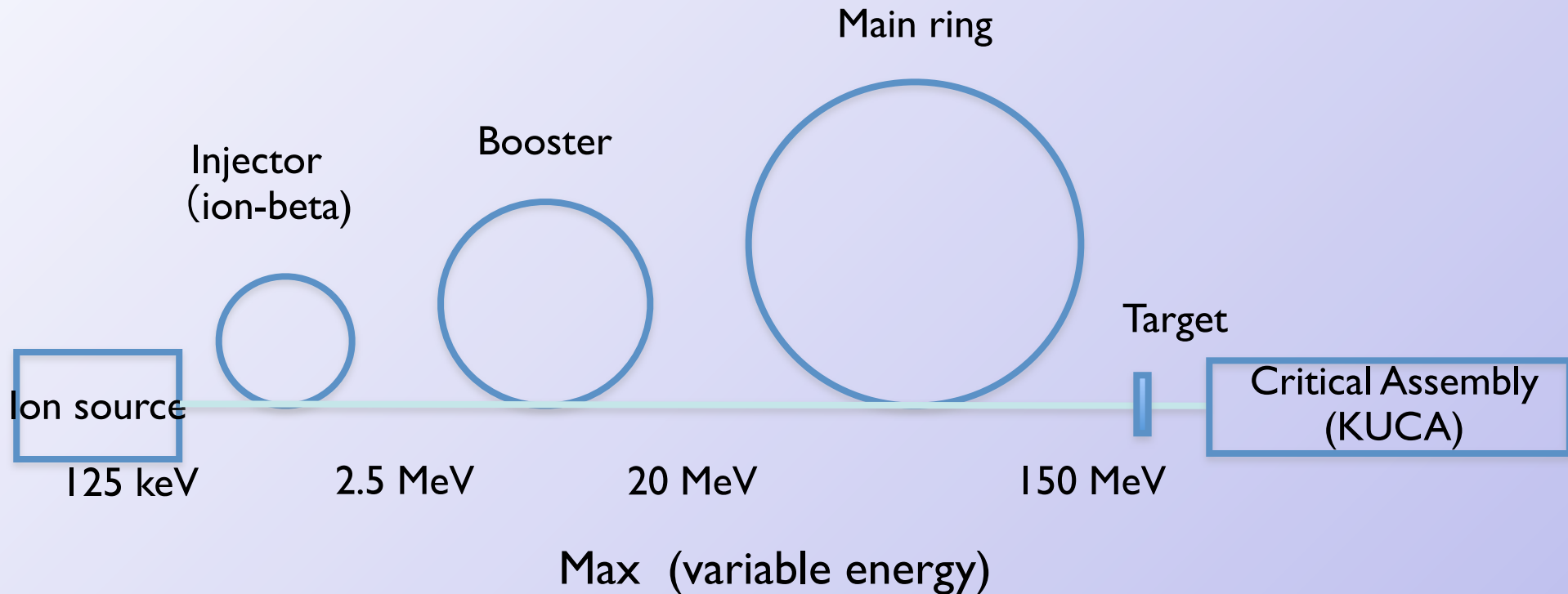


H⁻ injection at 150MeV-FFAG in KURRI

Kota Okabe (Fukui University)

FFAG - KUCA ADSR system schematic diagram (present)



Basic parameters for ADSR experiments at KURRI

- Reactor output power $\sim 10\text{W}$
- Neutron multiplication $< 100(\text{max.})$
- Beam power of FFAG $< 0.1\text{W}$
- Beam energy of FFAG $100 - 150\text{MeV}$
- Beam current of FFAG $< 1\text{nA}$

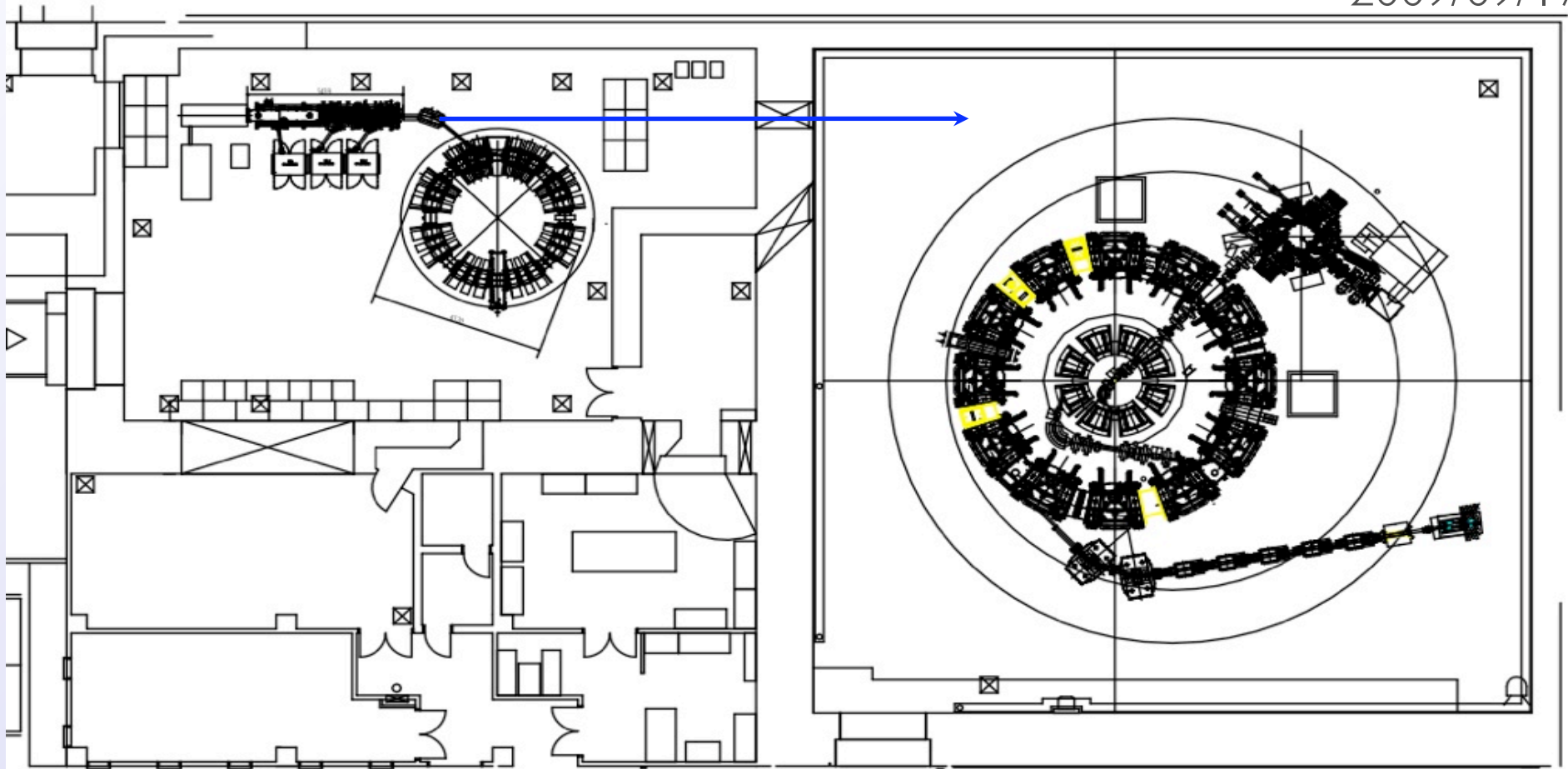
FFAG-Main Ring Charge-exchange Injection System

MR beam intensity upgrade $\sim 1 \mu\text{A}_o$

- Charge-exchange Injection method
- New Injection
 - FFAG-ERIT H-Linac(11 MeV) (used for FFAG-ERIT)
- Space charge limit
 - Main Ring $\sim 1 \times 10^{12}$ ppp ($10 \mu\text{A}@60\text{Hz}$)
- Research for Accelerator Physics (Space charge effects)

Layout of Accelerator in Innovation Laboratory

2009/09/17

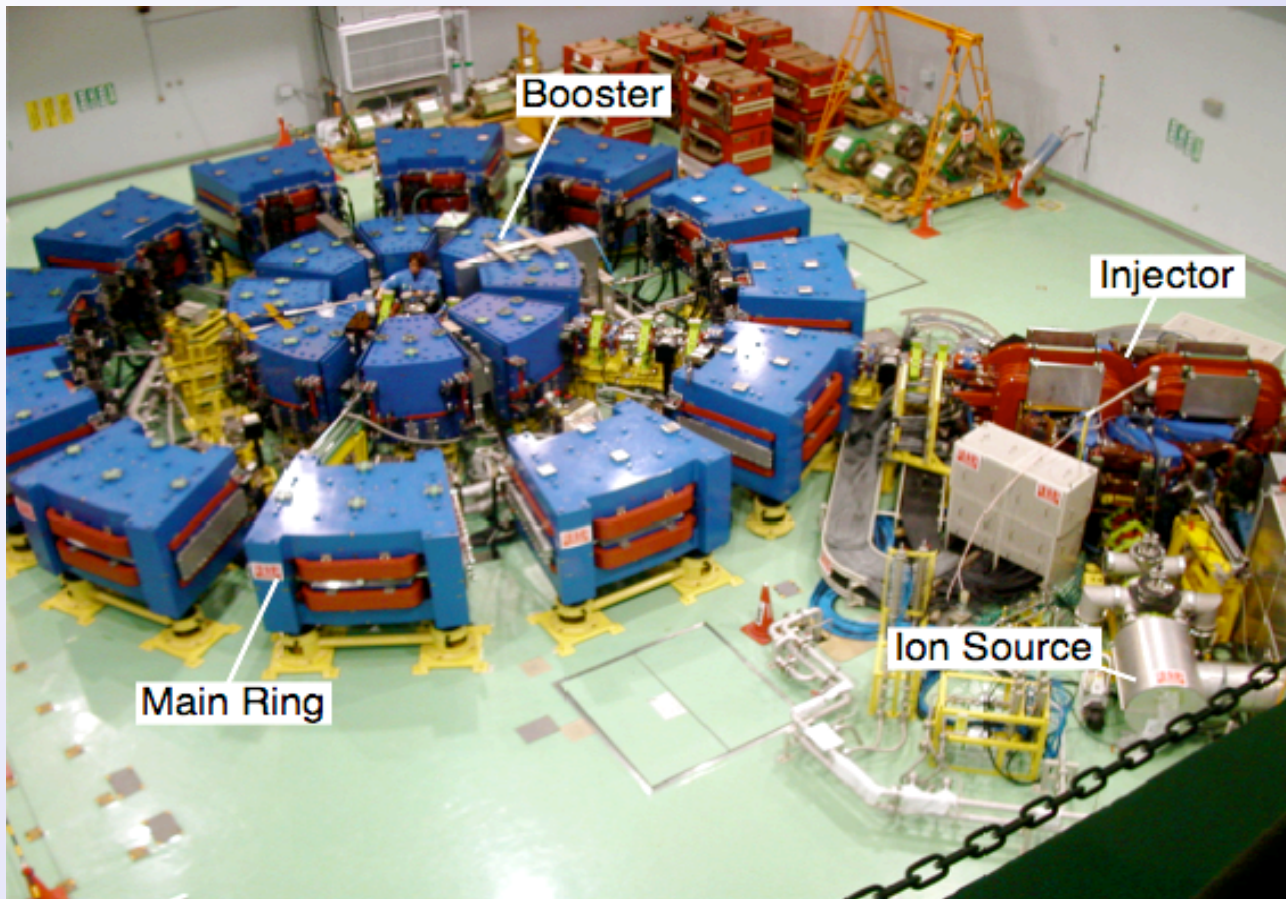


Contents (H⁻ Injection for the FFAG in KURRI)

- Comparison of present Injector (Ion-beta , Booster) and Linac
- Beam transport line for beam injection
- Charge exchange injection for the 150MeV-FFAG
 - Low energy H⁻ injection system
 - Stripping foil
 - Injection scheme
 - Energy loss and emittance growth
 - Off-center injection
 - How to escape the stripping foil after injection
- Summary

Comparison of present injection (ion-beta, booster) and Linac

Main Spec of Ion-Beta + Booster



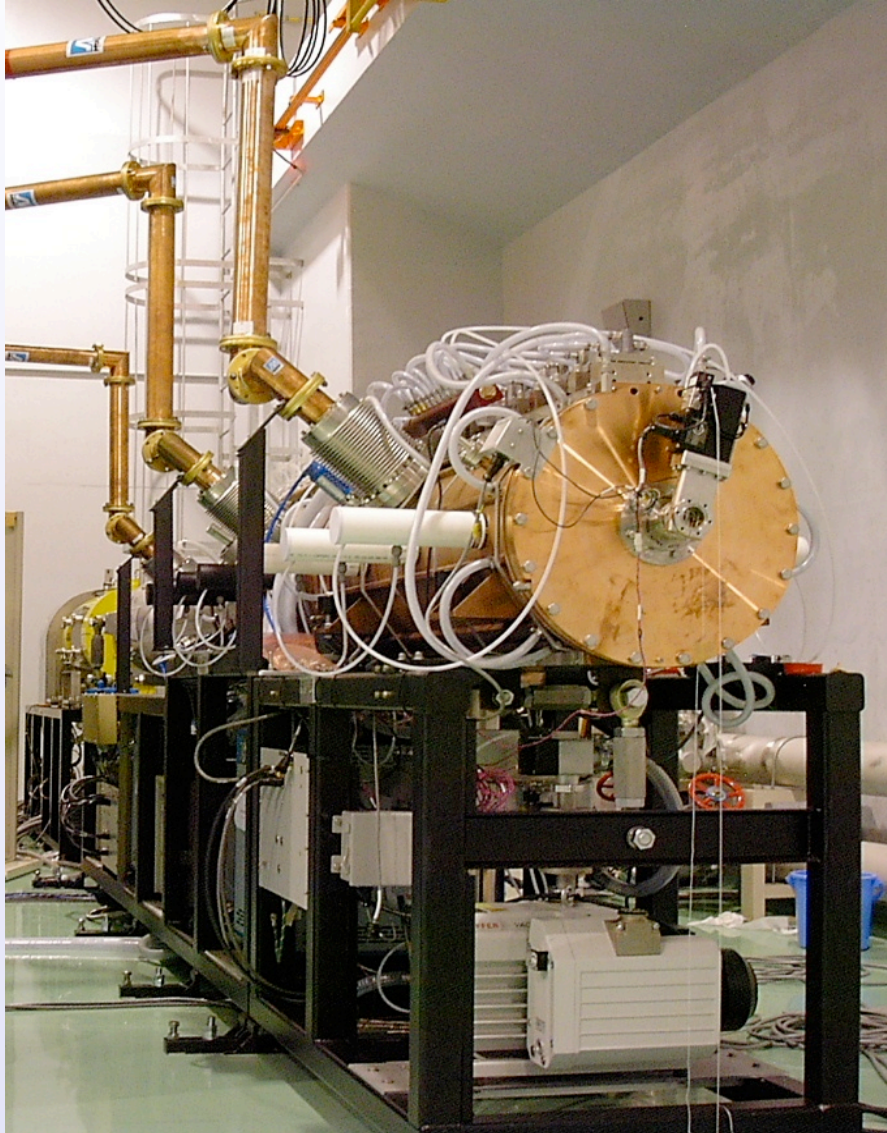
Ion-Beta

- Ion : H^+
- E_{inj} : 0.12 MeV
- E_{ext} : 1.5 MeV
- Beam intensity: 1.6×10^9 ppp
- Rep. : 30 Hz

Booster

- E_{inj} : 1.5 MeV
- E_{ext} : 11.5 MeV
- (Curr. : 2.9 nA)
- : 6.0×10^8 ppp
- Rep. : 30 Hz

Spec of Linac + H⁻ Ion Source



Linac beam parameter

- ion : H⁻
- E_{ext} : 11 MeV
- Beam Pulse width(MAX) : 100 μsec
- Peak Curr.(MAX) : ~5 mA
: ~3.12*10¹²[ppp]
- rep. rate : 1 Hz~200 Hz

Horizontal

norm. emittance (90%) : 0.680 mm•mrad

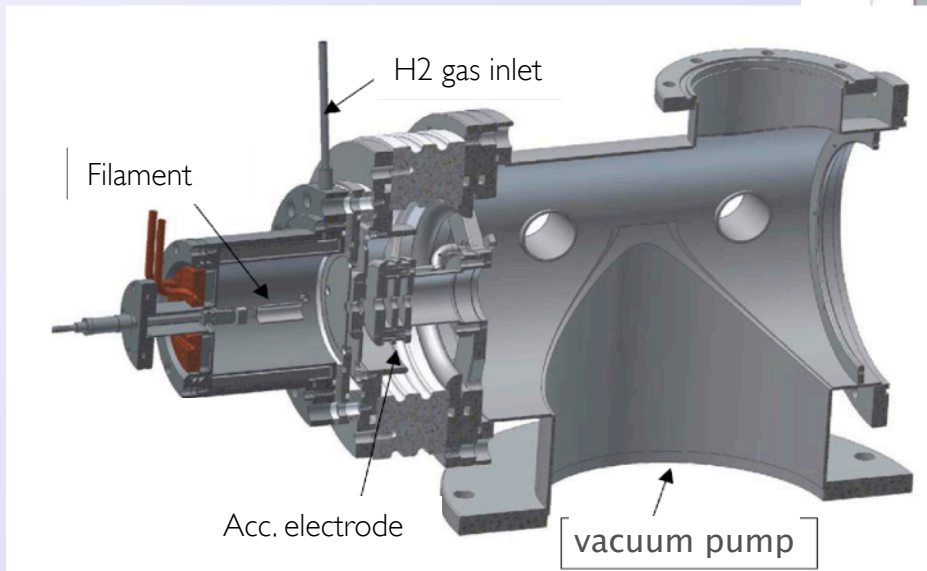
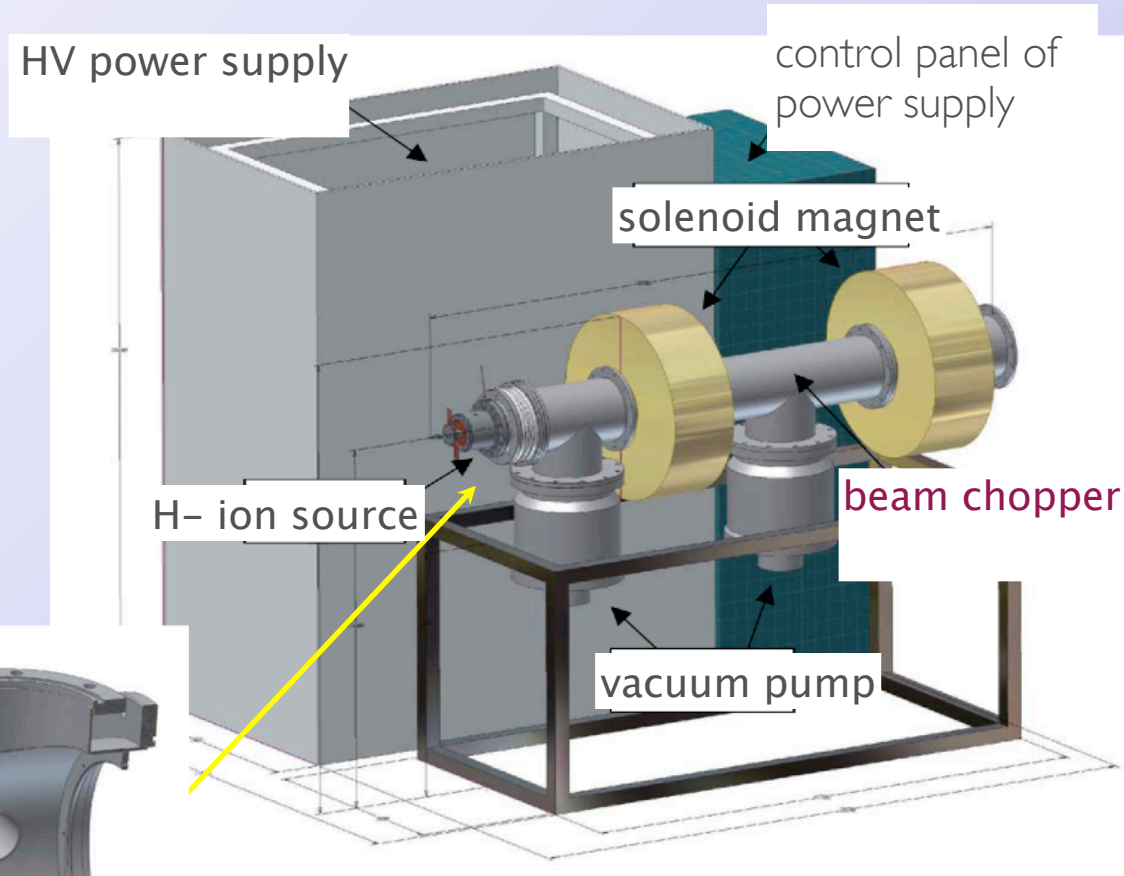
Vertical

norm. emittance (90%) : 0.630 mm mrad

Ene. 90% : ΔE ~ 45 KeV

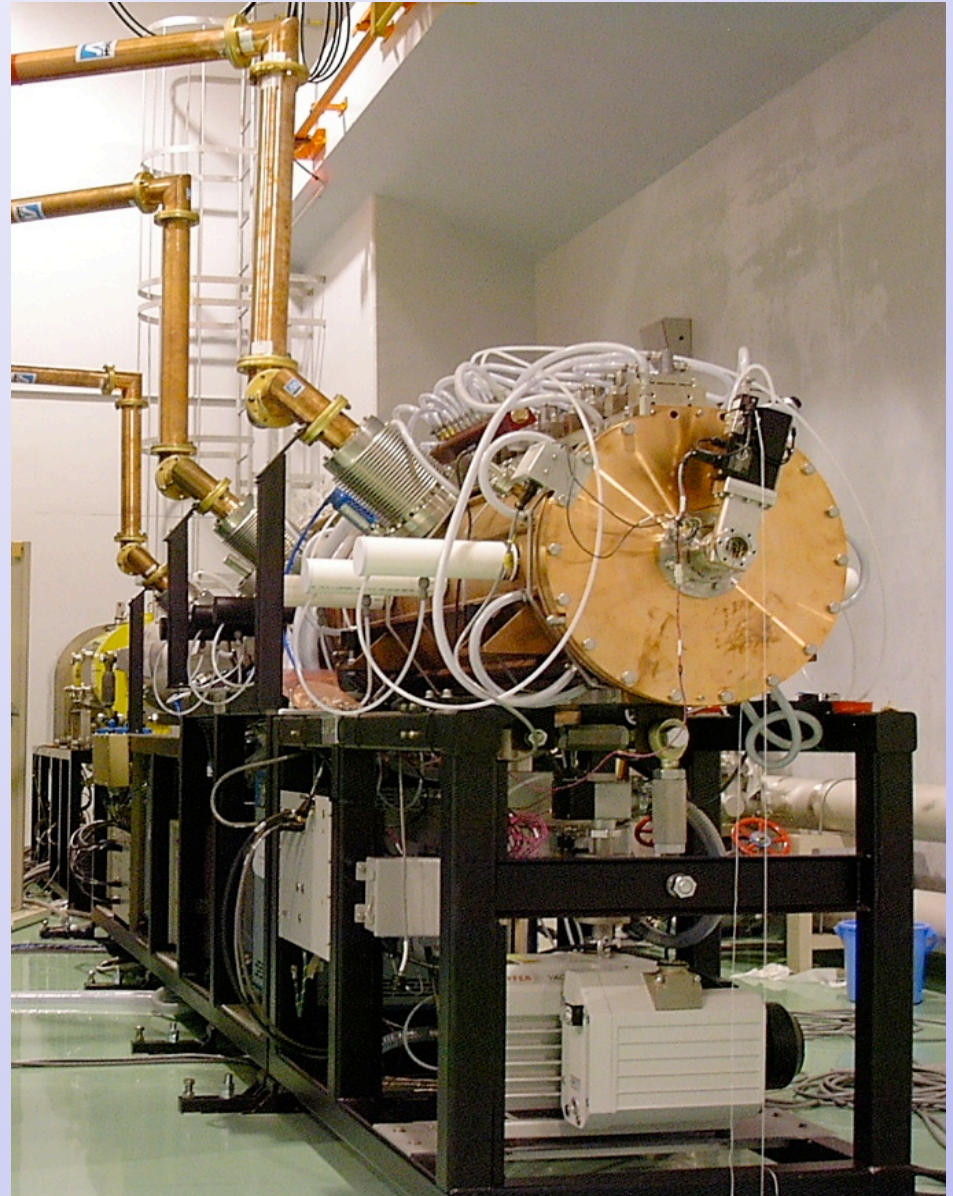
H⁻ Ion Source

- particle: negative hydrogen
- extraction energy : 30 keV
- max rep. rate : 200Hz
- beam duration : >4%(300μA)
- beam current :
 - >100μA (ave.)
 - ~5mA (peak)
- nor. emittance : <1 πmm-mrad
- with chopper (~1.6MHz)

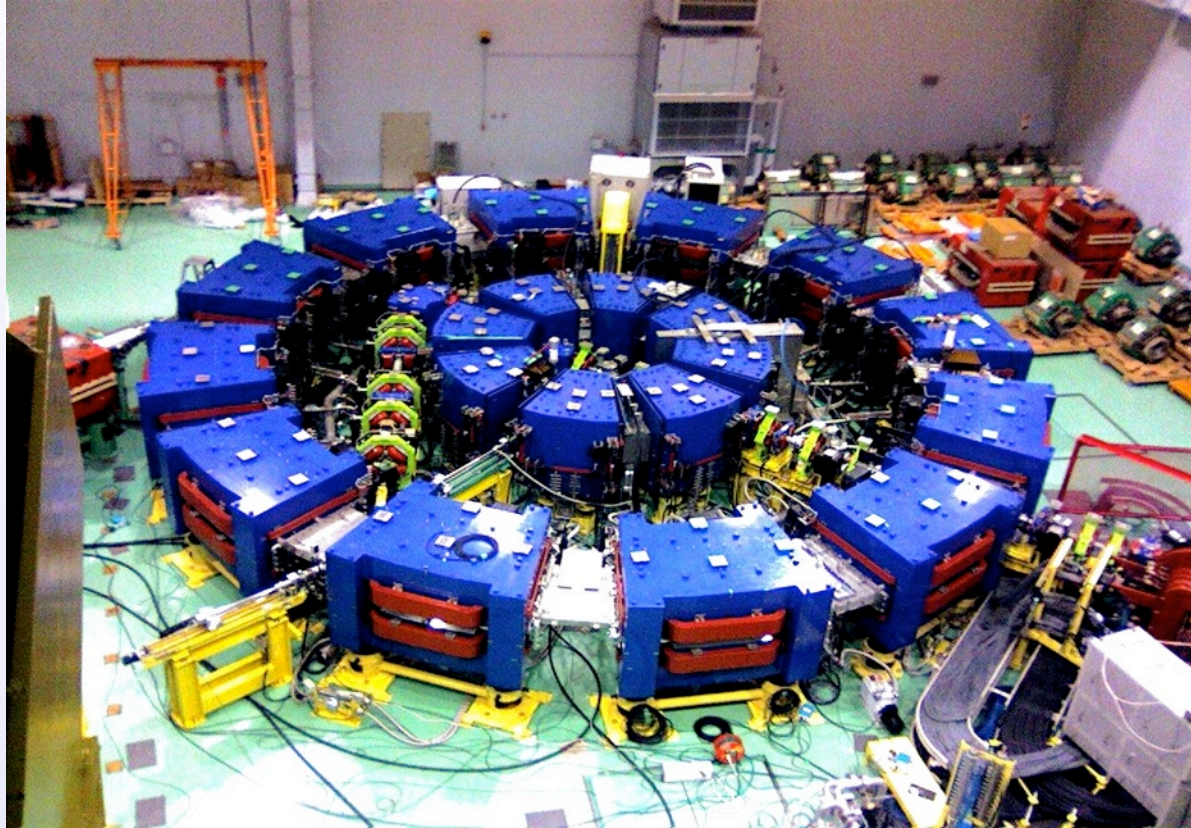


Injection Linac

- Beam energy 11 MeV
- Configuration of Linac
 - RFQ(3.5MeV)
 - DTL1(7MeV)
 - DTL2(11MeV)
- Length 5.3m
- Frequency 425MHz



FFAG Main-Ring



11 MeV - 100 MeV-FFAG

Injection energy(11 MeV)

- rev. freq : 1.582 MHz
- $\nu_x=3.68$, $\nu_y=1.34$
- RF voltage : 2kV

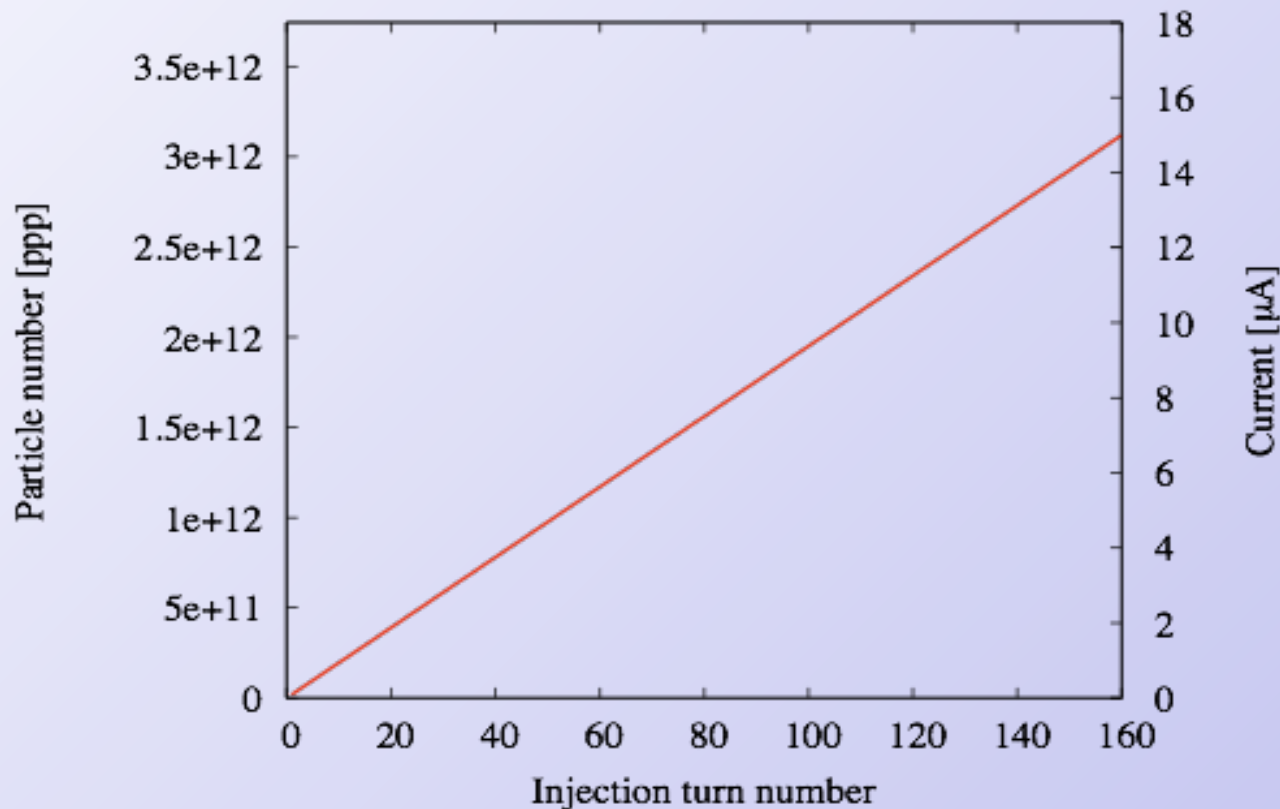
Linac beam will be injected with H⁻ injection method

Injection Efficiency

MIAN-RING@11 MeV rev. freq : 1.582 MHz, (632nsec)

MAX ~160 turn injection (linac-beam pulse: ~100 μ sec)

Rep. rate = 30Hz



Average current of 1 μ A will be attainable with 11 turns Injection.

Space Charge Limit(Main-Ring)

Laslett tune shift (direct space charge)

$$\Delta\nu_{y,\text{inc}} = -\frac{Nr_0}{\pi\beta^2\gamma^3} \frac{F/B}{\epsilon_y(1 + \sqrt{\epsilon_x/\epsilon_y})}$$

$$\Delta\nu_{y,\text{inc}} < 0.3$$

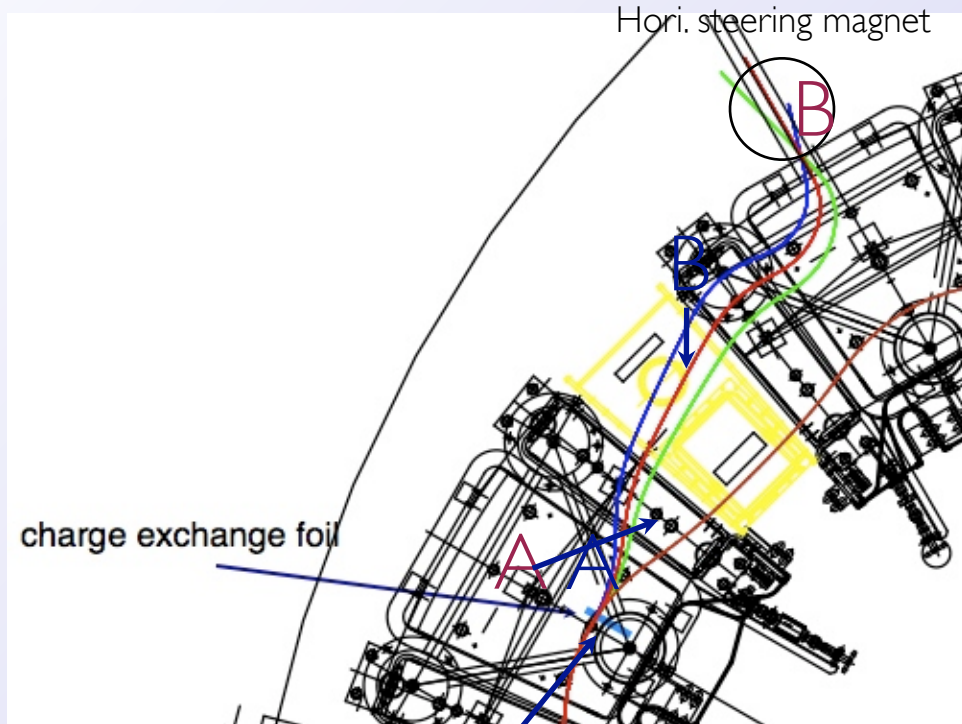
$$N \sim 1.3 \times 10^{12} \text{ ppp} \quad (12.4 \mu\text{A for } 60\text{Hz})$$

r_0	$1.53 \times 10^{-18} \text{ m}$	classical radius of proton
R_0	4.54 m	mean radius
β, γ	0.158, 1.013	12MeV
(ϵ_x, ϵ_y)	(200,100) $\pi\text{mm-mrad}$	emittance
B_f	0.5	
F	1.5	

Injection Beam Line

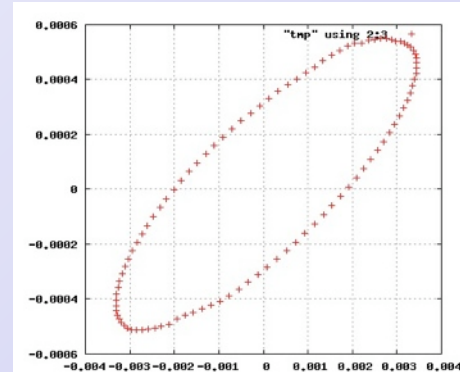
H⁻ injection orbit

Beam merging of H⁻ and H⁺ beam will be performed by main magnets of FFAG.

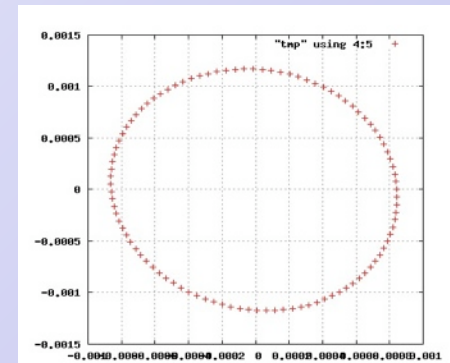


foil: 0.5deg upstream from the center of F magnet (red line)

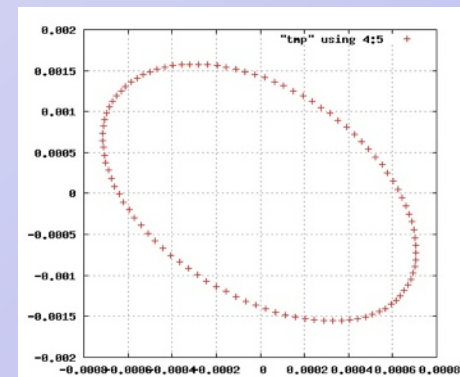
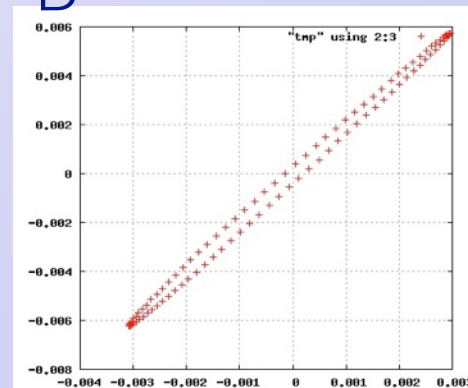
A $x-x'$



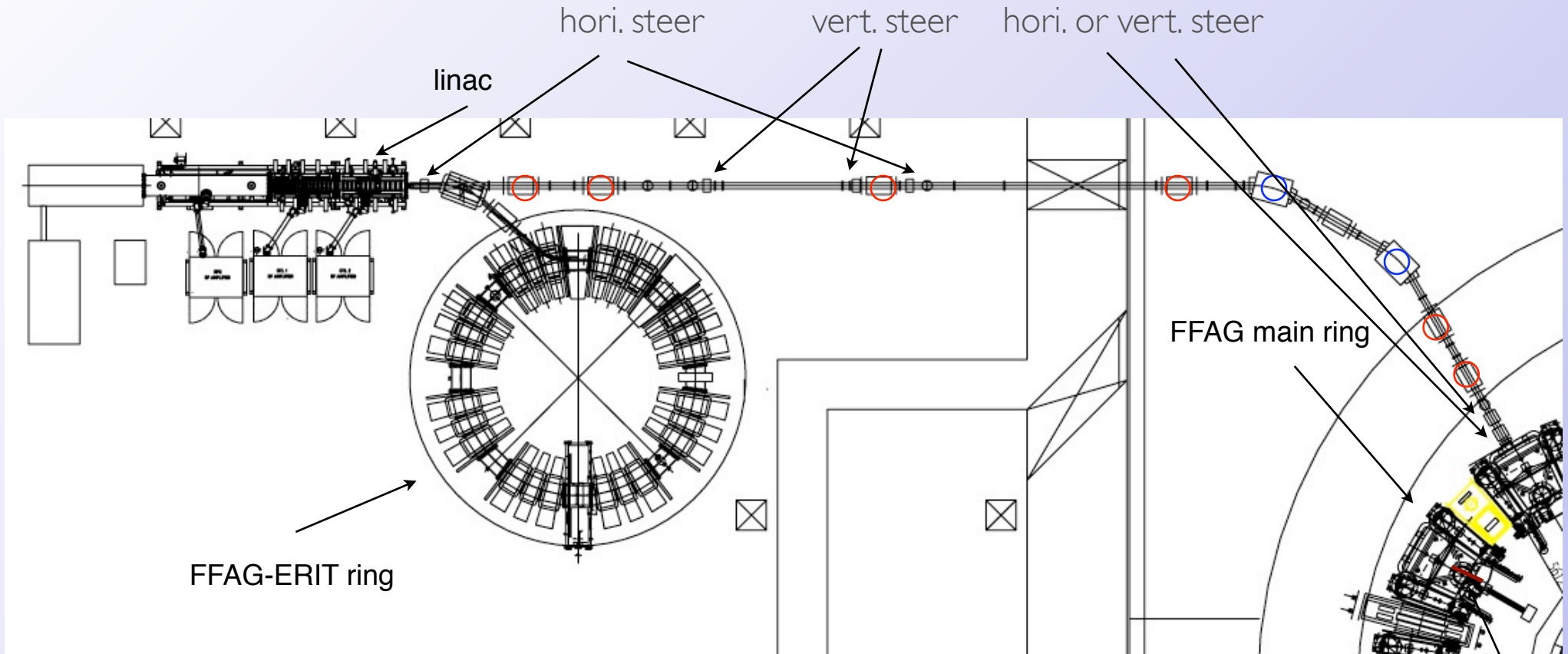
$y-y'$



B



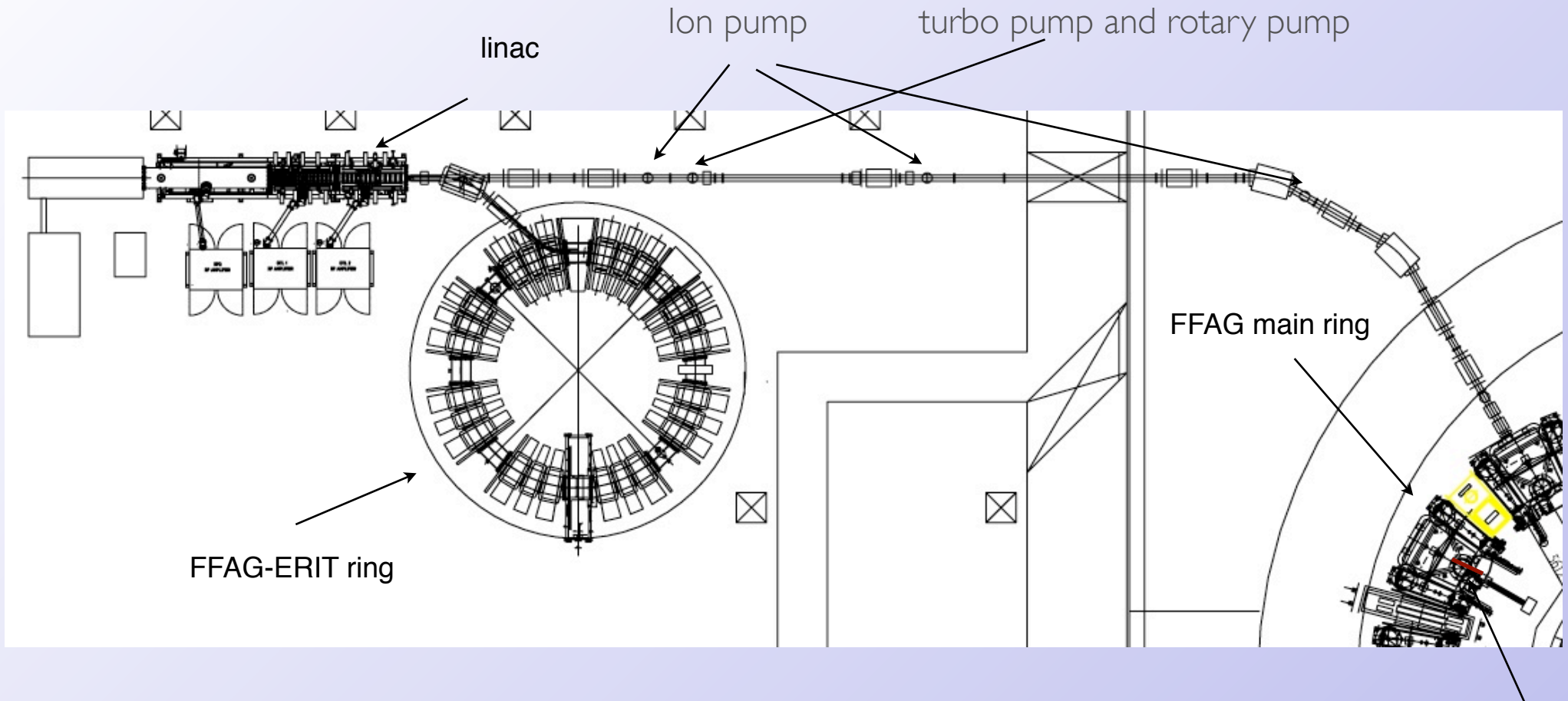
New beam-line(magnets)



Q Magnet $\times 7$, B Magnet(30deg) $\times 2$

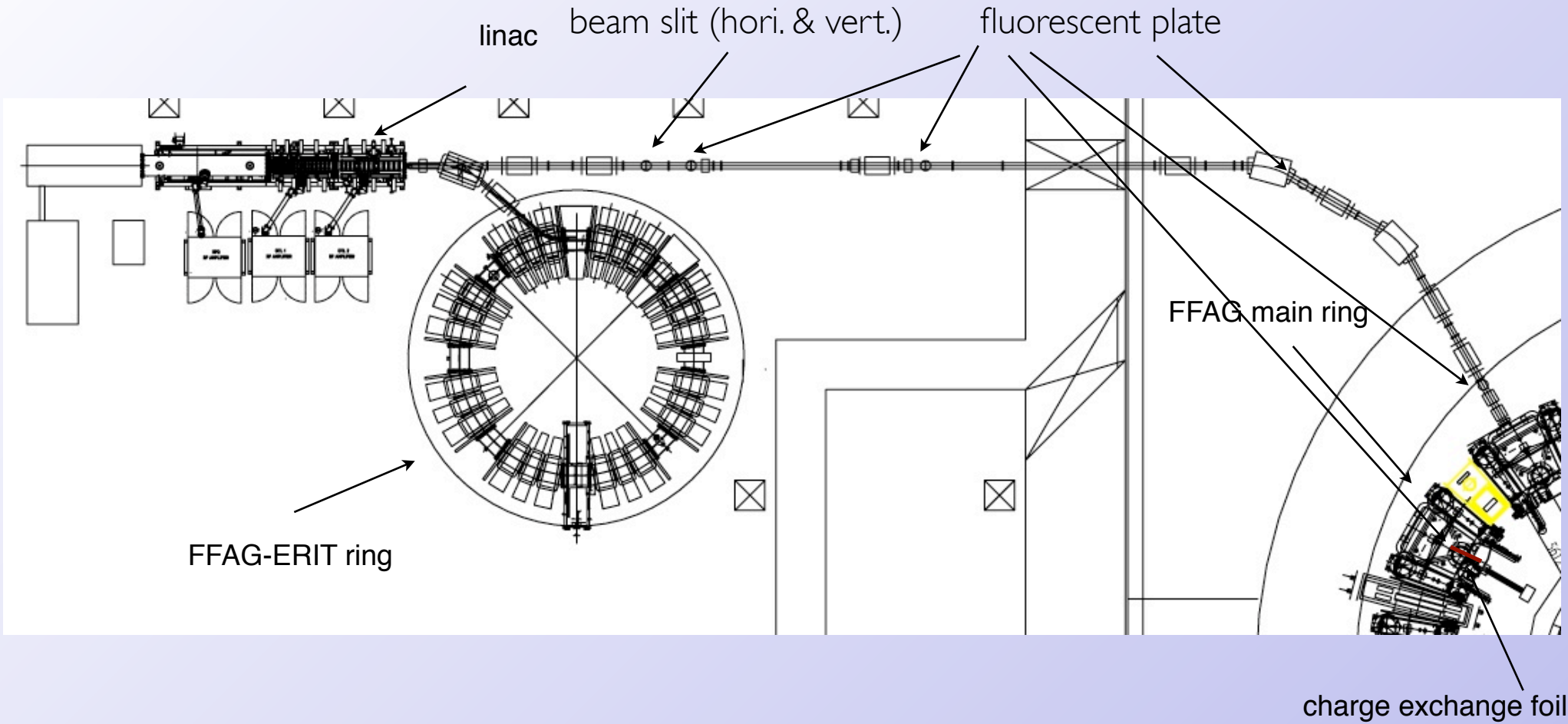
charge exchange foil

New beam-line(vacuum system)



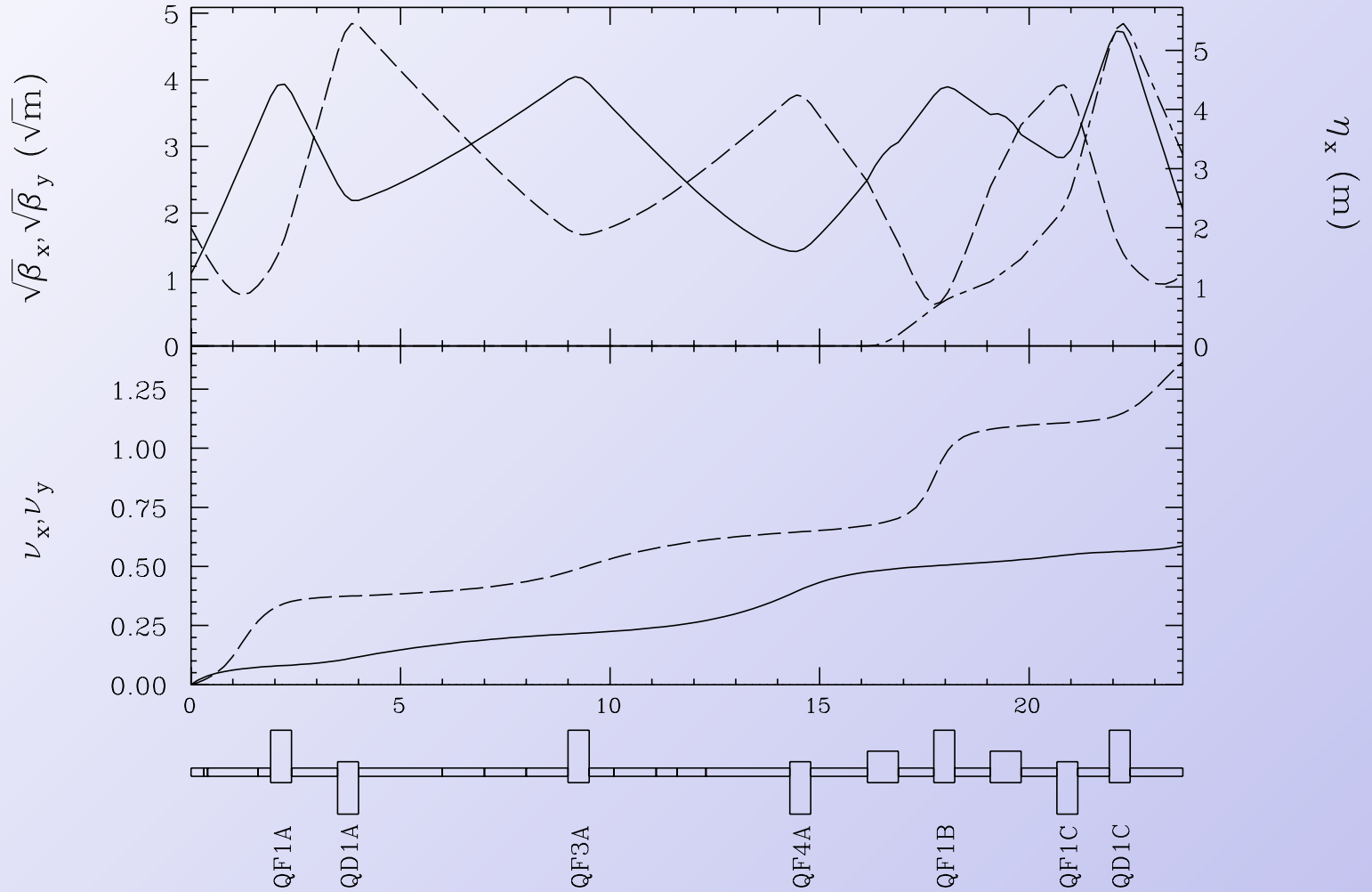
ion pump*3, turbo pump*1,
rotary pump*1

New beam-line (beam monitor)



SAD Result

02:48:41 Saturday 10/30/2010



Construction of beam line



2010 September ~ middle of November

Charge-Exchange Injection for the 150MeV-FFAG

Charge-Exchange Injection Method

- Thickness of carbon stripping foils is about $10\sim 20 \mu\text{g}/\text{cm}^2$
- Low energy injection(11 MeV) , Problems of energy loss and emittance growth
- Energy loss will be recovered by RF acceleration.
- Lowering the energy loss and emittance growth by off-center injection.
- Analysis of longitudinal painting will be required.
- Orbit shift by acceleration for escaping method from stripping foil.

scheme

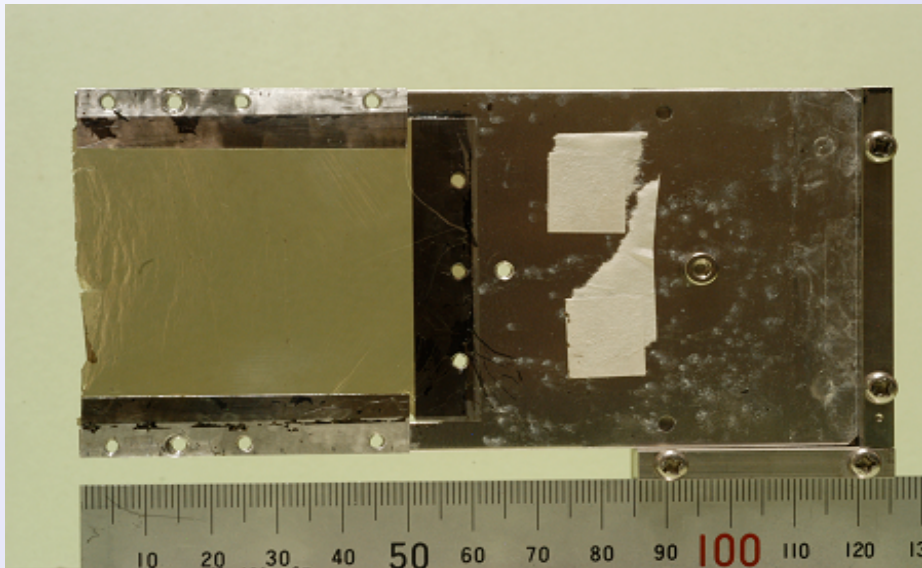
1. Multi-turn injection method by charge-exchange
2. RF capture with beam injection
3. RF acceleration after beam injection

Issues

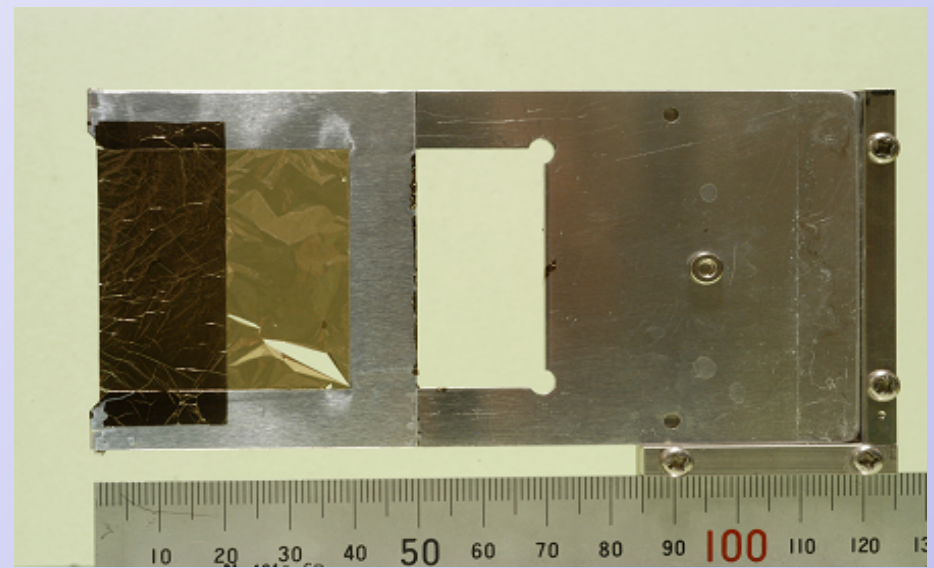
- Stripping Foil
 - Thickness of stripping foil
 - Estimation of energy loss
 - How to make stripping foil
 - Setting method , Changing method
- Injection Scheme
 - emittance growth
 - Effects of off-center injection
 - How to escape the stripping foil

Stripping Foil

- Carbon foil ($10 \sim 20 \mu\text{g}/\text{cm}^2$)
- Trial fabrication of stripping foil ($10 \mu\text{g}/\text{cm}^2$, $20 \mu\text{g}/\text{cm}^2$)
- Stripping efficiency $\sim 98\%$



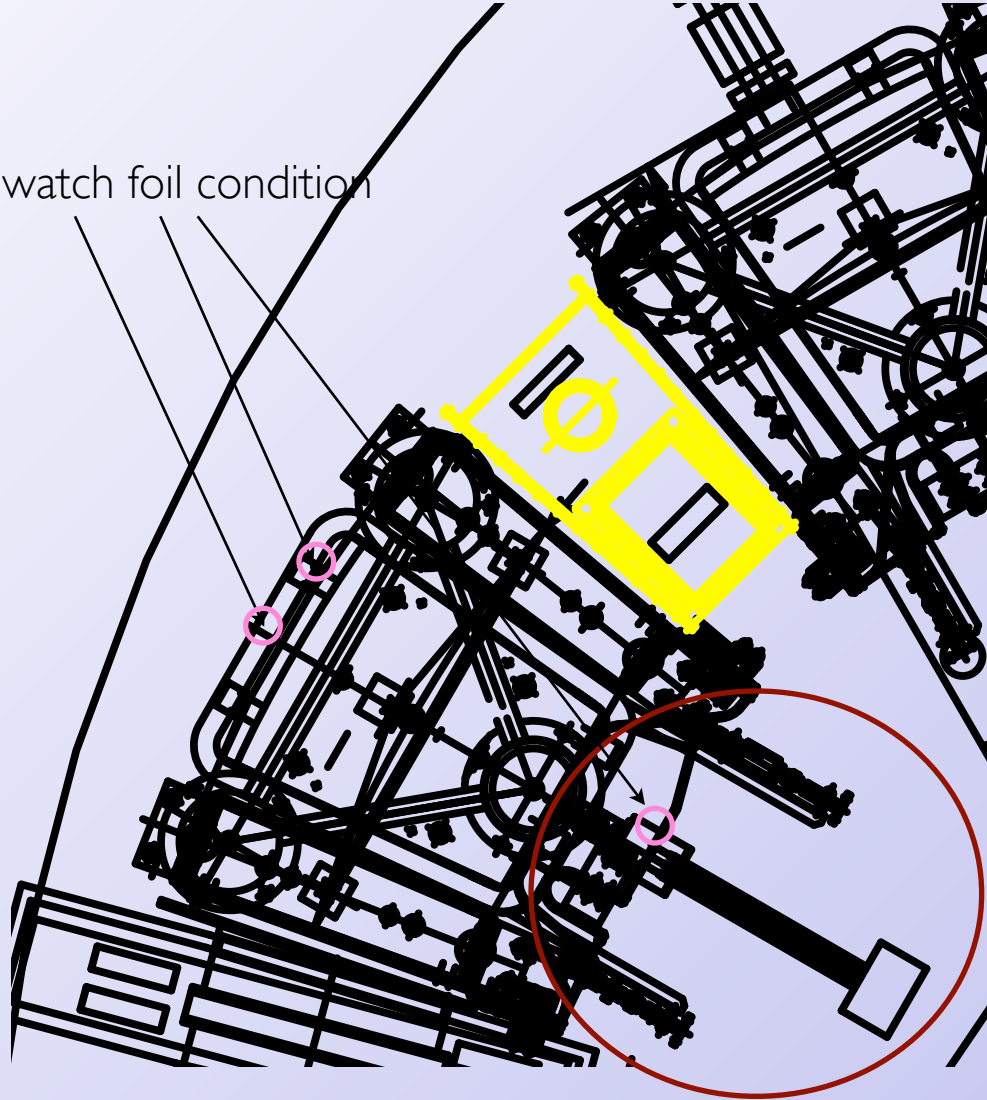
$5 \mu\text{g}/\text{cm}^2$ two layer = $10 \mu\text{g}/\text{cm}^2$



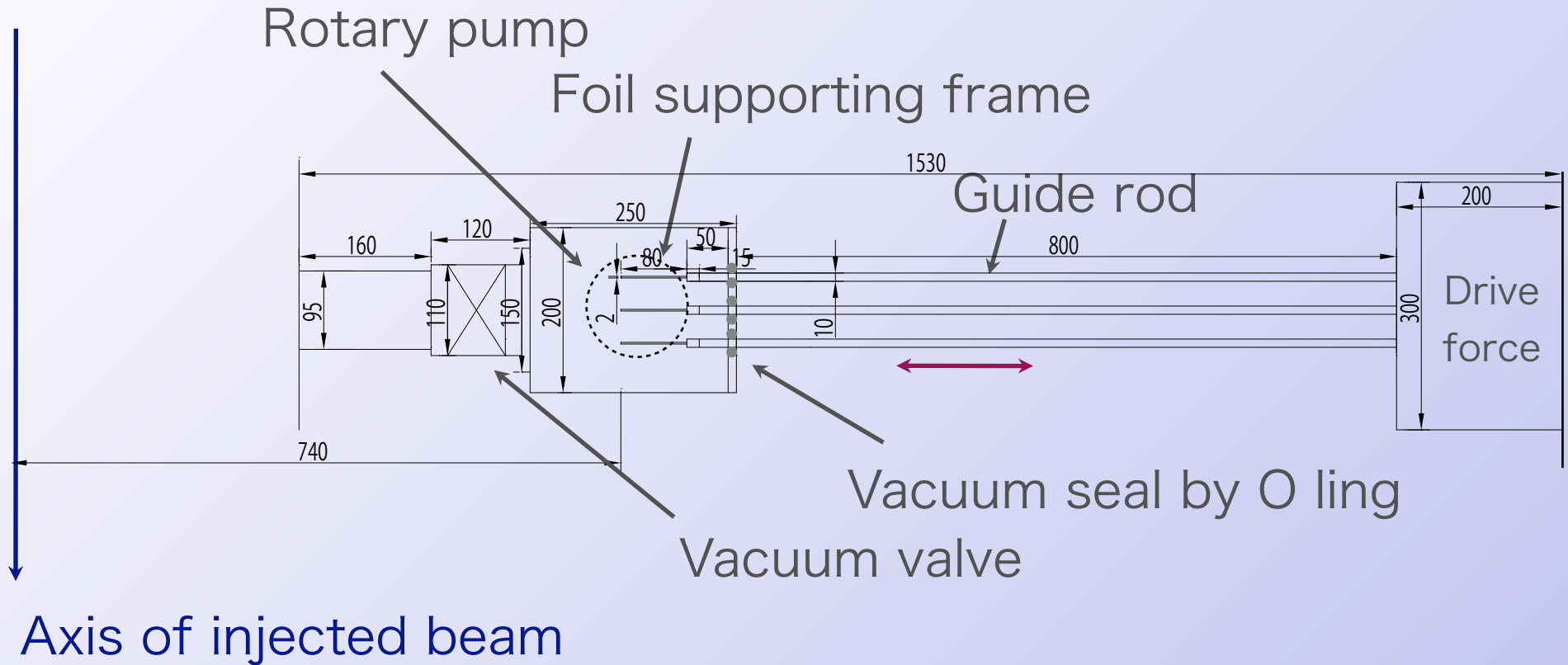
$15 \mu\text{g}/\text{cm}^2$ two layer (half part)

Foil change machine

View port to watch foil condition



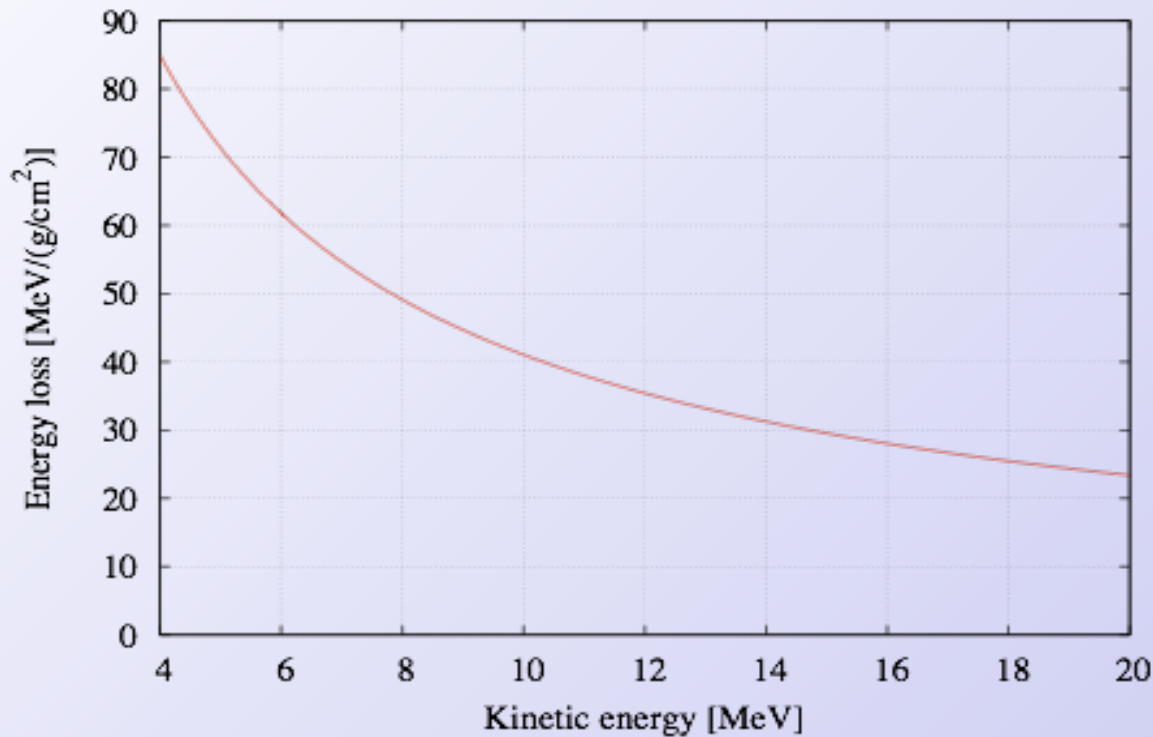
Mechanism for Foil Change



- Three foils will be exchangeable without vacuum breaking.
- Observing method for foil condition will be required.

Energy Loss

Energy loss depends on the foil thickness. Energy loss will be recovered by RF acceleration.



- Striping foil : Carbon
- Energy loss
20 $\mu\text{g}/\text{cm}^2$: 760eV
10 $\mu\text{g}/\text{cm}^2$: 380eV
- RF voltage : 2kV
- Bucket height $\Delta E =$
120keV

Emittance Blow up(I)

Low energy injection(11 MeV), circulated beam hit foil many times.
Energy loss and emittance growth are become problem.

Longitudinal

$$\frac{d\langle\sigma_E^2\rangle}{ds} = -2\left.\frac{\partial(dE/ds)}{\partial E}\right|_0 \langle\sigma_E^2\rangle + \frac{d\langle\Delta E_{rms}^2\rangle}{ds}$$

Horizontal

$$\frac{d\varepsilon_x}{ds} = -\frac{1}{\beta^2 E} \frac{dE}{ds} \varepsilon_x + \frac{\beta_x E_s^2}{2\beta^3 m_p c^2 L_R E}$$

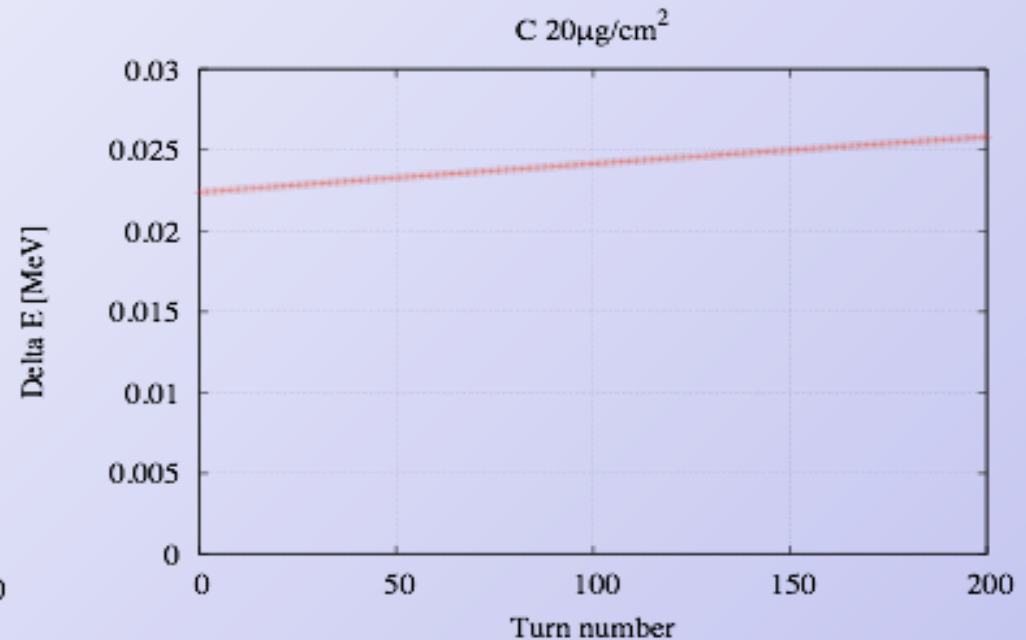
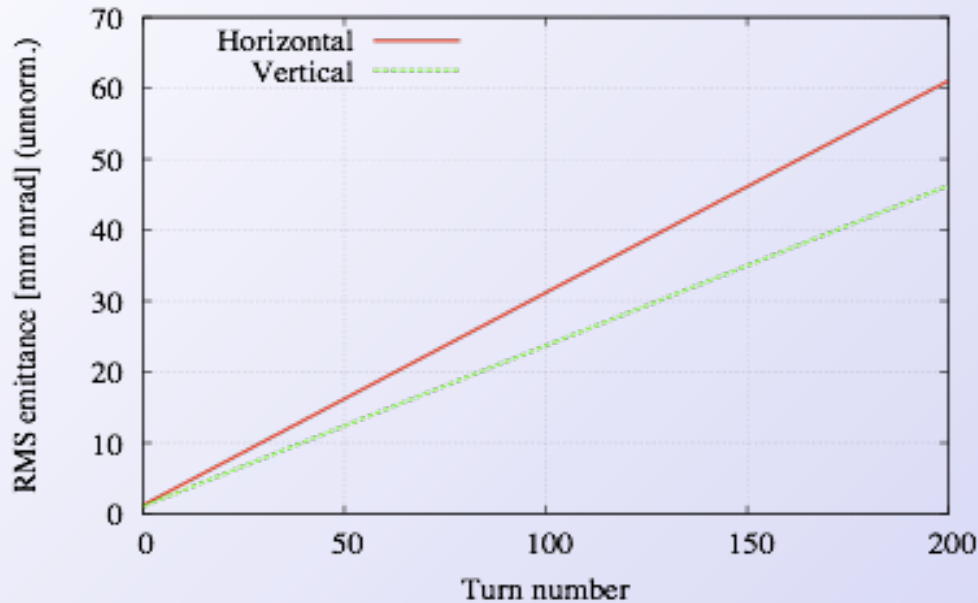
Vertical

$$\frac{d\varepsilon_y}{ds} = -\frac{1}{\beta^2 E} \frac{dE}{ds} \varepsilon_y + \frac{\beta_y E_s^2}{2\beta^3 m_p c^2 L_R E}$$

Emittance Blow up(2)

Foil thickness : $20 \mu\text{g}/\text{cm}^2$

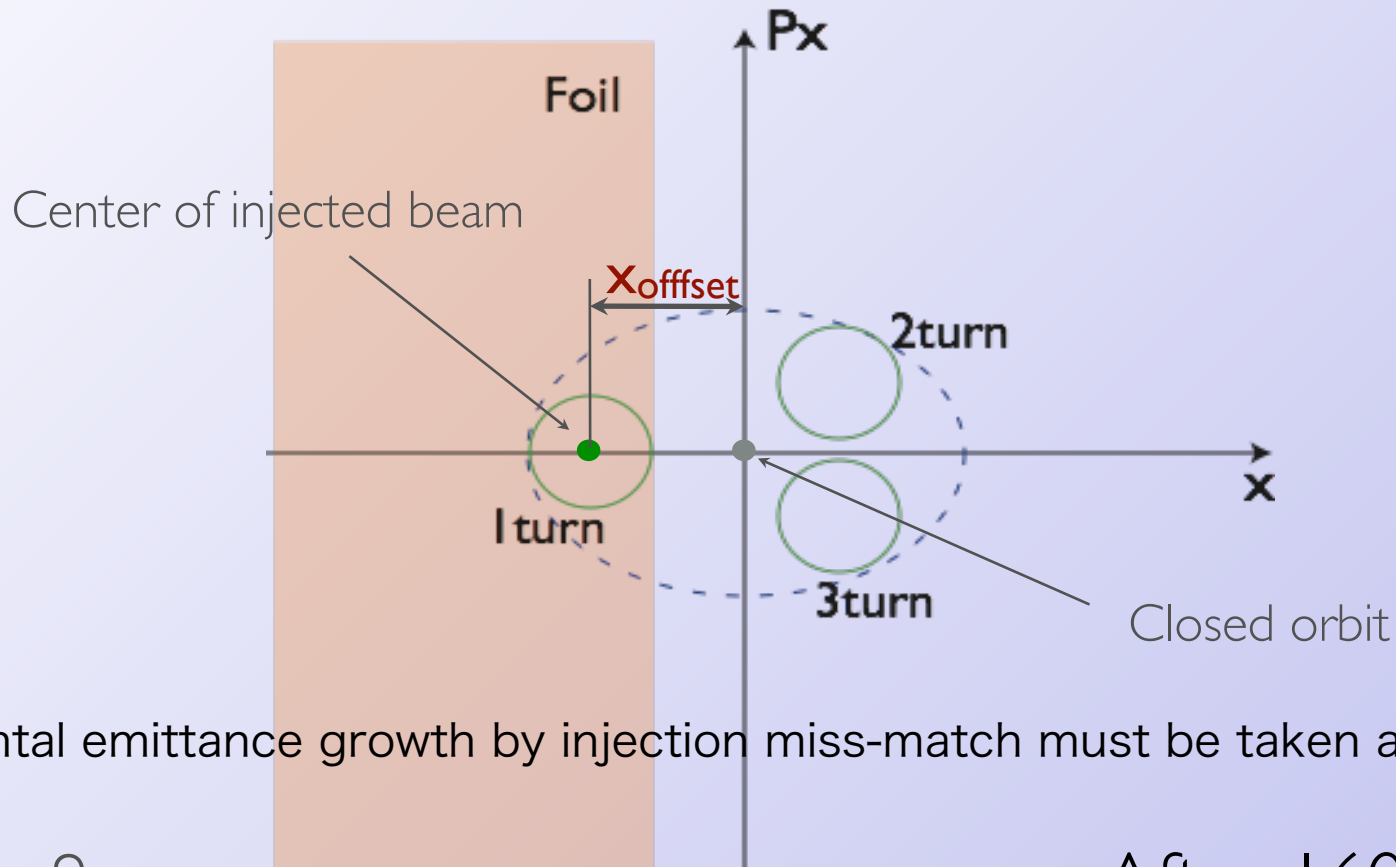
C $20\mu\text{g}/\text{cm}^2$



- disp. : $0.54[\text{m}]$
- hori. beta : $3.31[\text{m}]@\text{foil}$
- vert. beta : $2.50[\text{m}]@\text{foil}$

Off-center Injection

Decrease the hitting probability



Horizontal emittance growth by injection miss-match must be taken account.

off set $\sim 9\text{mm}$

After 160 turn

$$\epsilon_x \sim 18 \text{ mm mrad}$$

$$2\sigma_x = 15.4\text{mm}$$

$$\epsilon_y \sim 12 \text{ mm mrad}$$

$$2\sigma_y = 11.0\text{mm}$$

Turn Number required for 10mm Shift

$$V_{rf} = 2\text{kV}$$

sync. phase[deg]	43	63	73
bucket height[keV]	75	33	17
turn number	666	400	357

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

bucket height[keV]	146	81	52
turn number	312	169	141

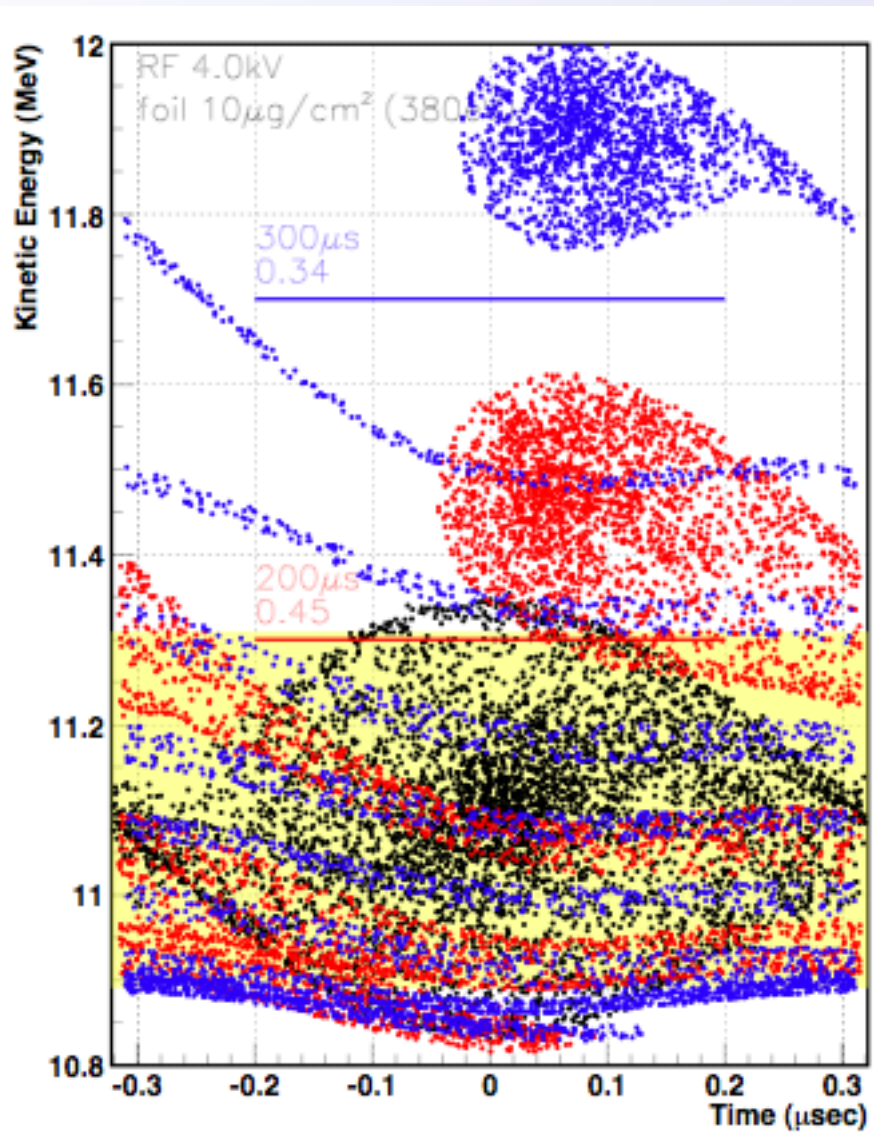
Simulation of accelerate after capture

- Linac beam : 100us(flat), (11.1+-0.03) MeV
- Foil : 10ug/mm(E loss 380eV), 10mm width
- RF voltage : 4kV

Flow of beam injection

1. Capture by stationary bucket during injection(100us)
2. After injection, acc phase 40deg.

Results of acc. after cap.



continues beam injection

34% of the beam was accelerated beyond 11.7 MeV

After 300 us.

Foil was 248 times hit by a particle (average).

45% -- 11.3 MeV -- 200us -- 111.

Summary

- Comparison of Injectors
 - Beam intensity
 - Ion-beta & booster(30Hz) $6.0 * 10^8$ [ppp]
 - H-Linac (30Hz) $3.1 * 10^{12}$ [ppp]
 - H-beam from Linac will be injected by charge-exchange injection method.
Designed average current is $1 \mu\text{A}$.(11 turn injection)
 - Maximum current is $15 \mu\text{A}$ with 160 turn injection.
- Injection beam line
 - Beam merging of H- and H+ beam will be performed by main magnets of FFAG.
 - Stripping foil position has decided to be at the center of F-magnet by beam tracking simulation.
 - Beam transport line has designed by SAD.

- Striping Foil
 - Carbon foil with its thickness 10~20 $\mu\text{g}/\text{cm}^2$
 - 10 $\mu\text{g}/\text{cm}^2$ foil is very fragile and hard to handling. 20 $\mu\text{g}/\text{cm}^2$ is rather easy for handling.
 - We are now designing the system that at least three carbon foils are changeable without vacuum breaking.
- Injection Scheme of H-injection
 - RF capture with H-injection process.
 - Escaping from stripping foil by orbit shift with RF acceleration.
 - Emittance blow up by multiple scattering with suppressed to the half value by lowering the hitting probability using off-center injection.
 - Emittance value after 160 turn is less than 20 $\text{mm}\cdot\text{mrad}$.
 - Orbit shift to escape the stripping foil will be performed by RF acceleration.
 - The upgrade of RF Voltage will be required for faster orbit shift.
- Construction of new beam line is almost completed.
- Beam commissioning of H- injection and acceleration will start from late November.