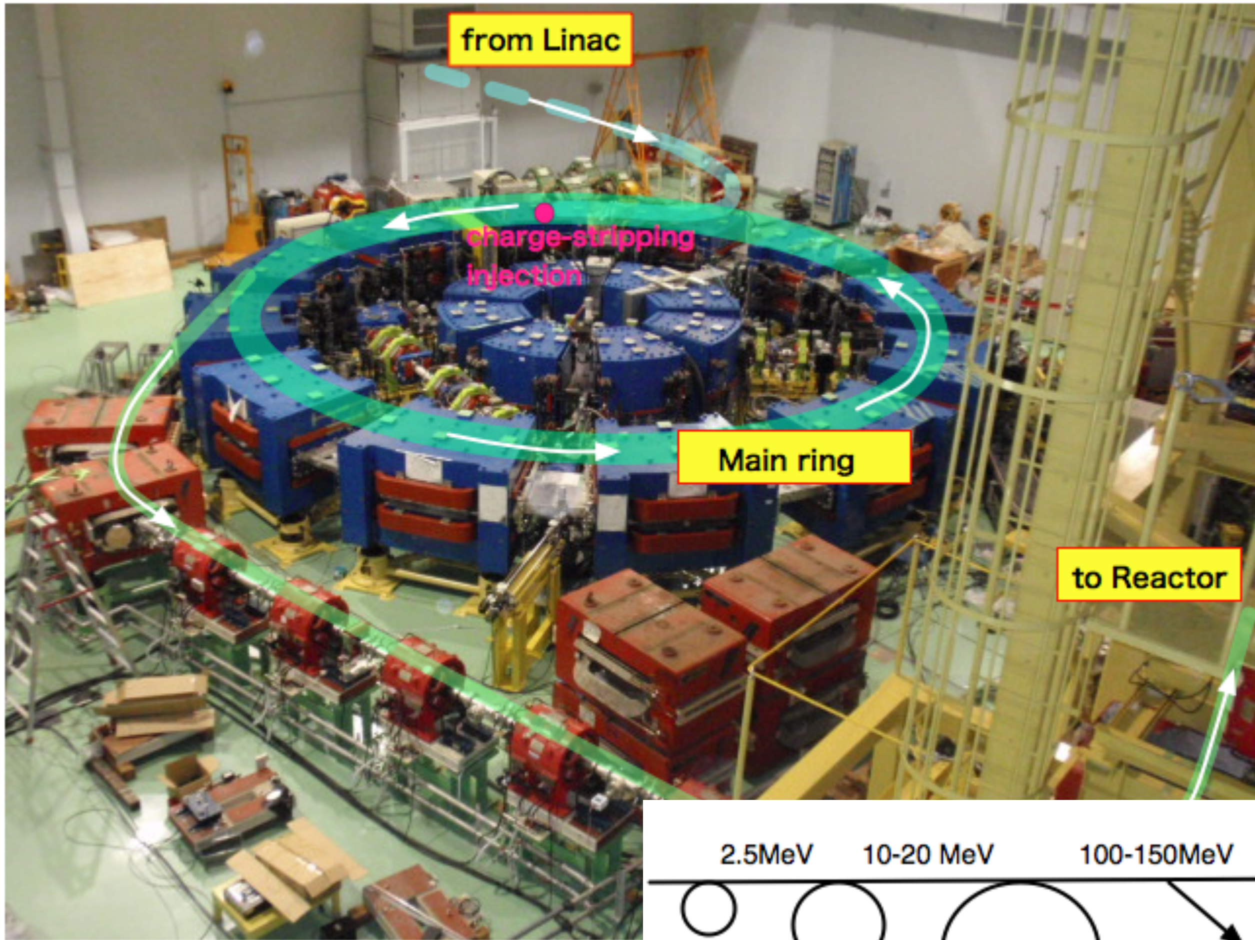
2006 - Construction
2009 First ADS experiments
2011 Replaced injector
Beam intensity x100

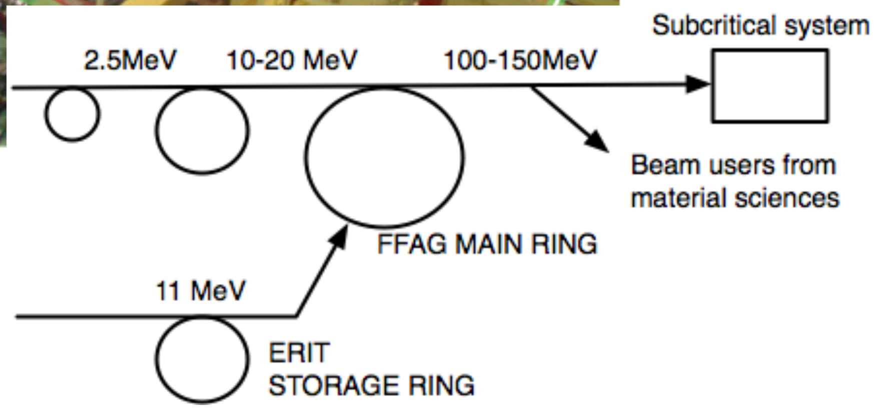
FFAG complex (1)





FFAG complex (2)





INTENSITY UPGRADE

(history)

March 2009（starting ADS exp.）

100MeV 50pA (a few pA @ CA target)

improve transport efficiency

(cavity voltage up 2.5kV →4kV)

March 2010

100MeV 100pA (30 pA @ CA target)

H- injection

March 2011

100MeV 1nA (100 pA @ CA target, unstable)

improve extraction efficiency

March 2012

100MeV 0.1uA equivalent* (100 pA @ CA target, broad beam)

energy up

November 2012

150MeV 0.1uA equivalent *

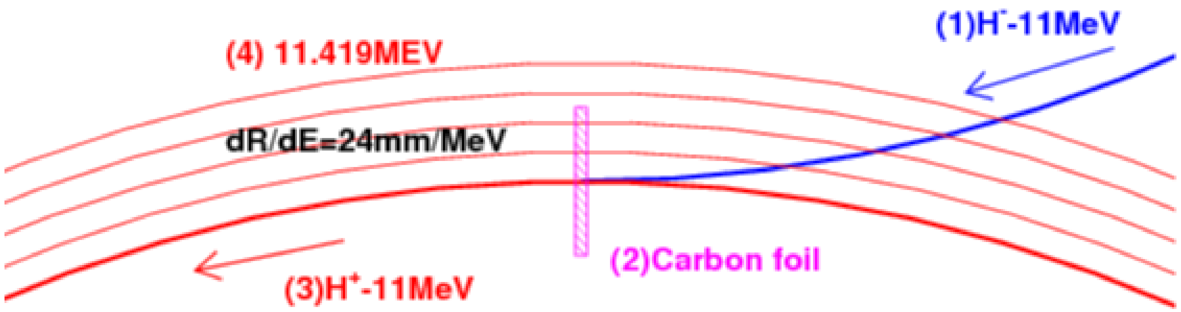
H- injection without bump-system

Stripping foil is located on the lowest energy closed-orbit. Injected beam escapes from the foil by rf acceleration.

$$\frac{dR}{dE} \simeq 24 \text{ mm/MeV}$$

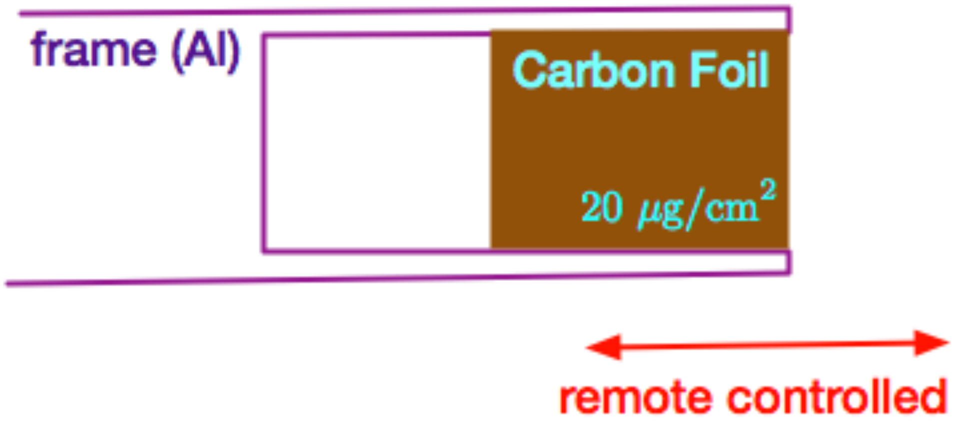
$$V_{rf} \leq 4 \text{ kV}$$

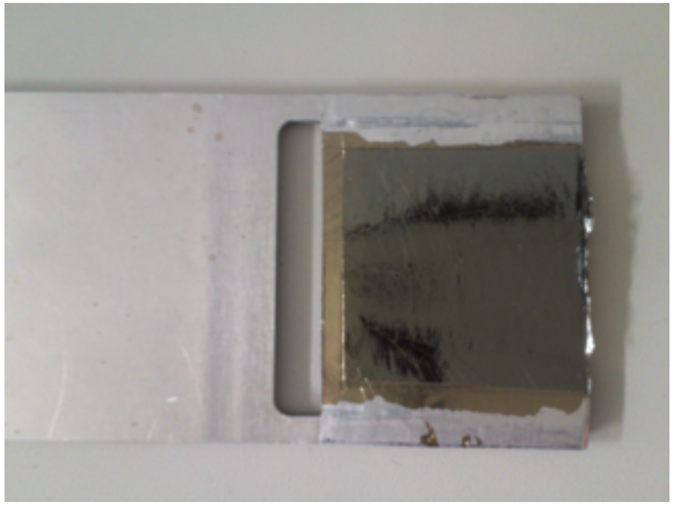
$$\Delta X_{\text{foil}} \simeq 25 \text{ mm}$$

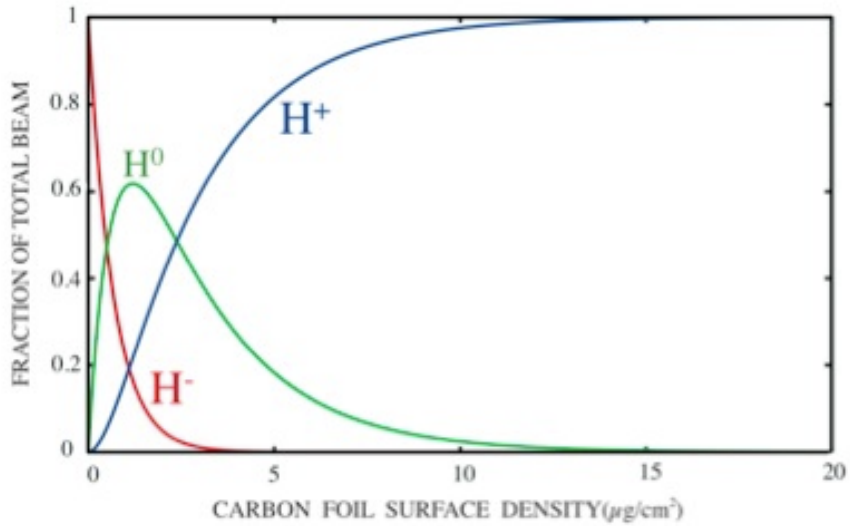


Beam hits a foil several hundreds times

Stripping foil

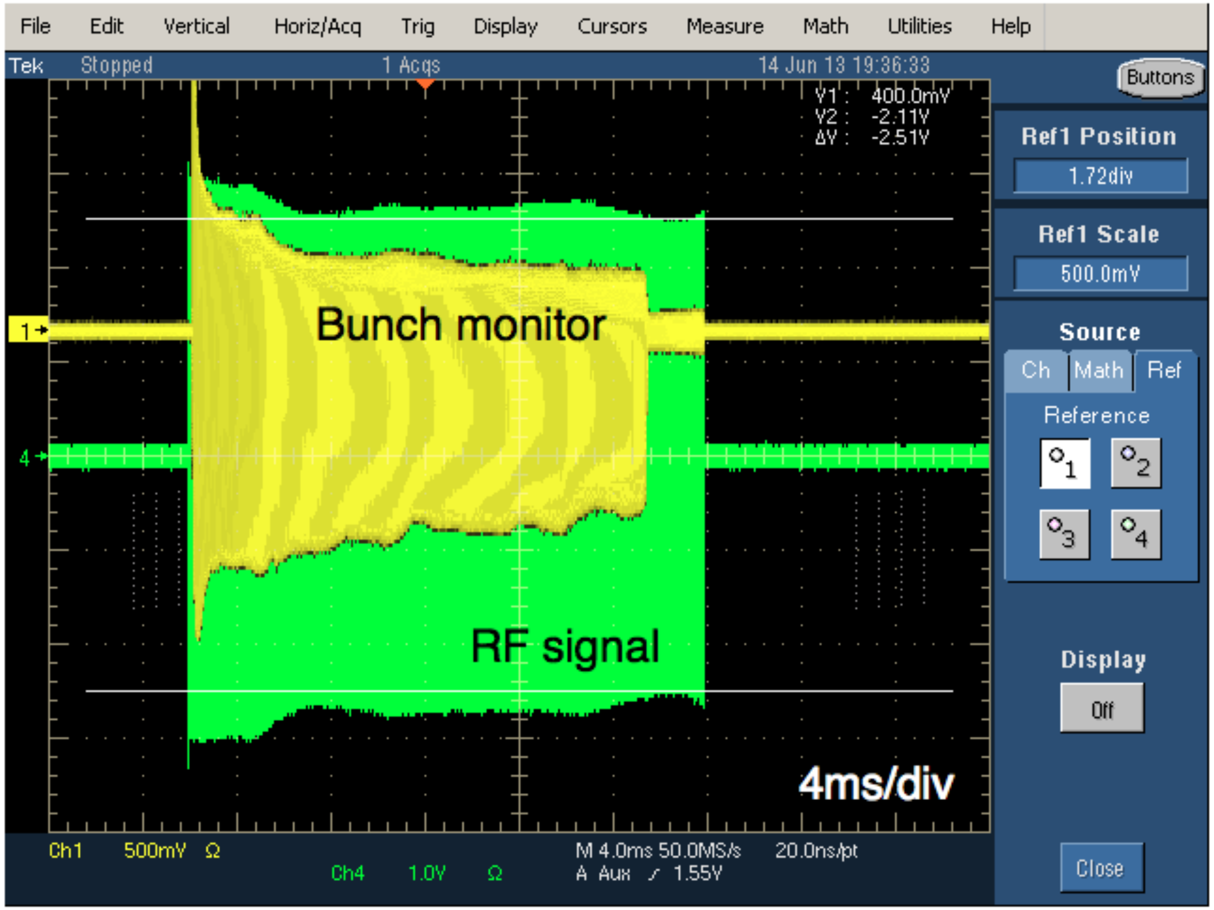






Stripping efficiency > 99%

Beam current in our FFAG



Typically, the beam is lost at injection energy by factor 100!

What is problem ?

When a circulating beam hits the foil many times,

Longitudinal

Energy loss ~ 760 eV / turn (Bethe-Bloch formula)

---> (1) Synchronous phase shift

(2) Boundary loss (next slide)

Transverse

emittance growth

~ 1.5π mm-mrad / turn in Rms (K.Okabe, with ICOOL sim)

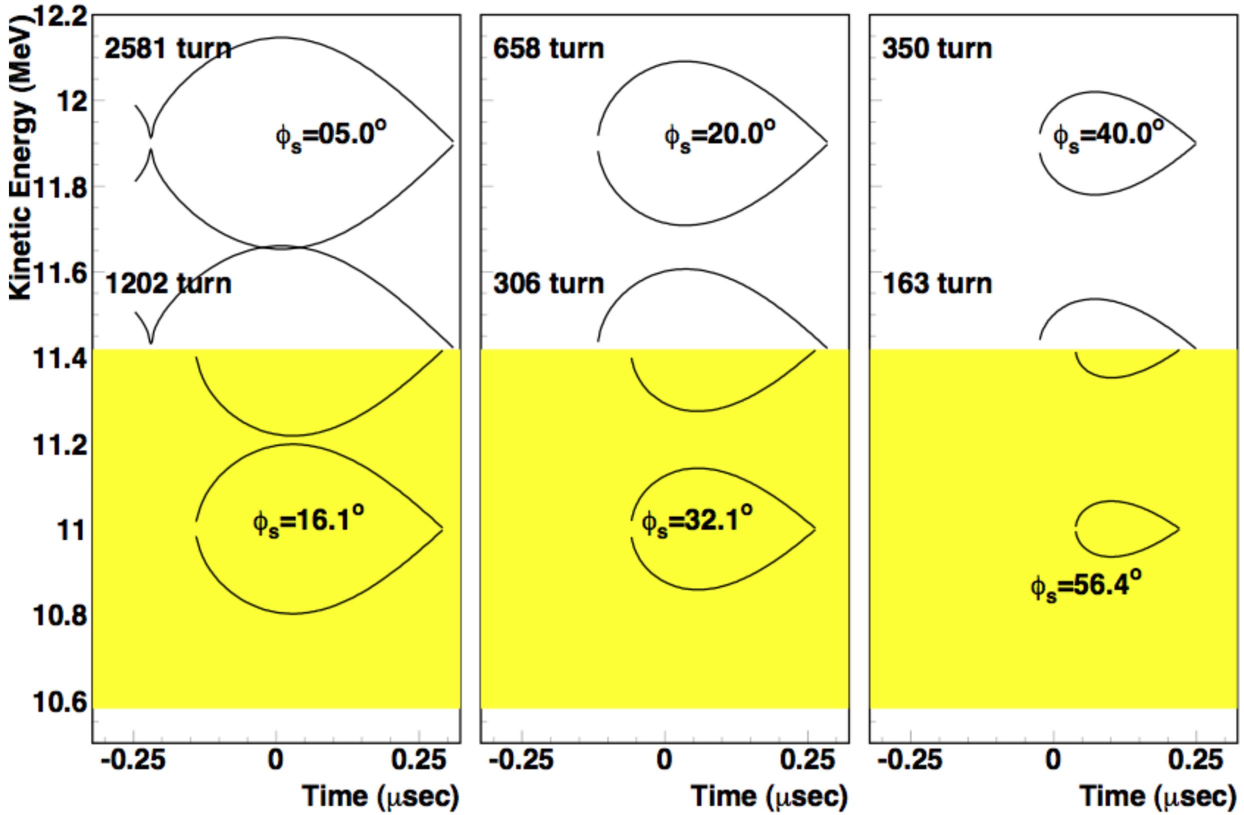
Overheating of the foil

---> This can give the intensity limit in future

Longitudinal (Boundary loss)

(1) $V \sin \phi_a = V \sin \phi_s - \Delta E_{loss}$

(2) Bucket modification at foil-boundary -- beam loss

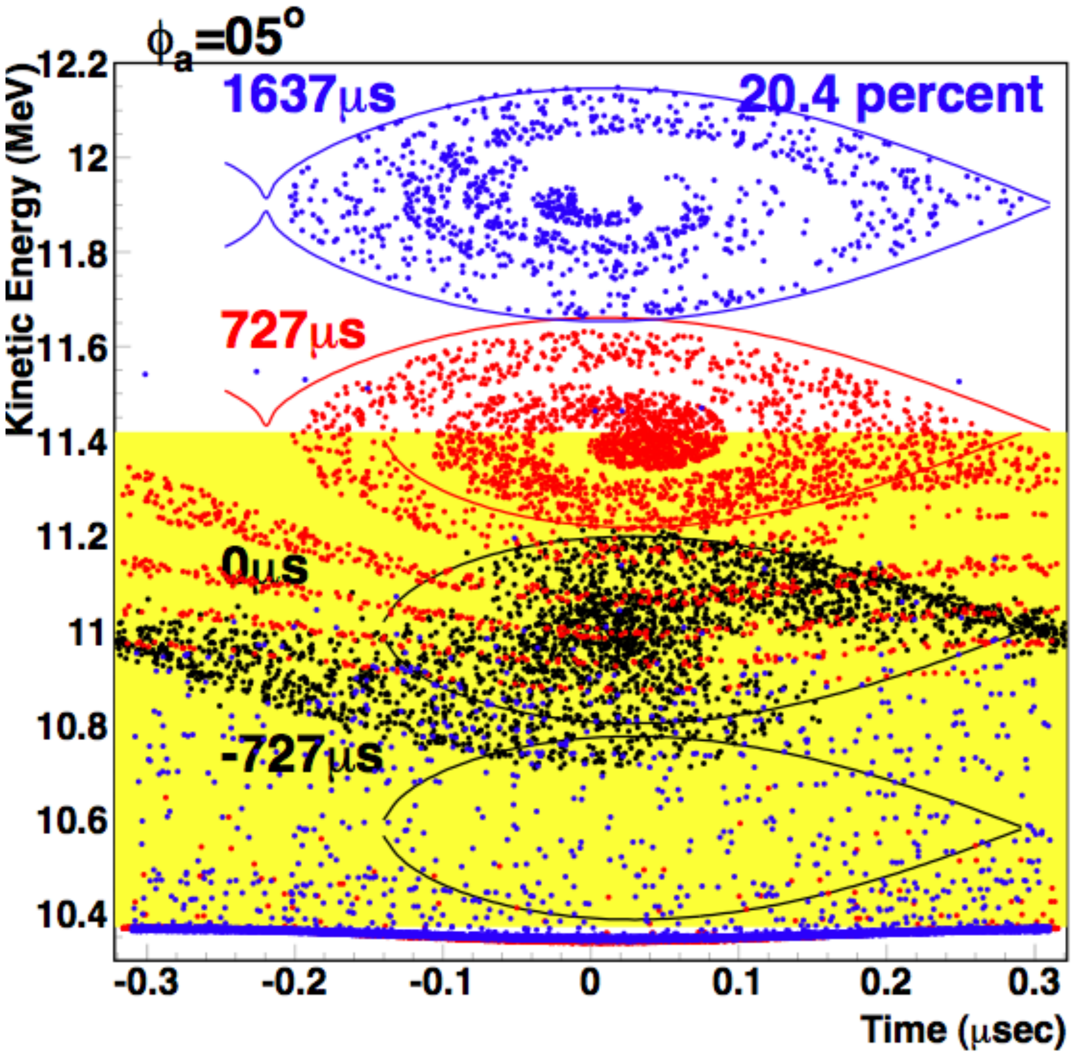


* Yellow hatch stands for the energy region where CO intersects the foil.

---> Simulation

Example (simulation)

Slow acceleration

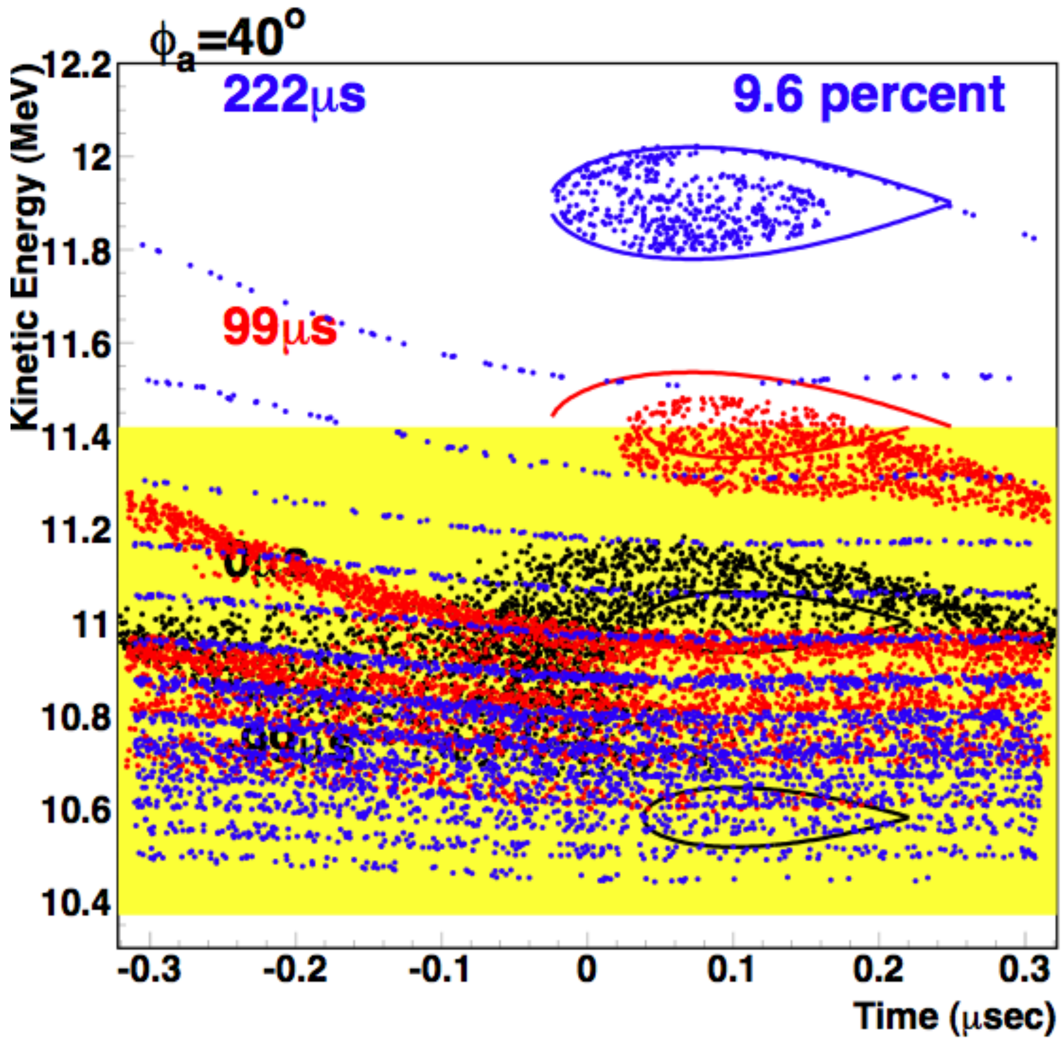


Bucket area wide
Stay at Foil long

= widely captured,
but
Many particle are lost
(emittance growth)

Example (simulation)

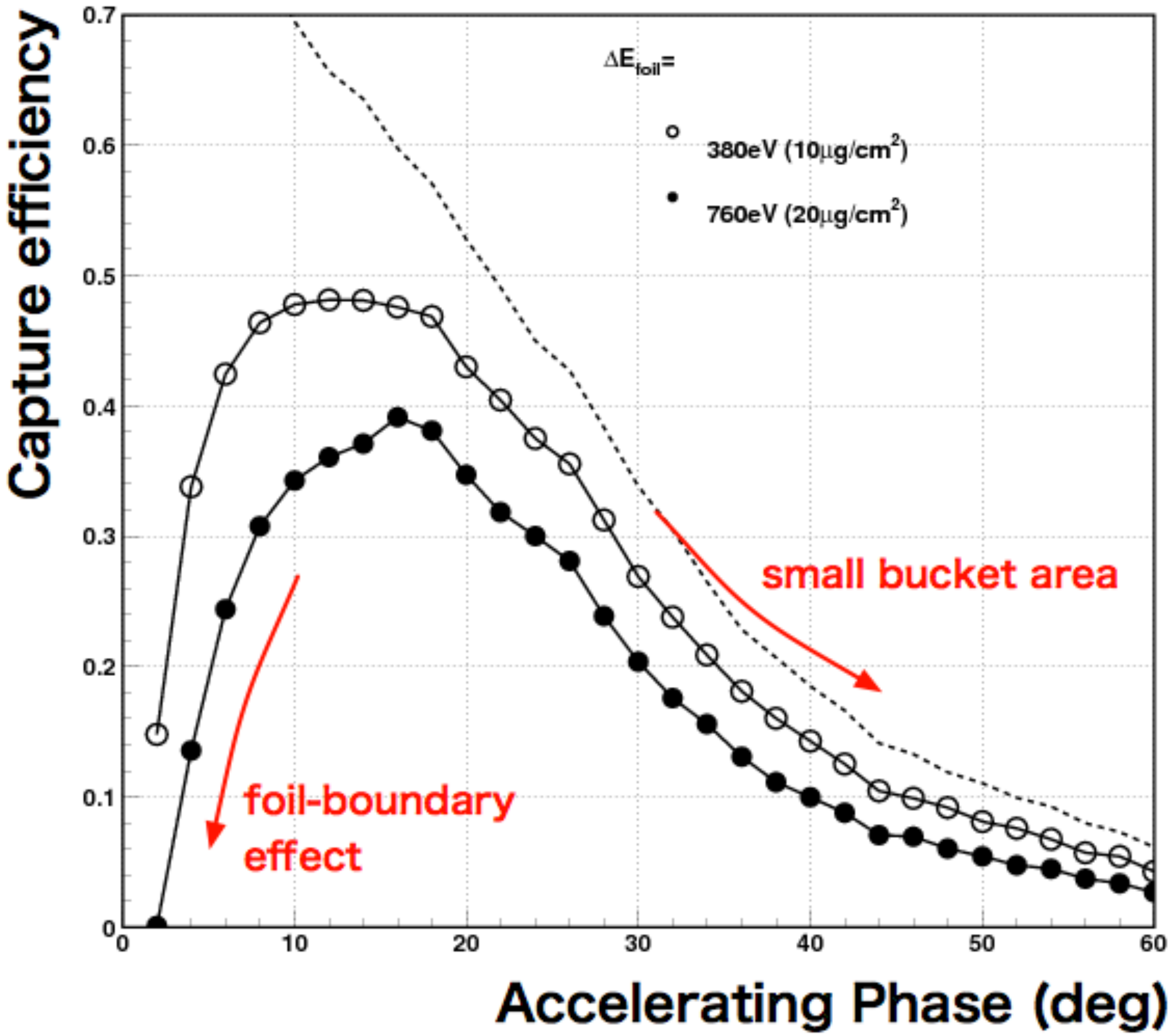
Fast acceleration



Bucket area narrow
Stay at Foil short

= less injection, but
less beam-loss

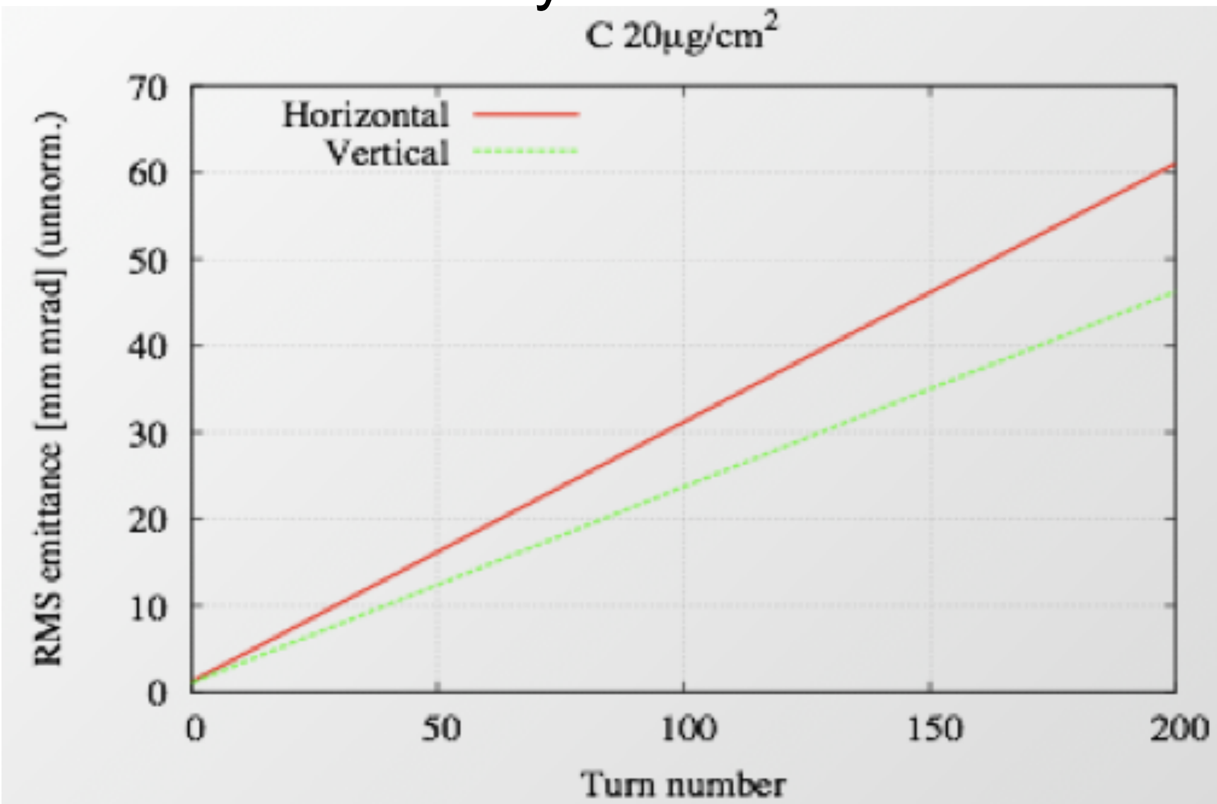
Simulation Results (summarized)



Transverse emittance growth

by multiple-scattering

Simulation by K.Okabe 2011



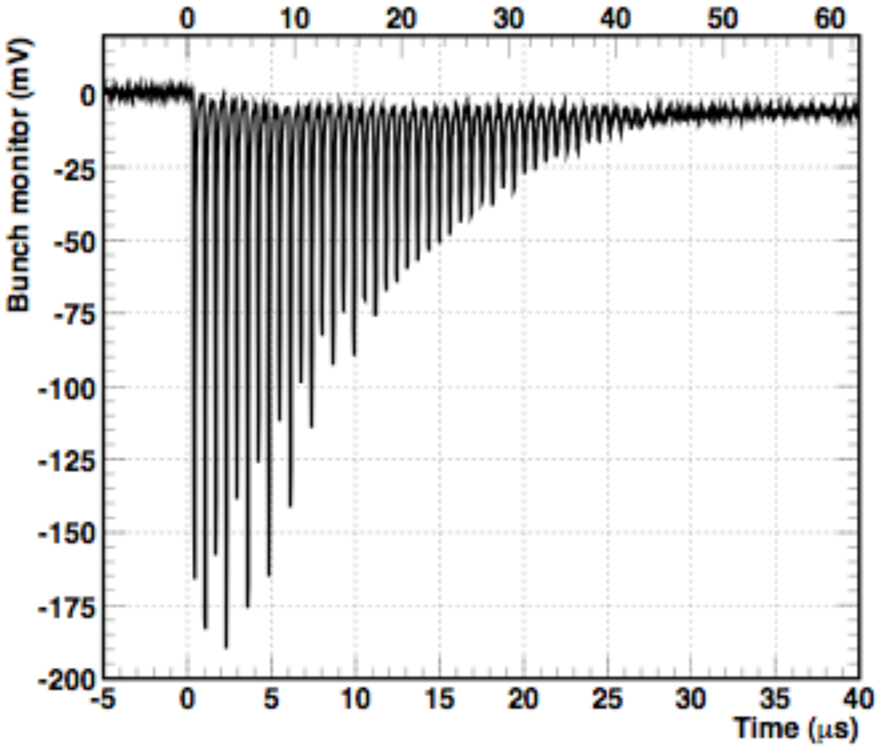
Results showed that rms emittance linearly increases with

$0.30\ \pi\text{mm.mrad/turn(H)}$
$0.25\ \pi\text{mm.mrad/turn(V)}$

Least acceptance

$$10\ \text{mm}^2/1.5\ \text{m} = 66\ \pi\text{mm.mrad}$$

Experiments



Capturing a short-pulse beam (~0.2us; =1/3 turn) by a stationary bucket

Capture frequency and injection phase (time) were optimized

However, beam survived only 40turns

The lifetime is determined by
- Emittance growth by multiple-scattering ?
- Vertical half-integer resonance ?

Possible improvement against emittance growth

-Thinner foil
to decrease the emittance growth.
20μg/cm^2 ---> 10μg/cm^2 ?

- Higher vertical aperture of foil frame
20mm ---> 30mm ?

- Fast acceleration after capture
Limited by the rf voltage

Additional RF Cavity

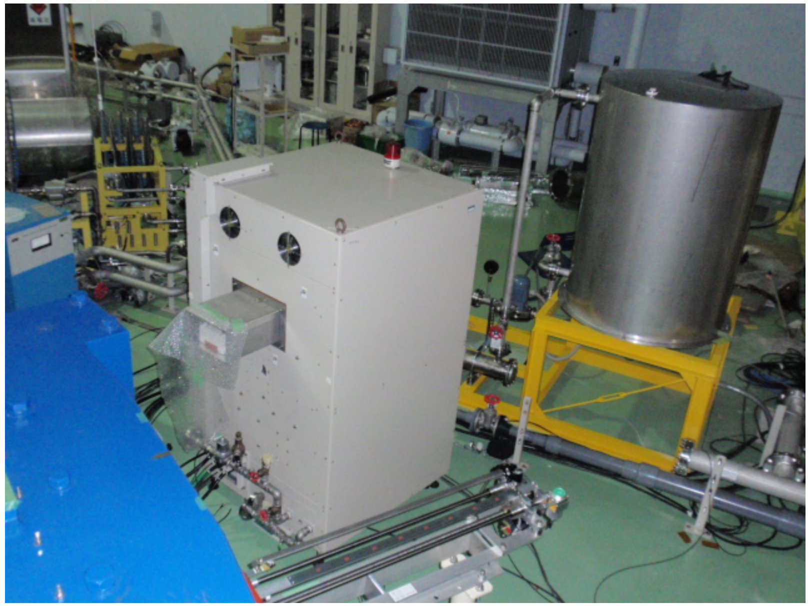
To increase rf voltage

(Install this fiscal year)

(1) Fast acceleration,
for (1A) higher repetition, and/or
(1B) larger turn separation at inj.

(2) Wide bucket area

New cavity to be installed
(half-side is shown)



RF amplifier

Space charge limit

With those efforts,
our FFAG reaches space-charge limit, someday!

Linac output (maximum)

$$5 \text{ mA} \times 100 \ \mu\text{s} \quad = 3 \times 10^{12} \, \text{protons}$$

Tune shift in main-ring

$$\Delta\nu = \frac{N r_0}{\pi \beta^2 \gamma^3} \frac{F/B}{\beta_x \epsilon_x (1 + \sqrt{\epsilon_y/\epsilon_x})} \quad = 0.3/0.6 \times 10^{12} \text{protons}$$

POSSIBLE ACCELERATOR STUDIES WITH OUR MACHINE

Using unique properties of FFAG,

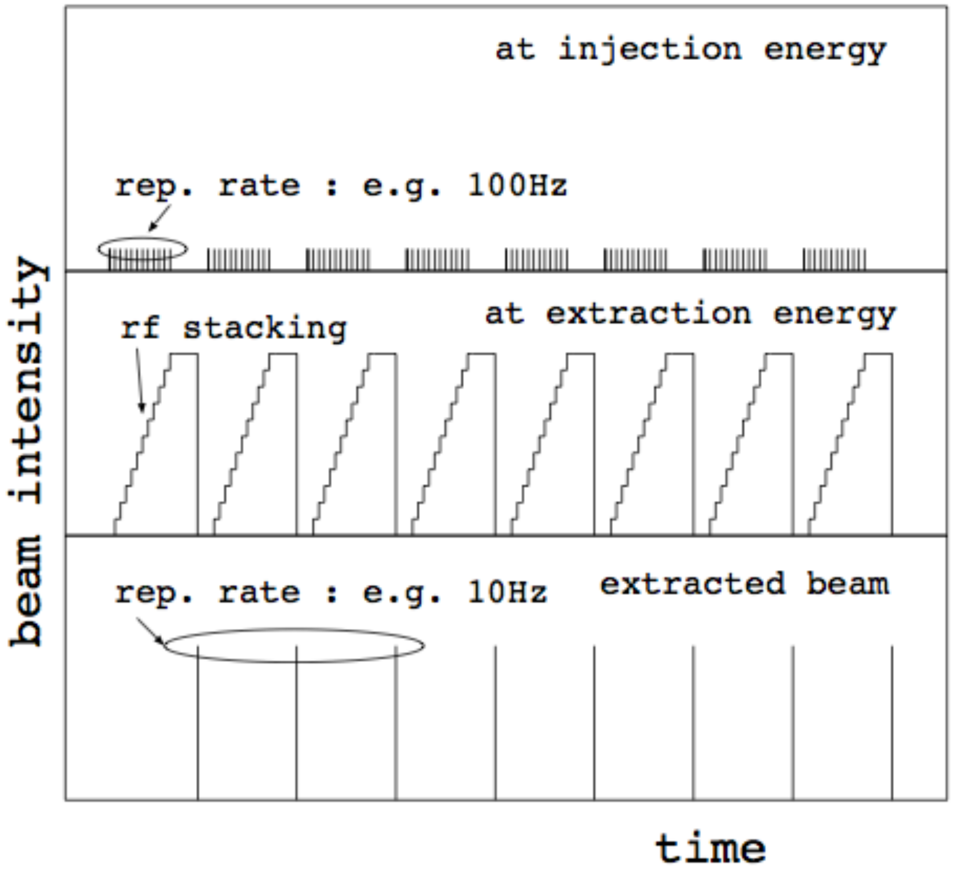
1. Beam stacking at top energy orbit
   High intensity, low repetition

2. Multi-fish acceleration
   High repetition

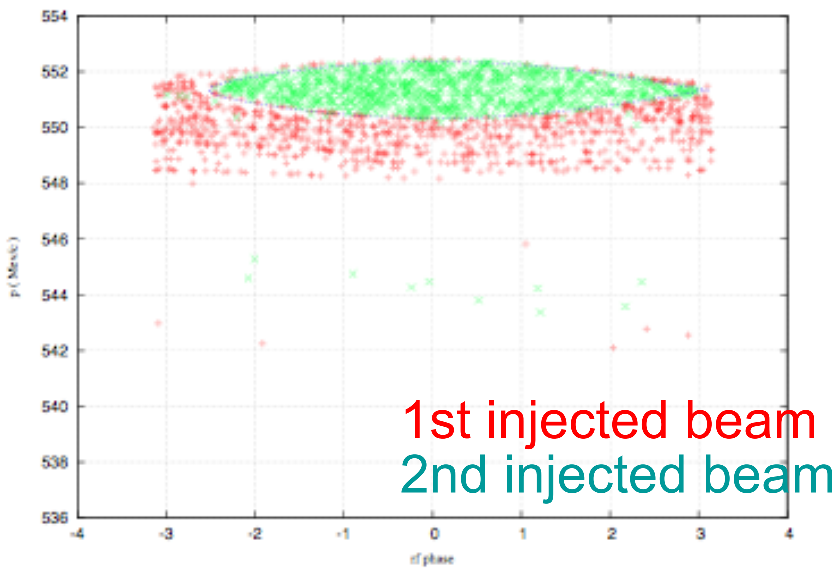
3. Continuous acceleration by
   . Stationary bucket acceleration and
     Serpentine acceleration
   . Harmonic number jump acceleration
   . Vertical FFAG

1. Beam stacking at top energy

can increase number of protons per pulse



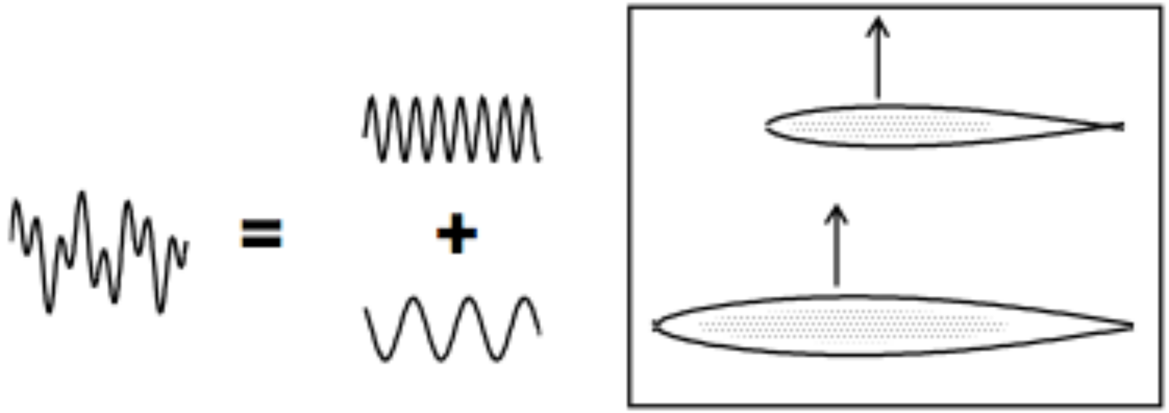
Adiabatic landing is useful to minimize emittance growth



2. Multi-Fish Acceleration

Y. Mori et al., PAC2001 (2001)

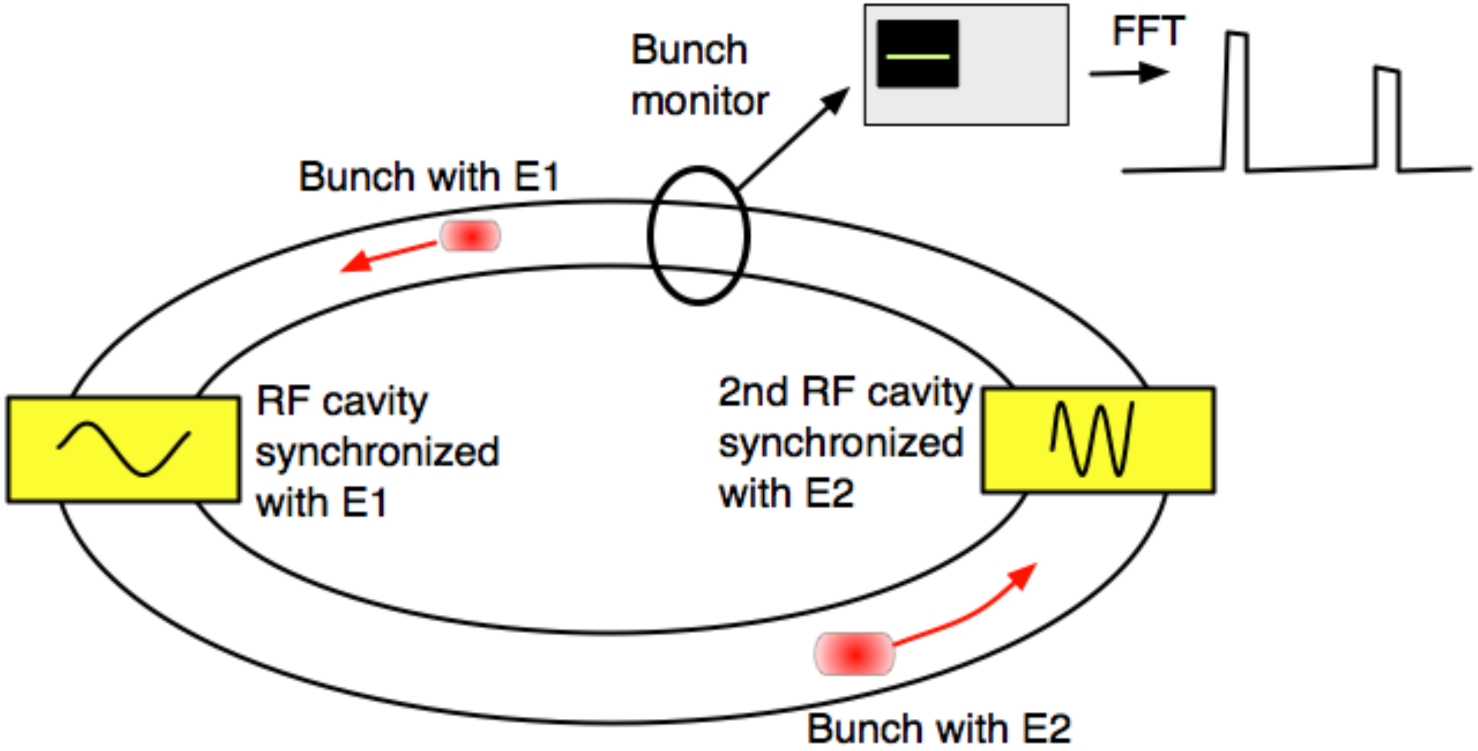
Two (or more) bunches with different energies
are accelerated simultaneously,
by applying different rf signal for each bunch.



Interference between rf buckets can be an issue,
when the frequency of them are close.

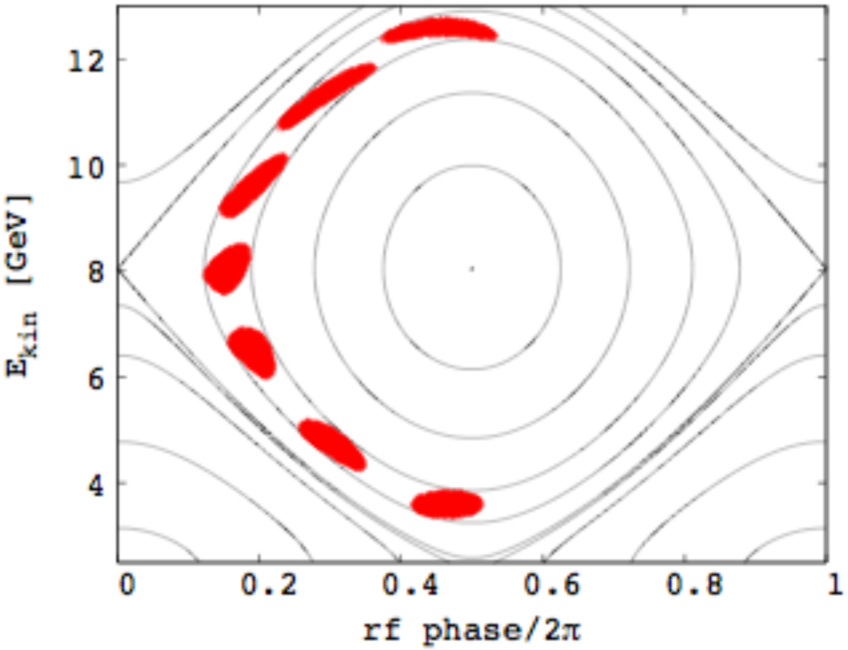
Demonstration of MF acceleration in our FFAG

is possible

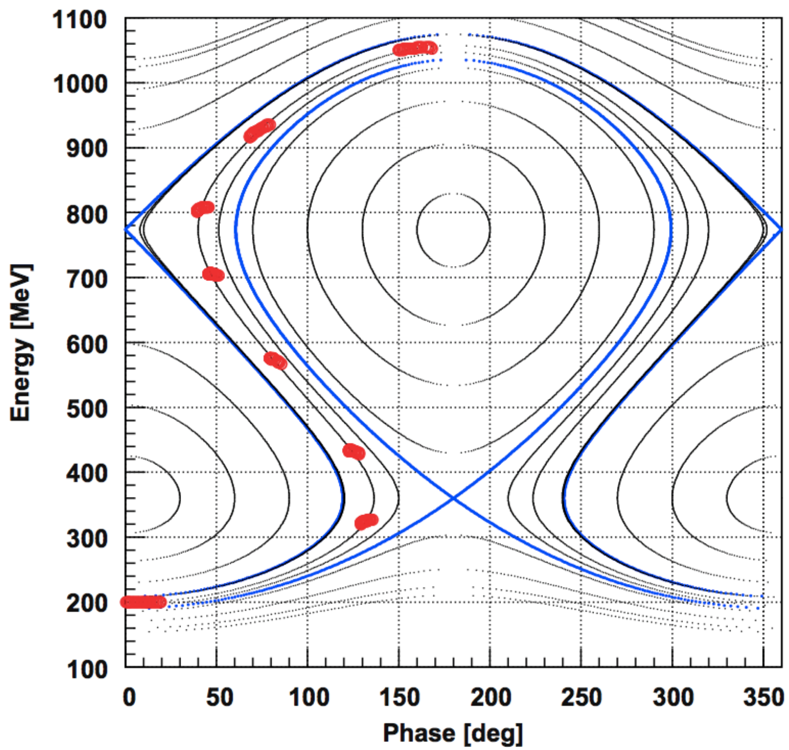


3. Continuous acceleration in FFAG (1)

Stationary bucket acceleration



When it is done near the transition energy
(called ‘serpentine’ acceleration)



First experiment with an electron FFAG,
E. Yamakawa et al. NIM-A716(2013)

Continuous acceleration in FFAG (2)

Harmonic number jump acceleration

Rf frequency is constant,
but a particle sees the same rf-phase with increasing harmonic number.

T. Planche, et.al. PAC09(2009)

Vertical FFAG

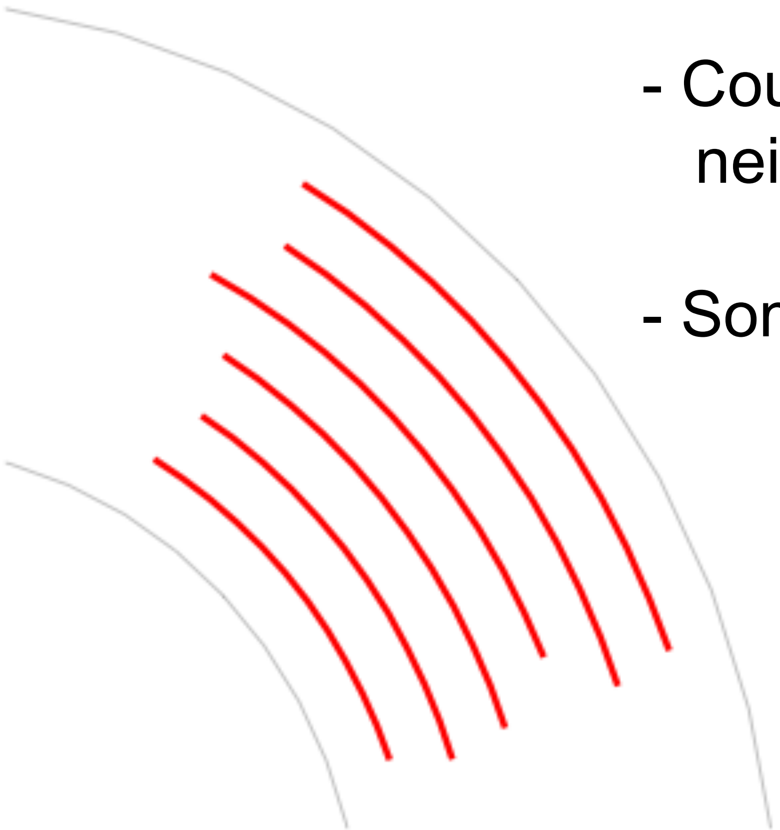
Closed orbit shifts in vertical direction with energy, and the circumference is constant of energy.

S.J. Brooks, IPAC12(2012)

This FFAG is isochronous at ultra-relativistic energy region.

Interaction between orbits

can play an important role,
but it is very complicated.

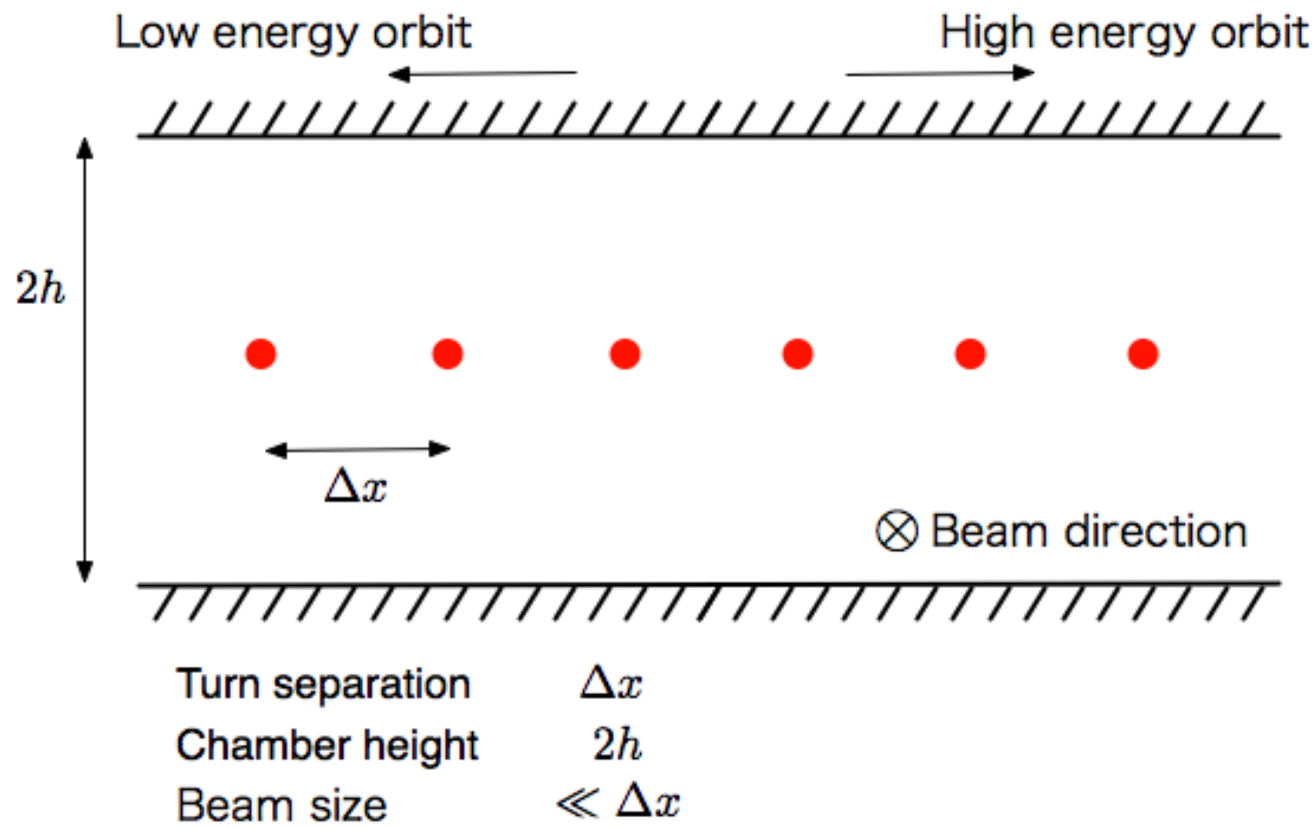


- Coupled betatron oscillations of neighboring orbit ?

- Some coupled resonance ?

Experimental studies are needed,
but is it possible?

With a Simple Model

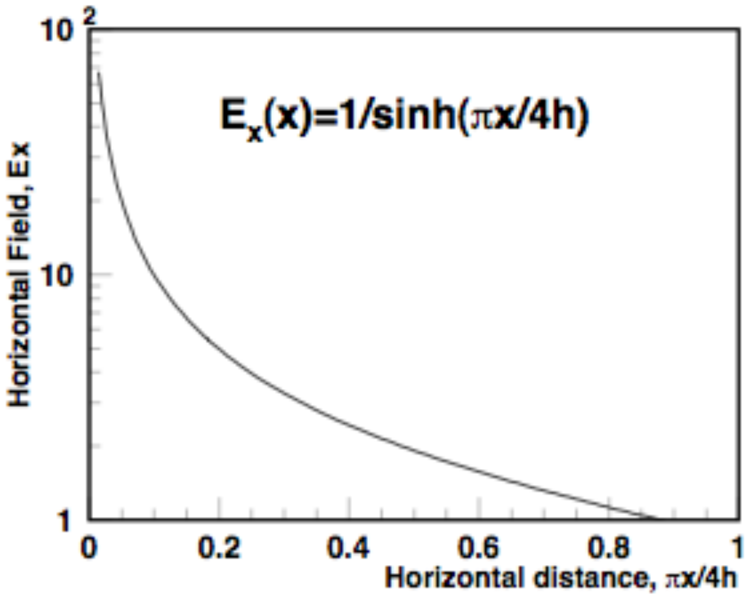


Each beam-center affects repulsing force from neighboring orbits

--> Horizontal focusing

--> Vertical defocusing

Field of a line charge between parallel plates



Horizontal field is rapidly decreasing with horizontal displacement.

$$U(x,y) = -\frac{\lambda}{4\pi\epsilon_0} \ln \frac{\cosh(\frac{\pi}{2h}(x-x_0)) - \cos(\frac{\pi}{2h}(y-y_0))}{\cosh(\frac{\pi}{2h}(x-x_0)) + \cos(\frac{\pi}{2h}(y+y_0))}$$

(B. Zotter, 1975?)

A theoretical treatment

Assume that one of static spiral orbit is found. For a small displacement $x(\phi)$,

Eq. of including neighboring orbits

$$\frac{d^2x(\phi)}{d\phi^2} = -\nu_0^2 x(\phi) + \sum_n \alpha_n[x(\phi + 2n\pi) - x(\phi)] + \alpha_n[x(\phi - 2n\pi) - x(\phi)]$$

(coupling is taken into account)

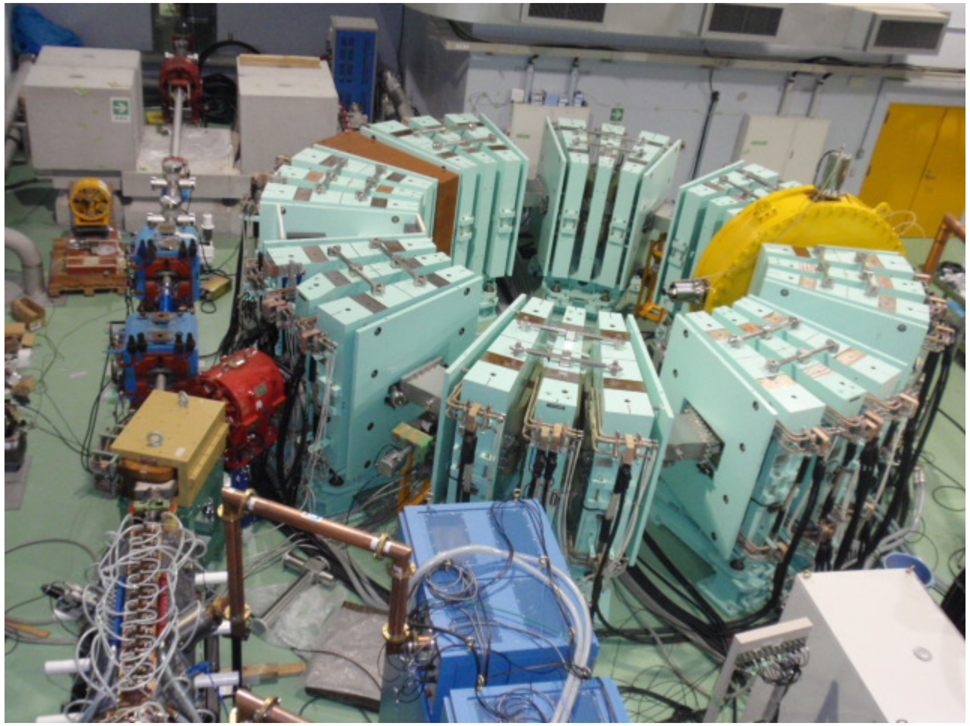
Static solution is in general

$$x(\phi) = X\exp(i\nu\phi) \quad \text{with} \quad \nu^2 = \nu_0^2 + \sum_{n=1}^{\infty} \alpha_n \sin^2 n\pi\nu$$

ν stands for the coherent horizontal tune, which is responsible to integer resonance.

Experiments of CW acceleration with our FFAG

(1) Stationary bucket acceleration in ERIT ring



ERIT
(Energy Recovery Internal Target)

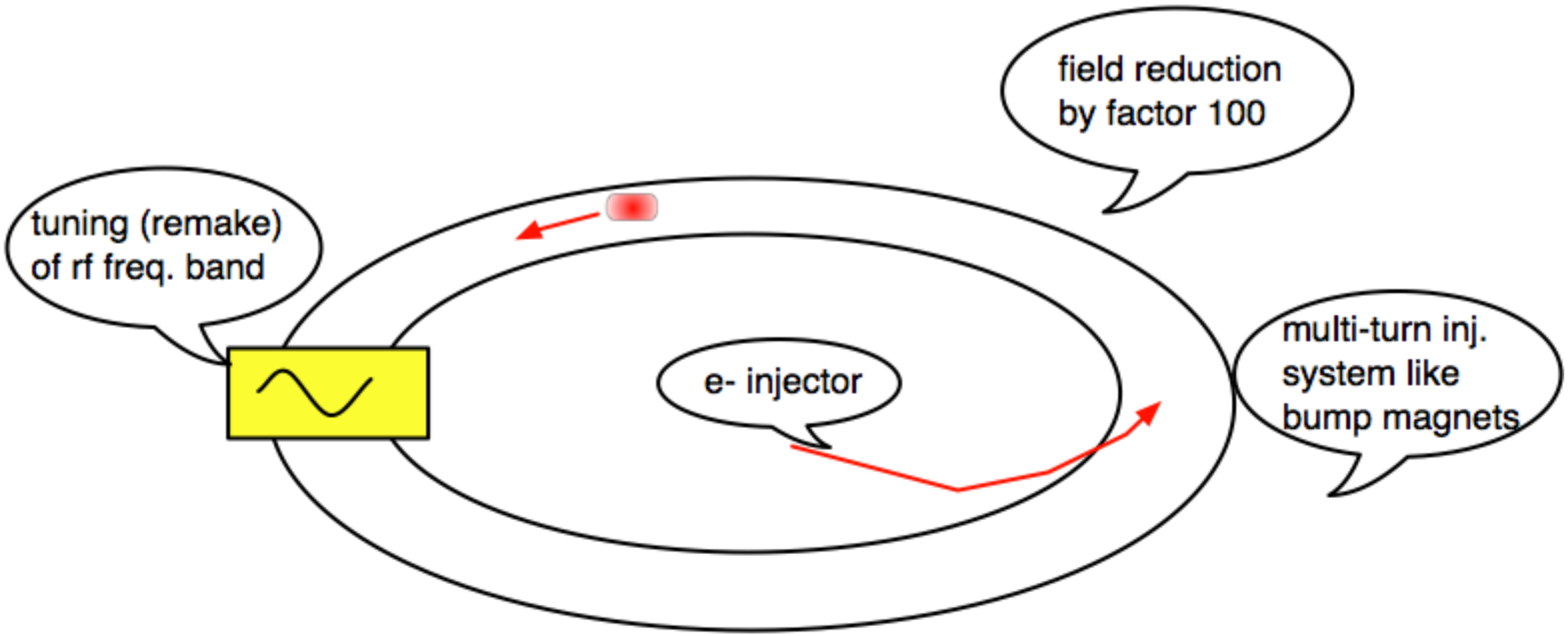
Scaling FFAG, k=1.92
11MeV proton, H- injection
Momentum acceptance +-20%
RF 230kV at 18MHz (h=5)
Bucket height +-1MeV

Injector
11MeV H- injection,
Peak current 5mA x 100us (max)

11 MeV -- 12 MeV (Orbit excursion is about 20cm)

(2) Serpentine acceleration of e- beam in the main ring

Transition gamma ~ 3
Bρ ~ 1/100 of 11 MeV proton
Revolution freq. ~ 10 MHz



SUMMARY

1. A 100 MeV proton FFAG complex has been constructed in KURRI, and started ADS studies.

2. H- injection without bump-system is adopted and the beam current reached 10^10protons/pulse. We still observe a rapid beam-loss of factor 100 at injection energy, which is assumed
the multiple-scattering in the stripping foil, or vertical resonance. We will overcome this beam-loss in future.

3. Our FFAG has possibilities of testing unique acceleration schemes of FFAG.
Experiments of stacking at top energy, multi-fish acceleration, and continuous acceleration are under consideration.