H^- Injection for the FFAG in KURRI

Kodai Okabe , Izumi Sakai (Fukui University)
Yoshihiro Ishi , Yoshiharu Mori (Kyoto University)
Yoshio Arakida (KEK)

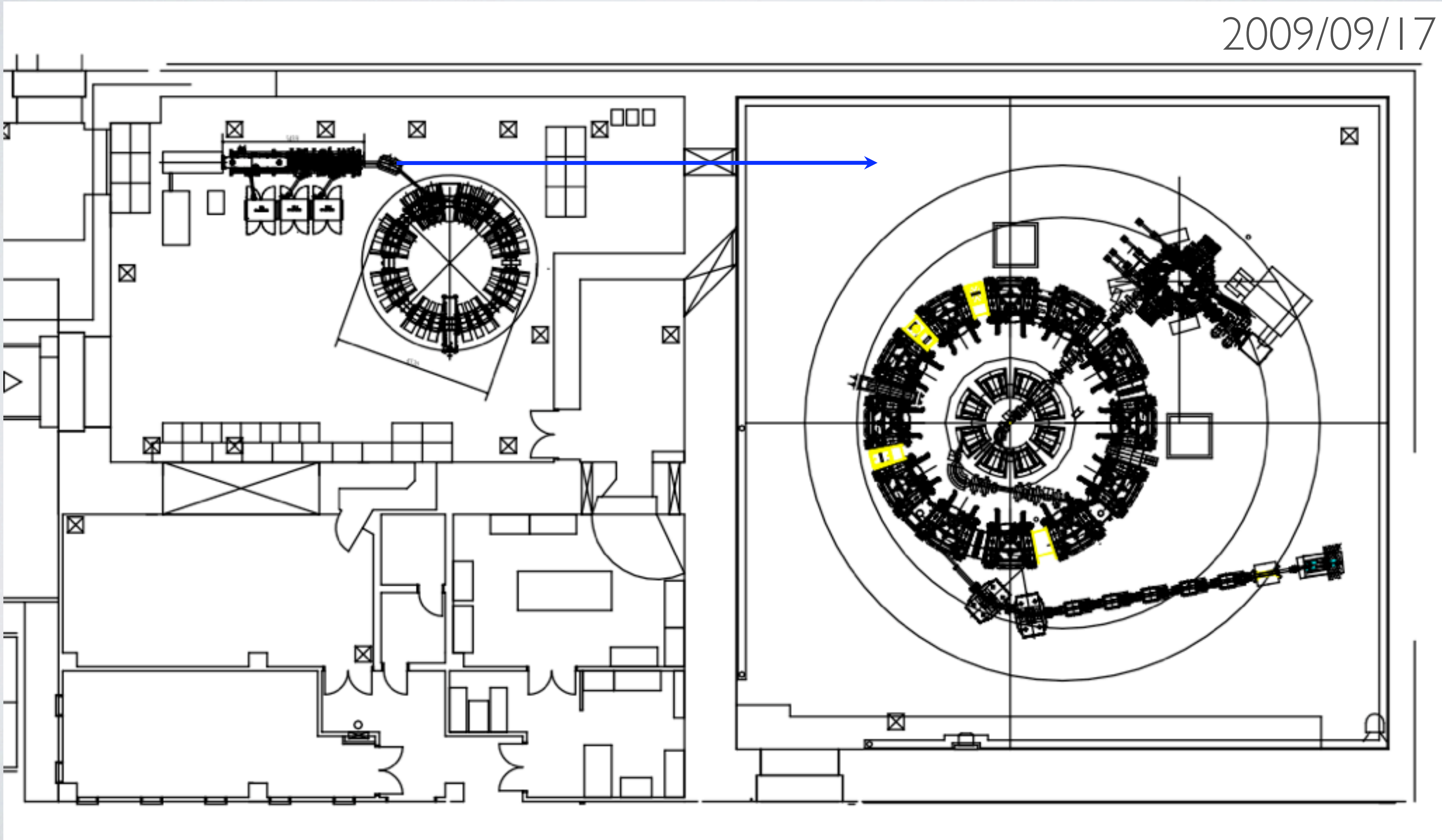
FFAG-Main Ring
Charge-exchange Injection System

MR beam intensity upgrade ~1μA

- Charge-exchange Injection method
- New Injection

  FFAG-ERIT H^-Linac(11MeV) (used for FFAG-ERIT)
- Space charge limit
  - Main Ring ~1x10^{12}ppp (10μA@60Hz)
- Research for Accelerator Physics (Space charge effects)

Layout of Accelerator in Innovation Laboratory



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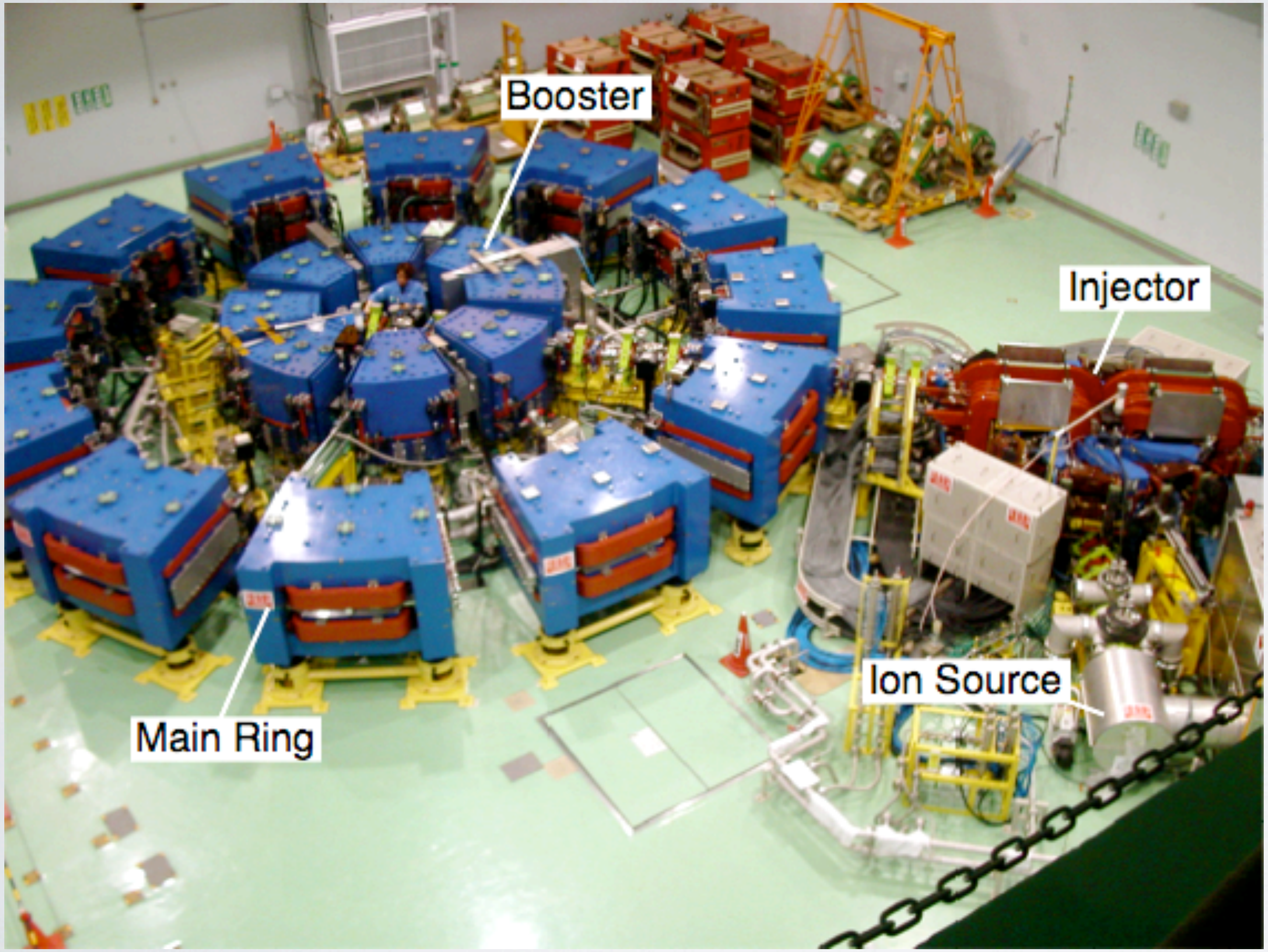
- Comparison of present Injector (Ion-beta , Booster) and Linac
- Beam transport line for beam injection
- Charge exchange injection for the 150MeV-FFAG
    - Low energy H- injection system
    - Stripping foil
    - Injection scheme
        - Energy loss and emittance growth
        - Off-center injection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

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

Main Spec of Ion-Beta + Booster



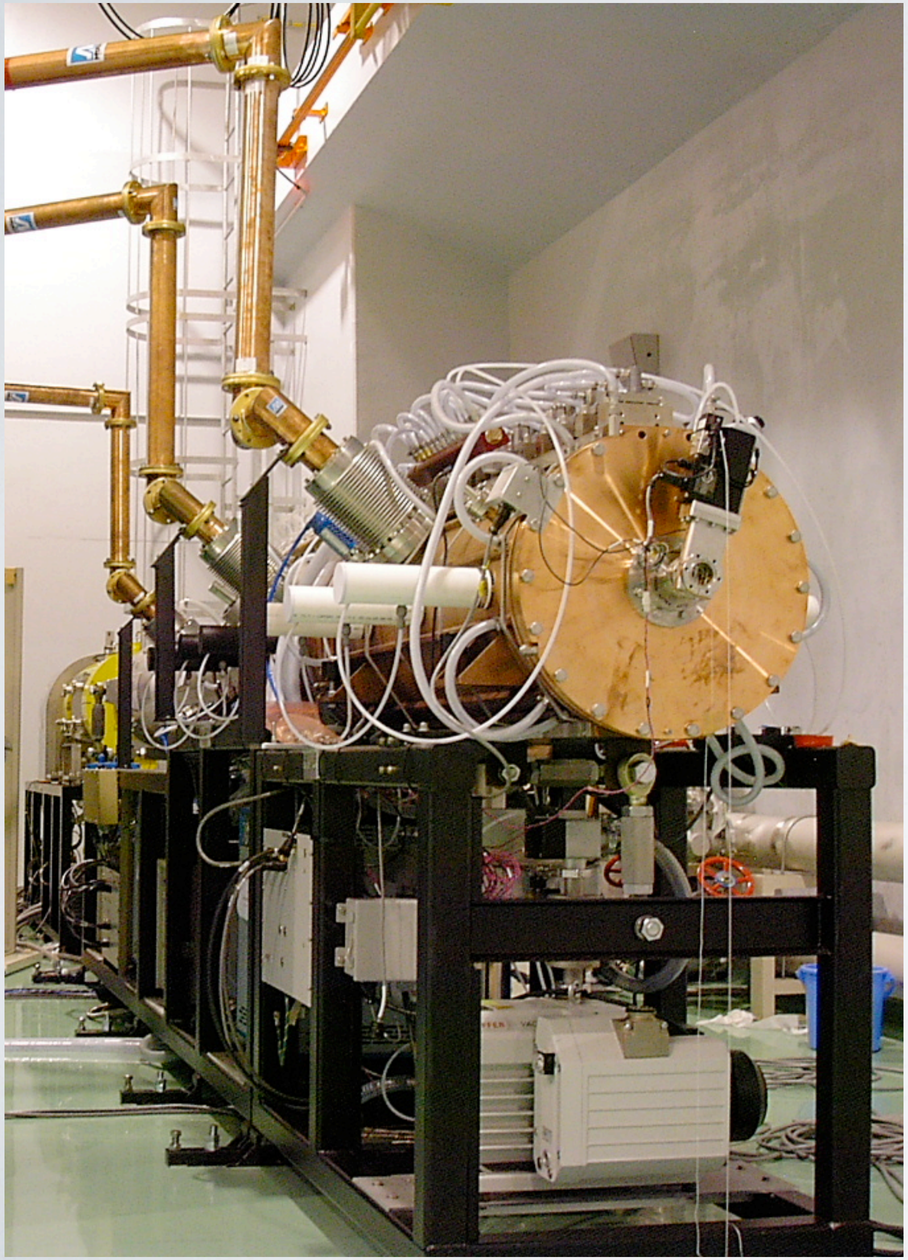
Ion-Beta

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

Booster

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

Spec of Linac + H^- Ion Source



Linac beam parameter

- ion : H^-
- E_{ext} : 11MeV
- Beam Pulse width(MAX) : 100 μsec
- Peak Curr.(MAX) : ~5 mA
  : ~$3.12*10^{12}$[ppp]
- rep. rate : 1Hz~200Hz

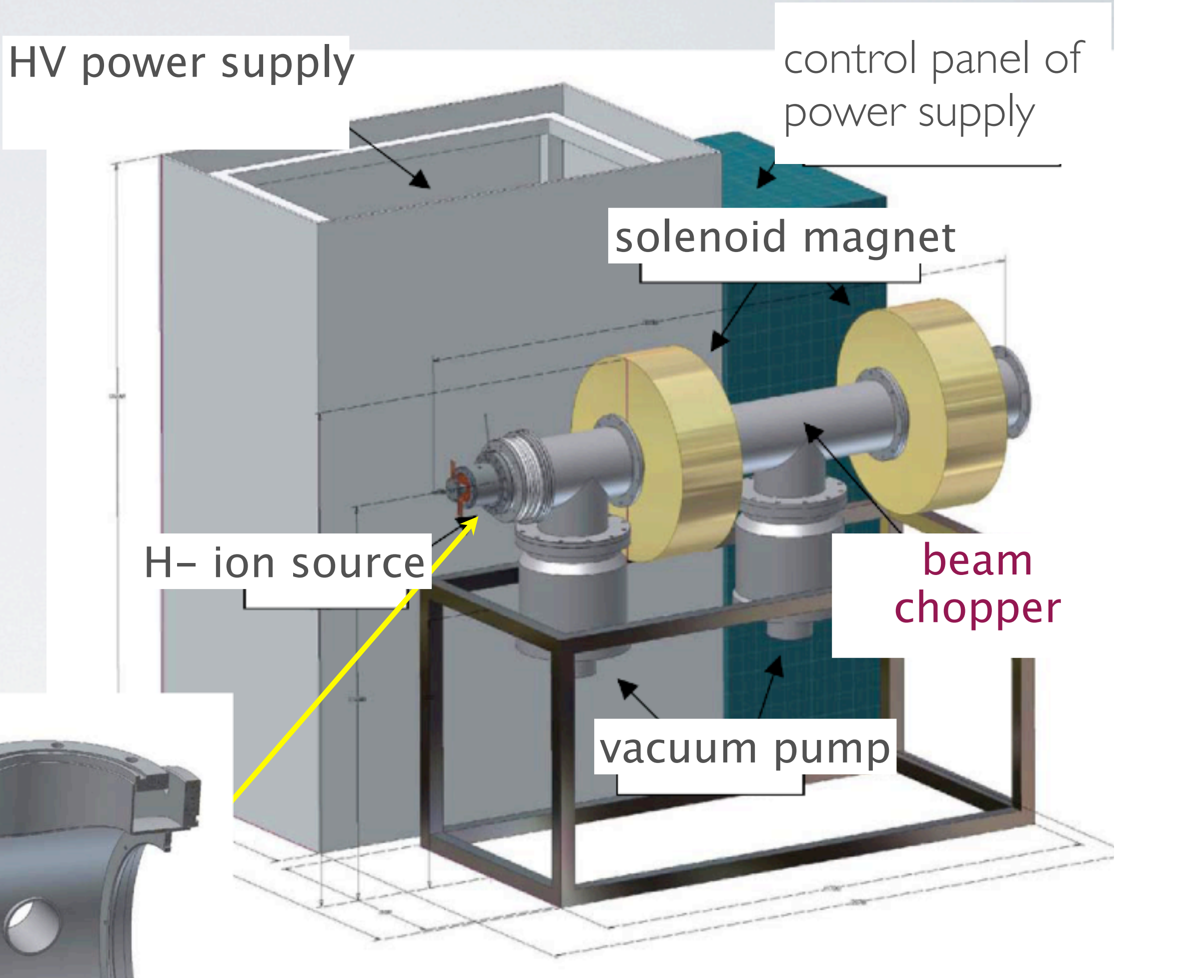
Horizontal
norm. emittance (90%) : 0.680 mm•mrad

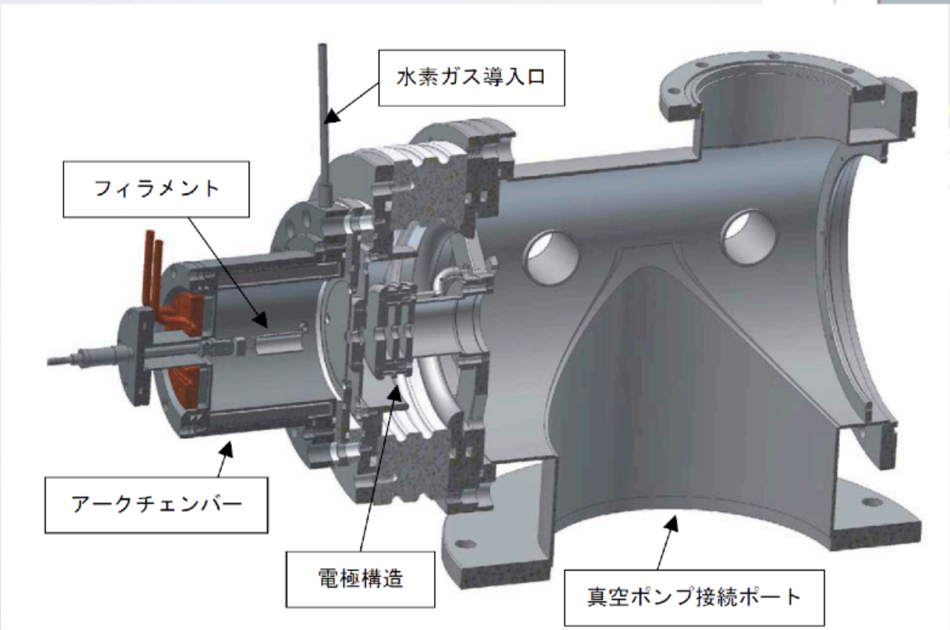
Vertical
norm. emittance (90%) : 0.630 mm mrad

Ene. 90% : ΔE ~ 45KeV

H⁻ Ion Source

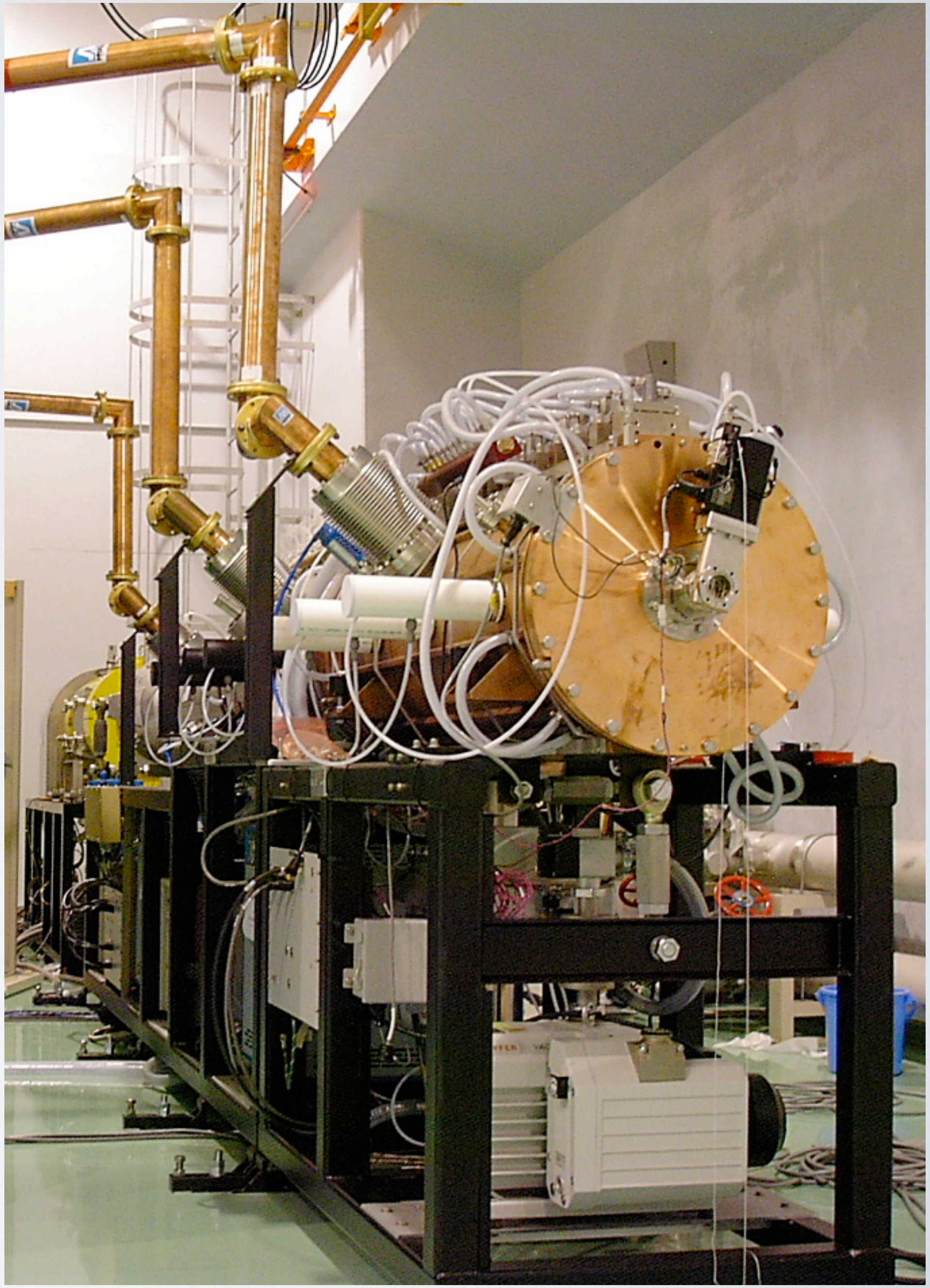
- particle: negative hydrogen
- extraction energy： 30 keV
- max rep. rate：200Hz
- beam duration：>4%(300μA)
- beam current：
  - >100μA（ave.)
  - ~5mA（peak)
- nor. emittance：<1πmm-mrad
- with chopper (~1.6MHz)



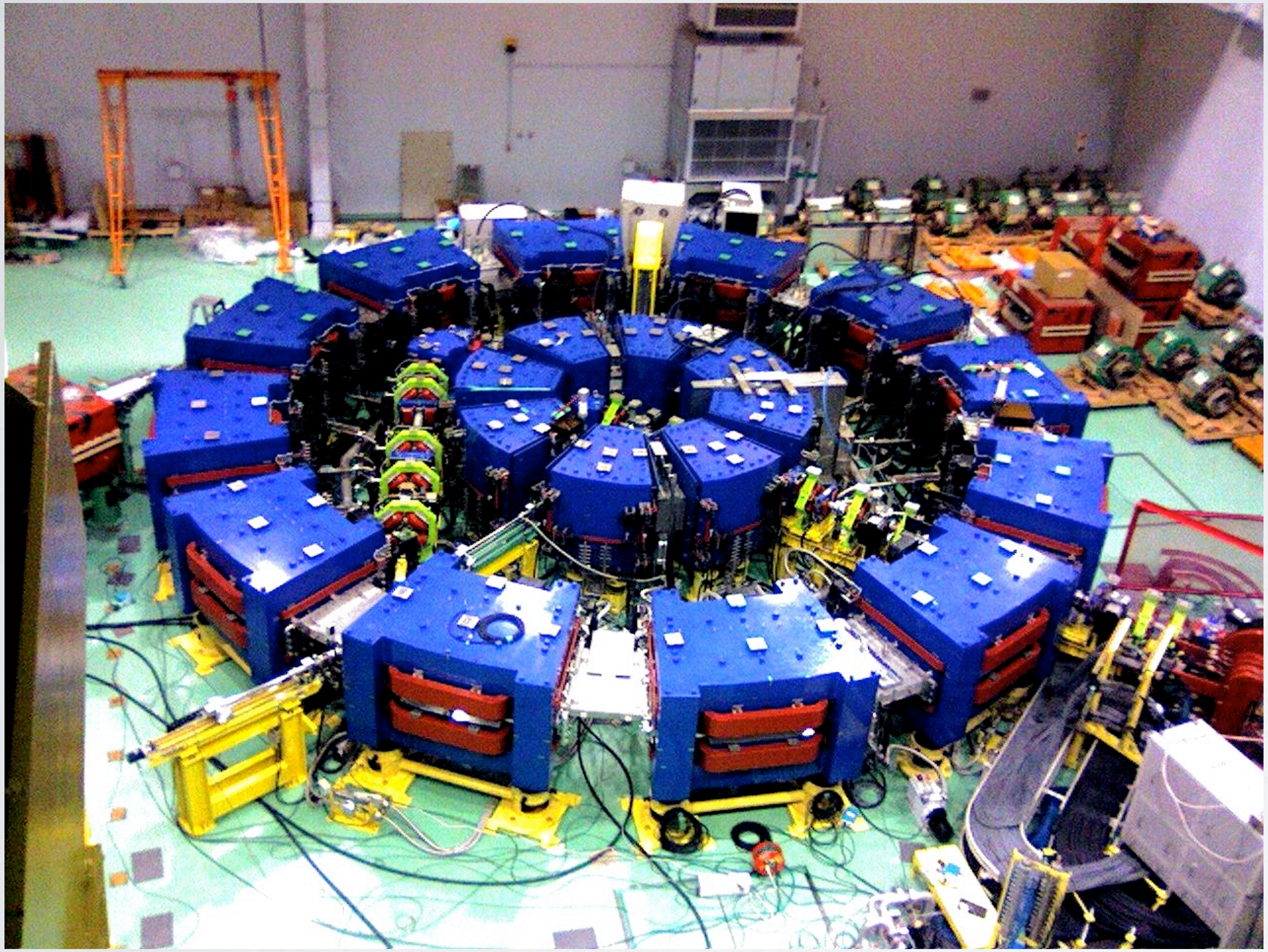


Injection Linac

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



Main-Ring



11MeV - 100MeV-FFAG

Injection energy(11MeV)

rev. freq : 1.582 MHz

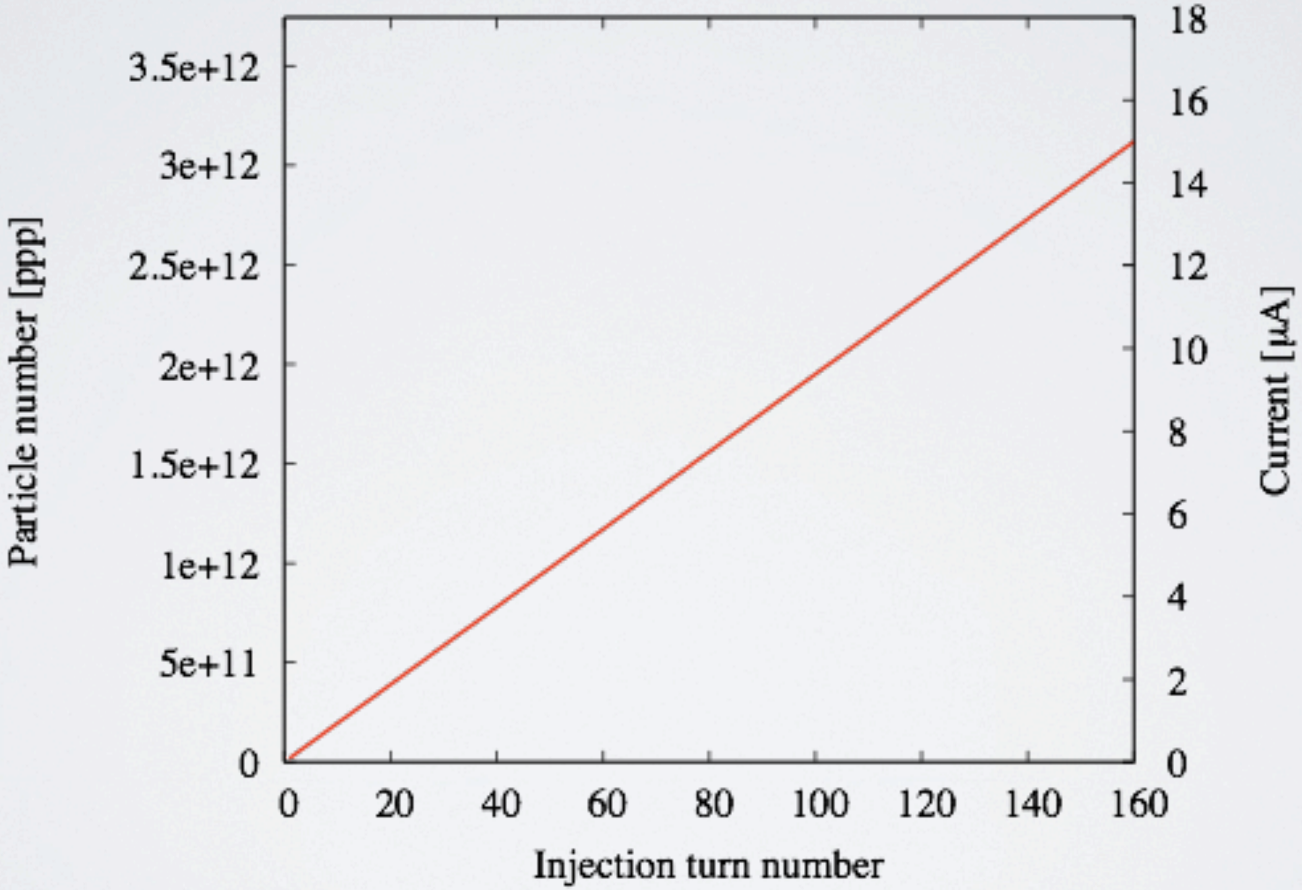
ν_x=3.68, ν_y=1.34

RF voltage : 2kV

Linac beam will be injected with H^- injection method

Injection Efficiency

MIAN-RING@11MeV   rev. freq : 1.582 MHz, (632nsec)
MAX ~160 turn injection(linac-beam pulse: ~100μsec)
Rep. rate = 30Hz



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

Space Charge Limit(Main-Ring)

Laslett tune shift (direct space charge)

$$\Delta\nu_{y,\mathrm{inc}} = -\frac{N r_0}{\pi\beta^2\gamma^3}\frac{F/B}{\epsilon_y(1+\sqrt{\epsilon_x/\epsilon_y})}$$

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

N ~ 1.3×10^{12} ppp (12.4 μA for 60Hz)

r_0	1.53×10^{-18} 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) πmm-mrad	emittance
B_f	0.5	
F	1.5	

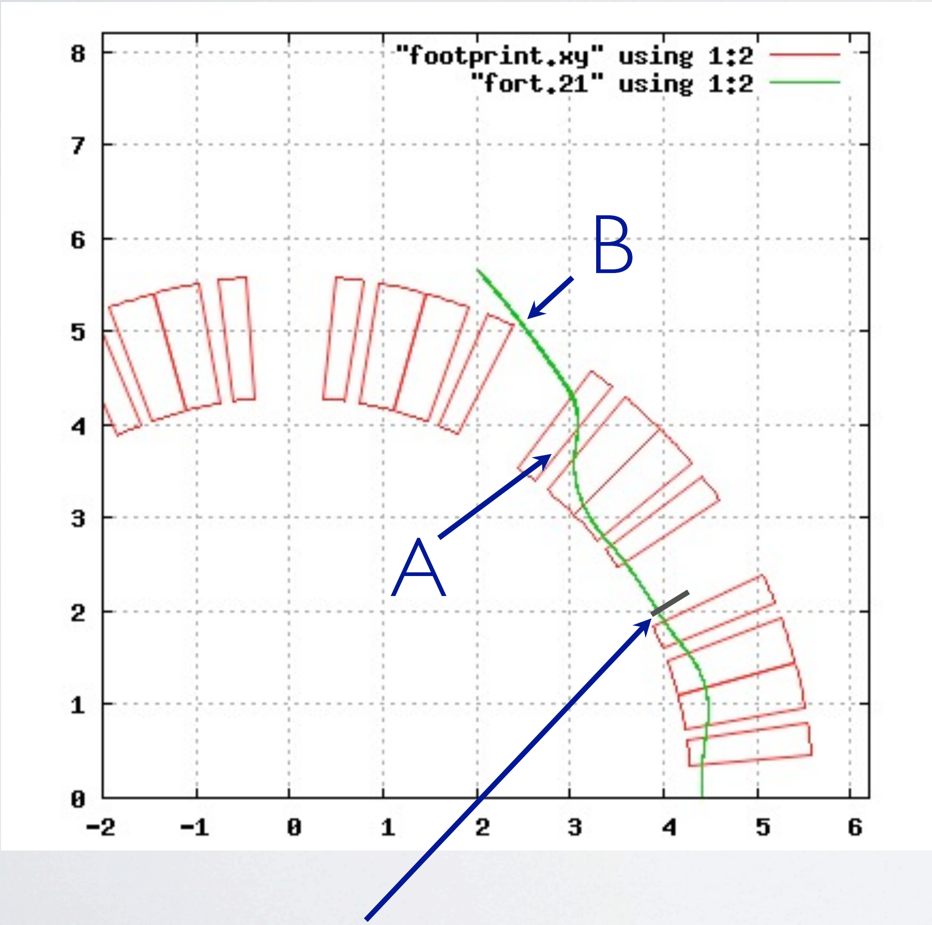
Injection Beam Line

BT-issues

- Injection orbit : merging method using main magnets of FFAG
- Mid. plane (FFAG-DDS 1250mm), (150MeV-FFAG 1200mm) : Vertical steering magnets for vertical orbit shift will be settled.
- Beam Monitor (Emittance Monitor)
- water, cable, PS

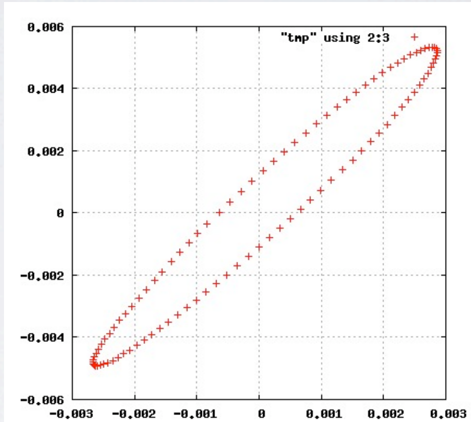
H⁻ injection orbit(case 1)

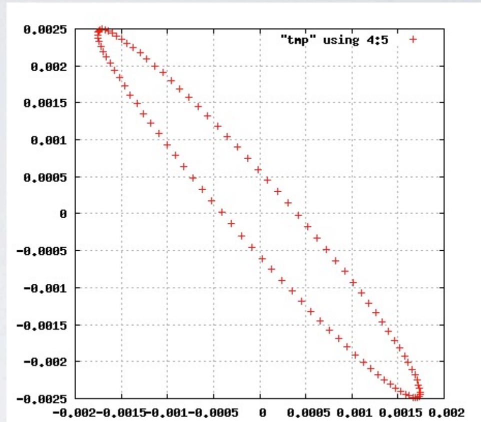
Injected beams will be merged to circulating beam using main magnets



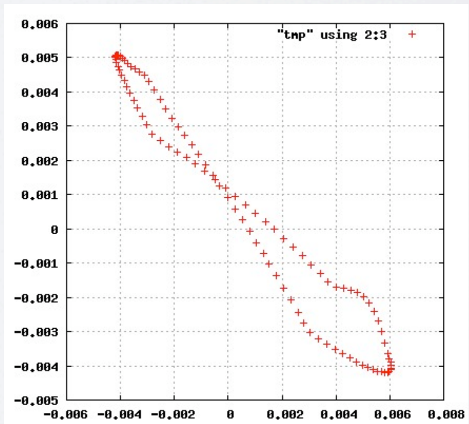
foil: 1.5deg downstream from the exit of D magnet

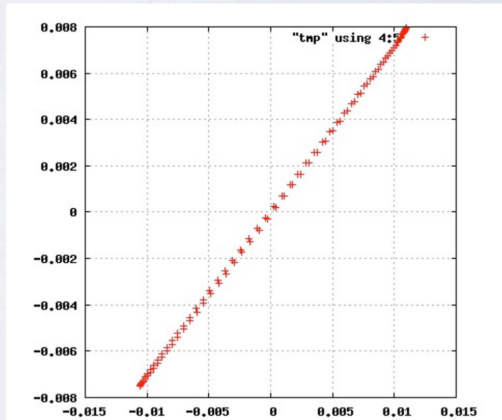
A x-x' y-y'



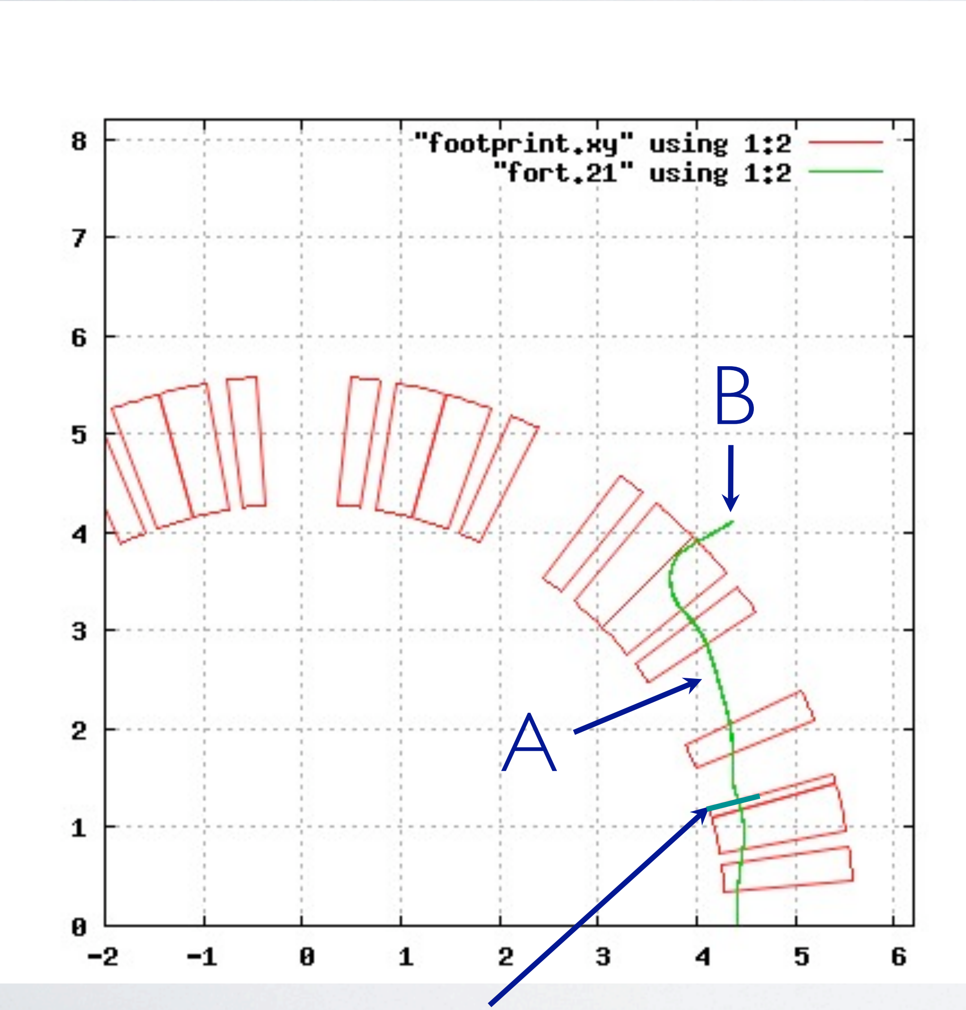


B



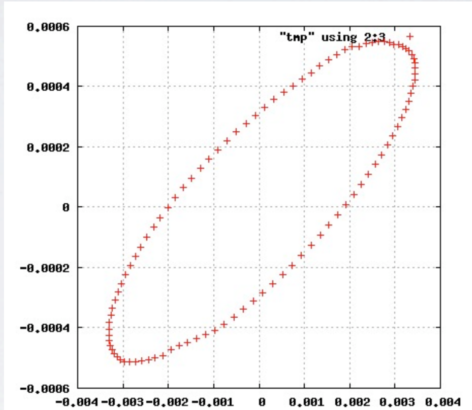


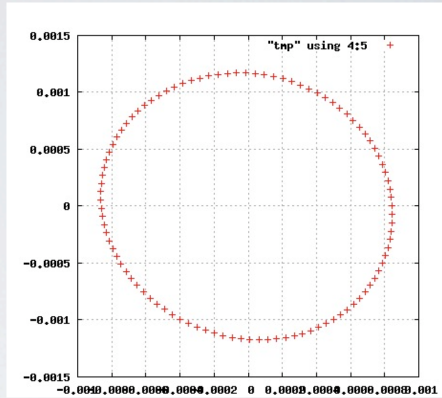
H$^-$ injection orbit(case 2)



foil: 1deg downstream from the center of F magnet

A x-x' y-y'





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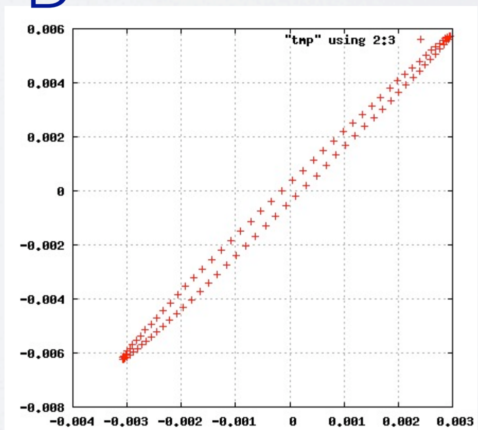
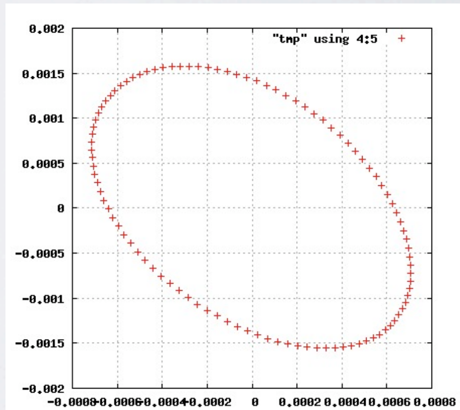
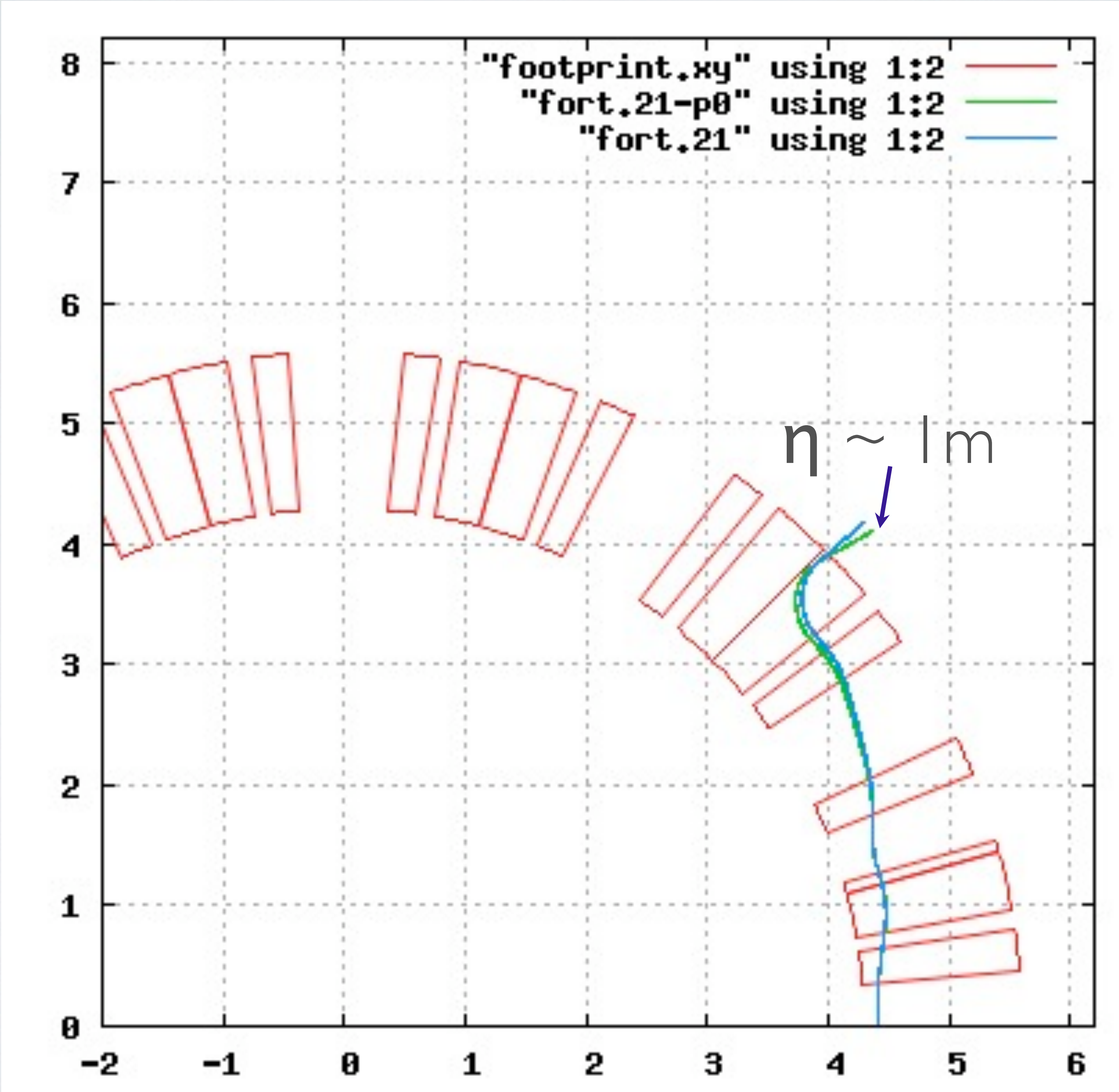
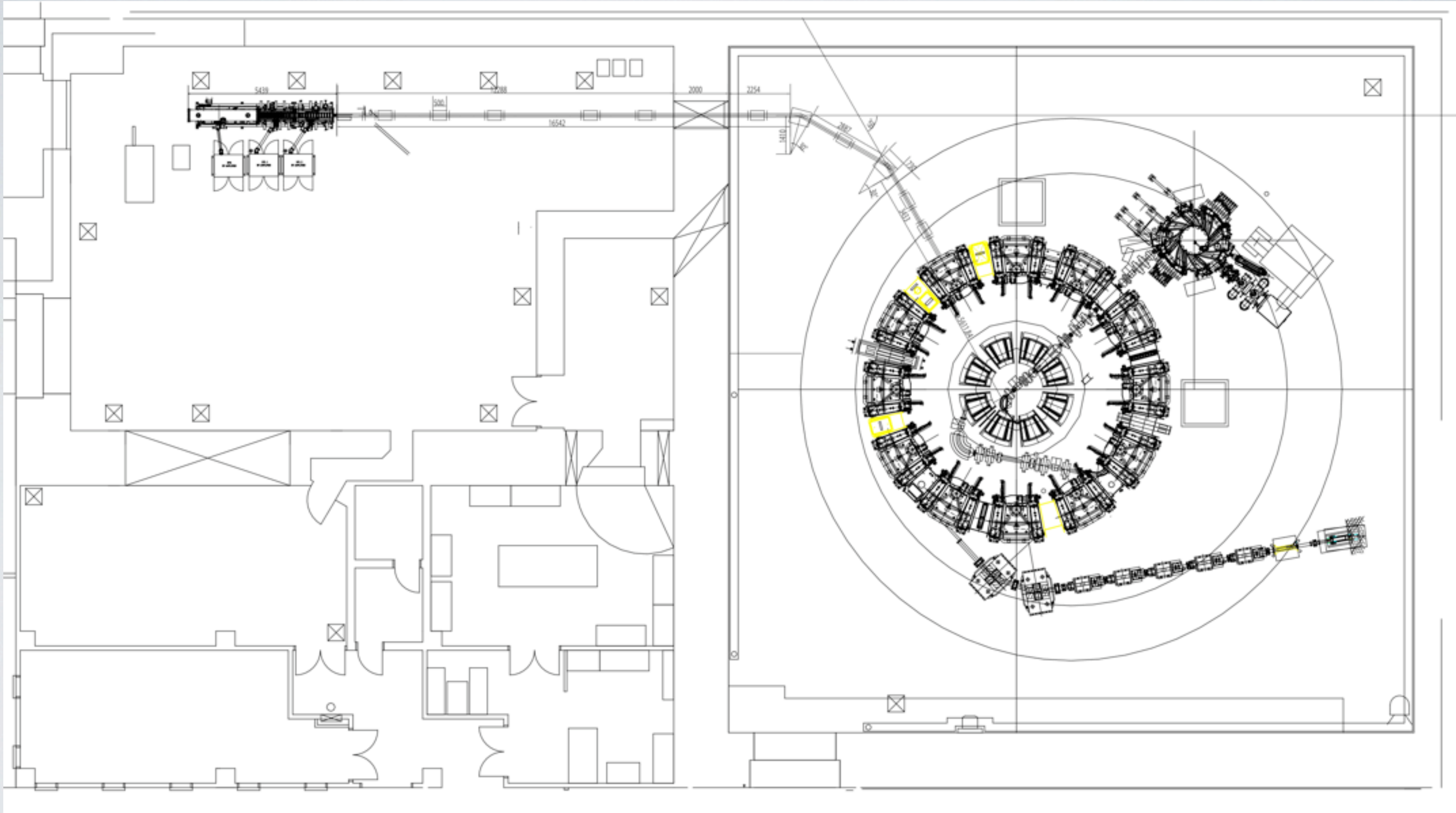




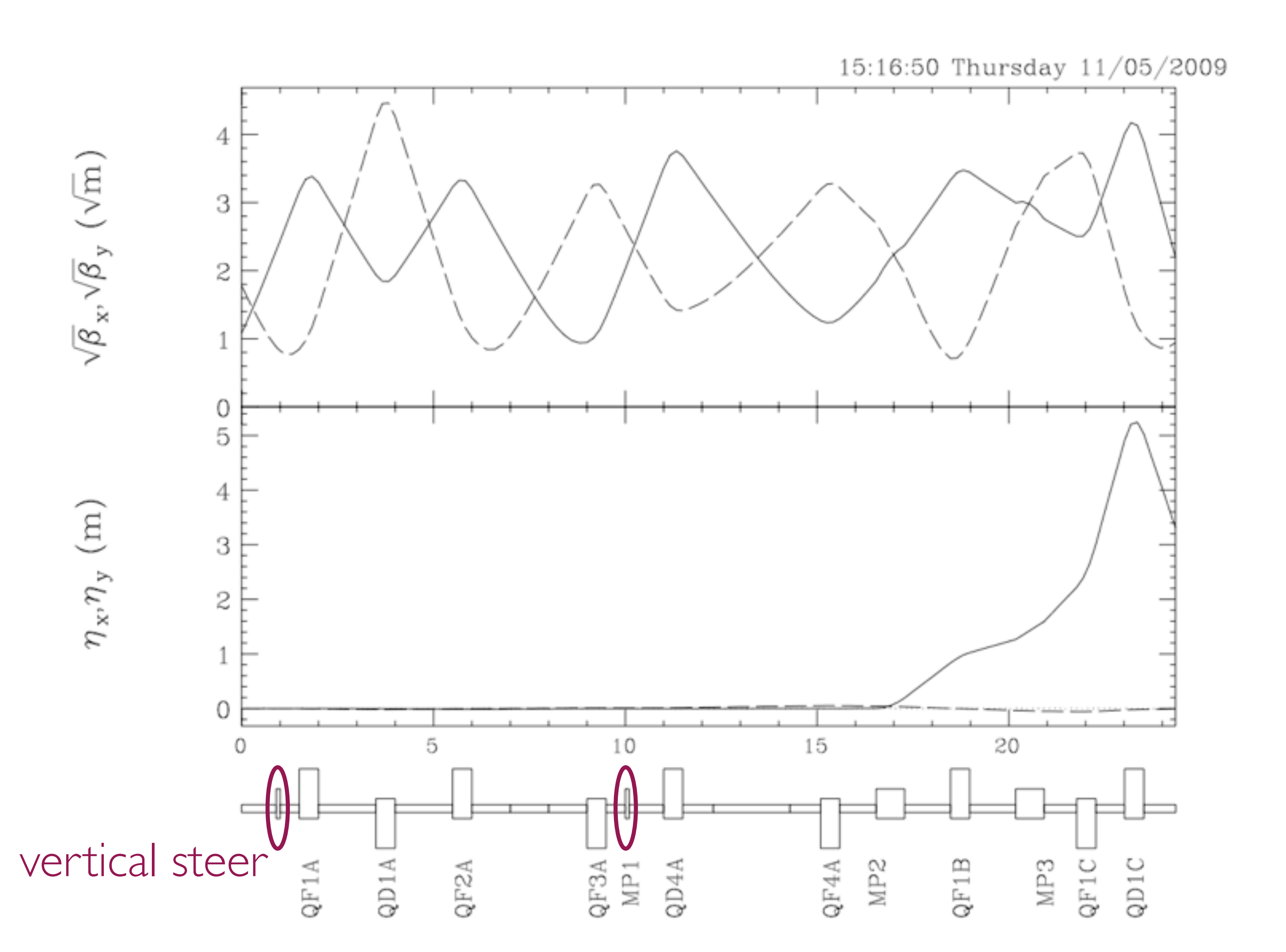

"footprint.xy" using 1:2
"fort.21-p0" using 1:2
"fort.21" using 1:2
η ~ 1m
8
7
6
5
4
3
2
1
0
-2
-1
0
1
2
3
4
5
6

New beam-line



Q Magnet ×9, B Magnet(30deg) × 2

SAD Result



15:16:50 Thursday 11/05/2009
$\sqrt{\beta_x}, \sqrt{\beta_y}$ ($\sqrt{m}$)
η_x, η_y (m)
0
1
2
3
4
5
10
15
20
vertical steer
QF1A
QD1A
QF2A
QF3A
MP1
QD4A
QF4A
MP2
QF1B
MP3
QF1C
QD1C

Charge-Exchange Injection for the 150MeV-FFAG

Charge-Exchange Injection Method

- Carbon striping foils 10~20 μg/cm^2
- Low energy injection(11MeV)， 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

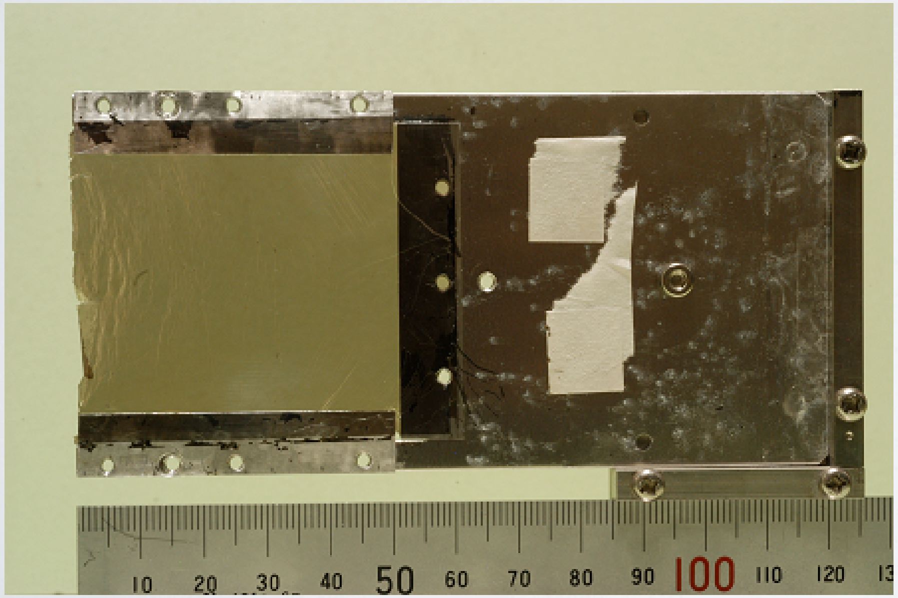
1. Multi-turn injection method by charge-exchange
2. RF capture with beam injection
3. RF acceleration after beam injection

Issues

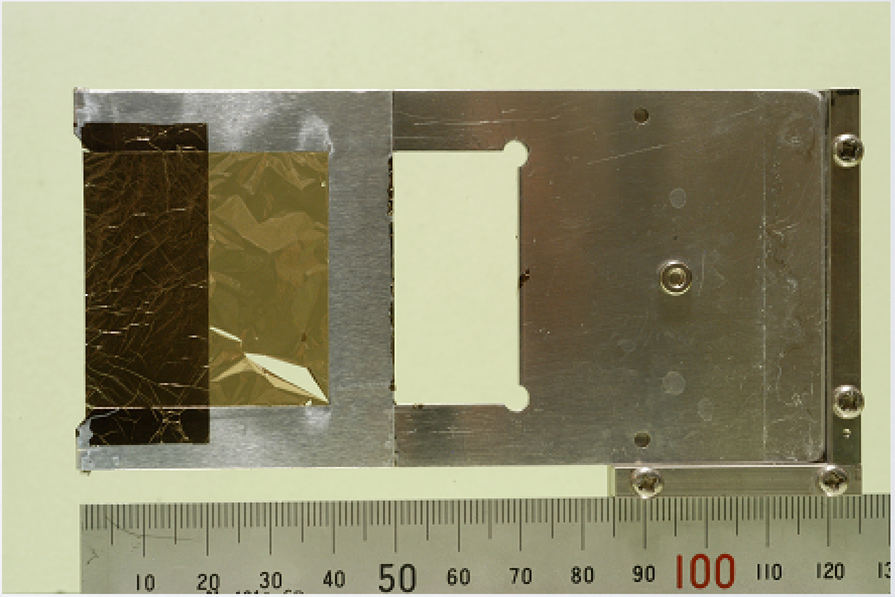
- **Stripping Foil**
  - How to make stripping foil
  - Setting method , Changing method
- **Injection Scheme**
  - Estimation of energy loss and emittance growth
  - Effects of off-center injection
  - How to escape the stripping foil
  - Temperature rise of stripping foil

Stripping Foil

- Carbon foil (10 ~ 20μg/cm²)
- Trial fabrication of stripping foil (10 μg/cm² ,20 μg/cm²)
- Stripping efficiency ~ 99% (for the KEK experience)

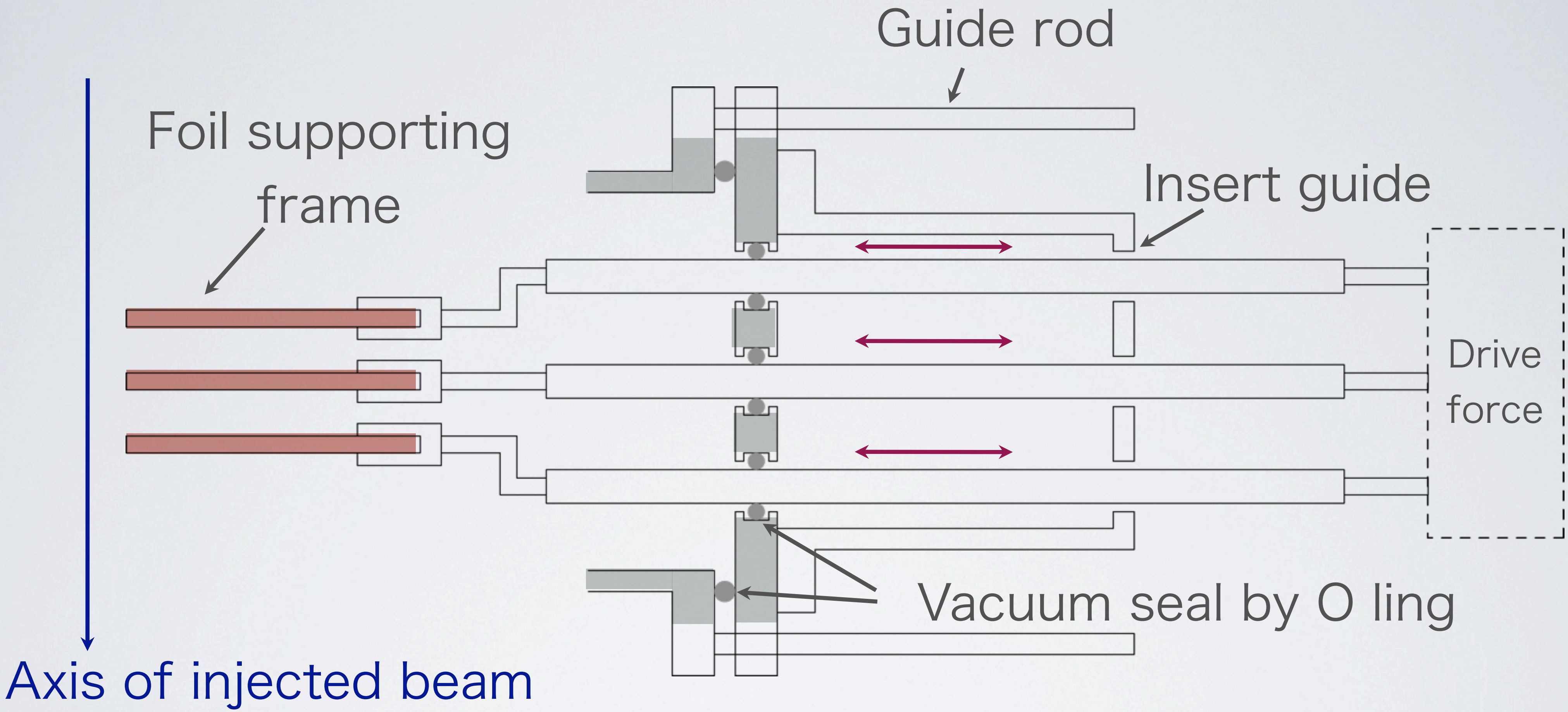


5μg/cm² two layer＝ 10 μg/cm²



15μg/cm² two layer (half part)

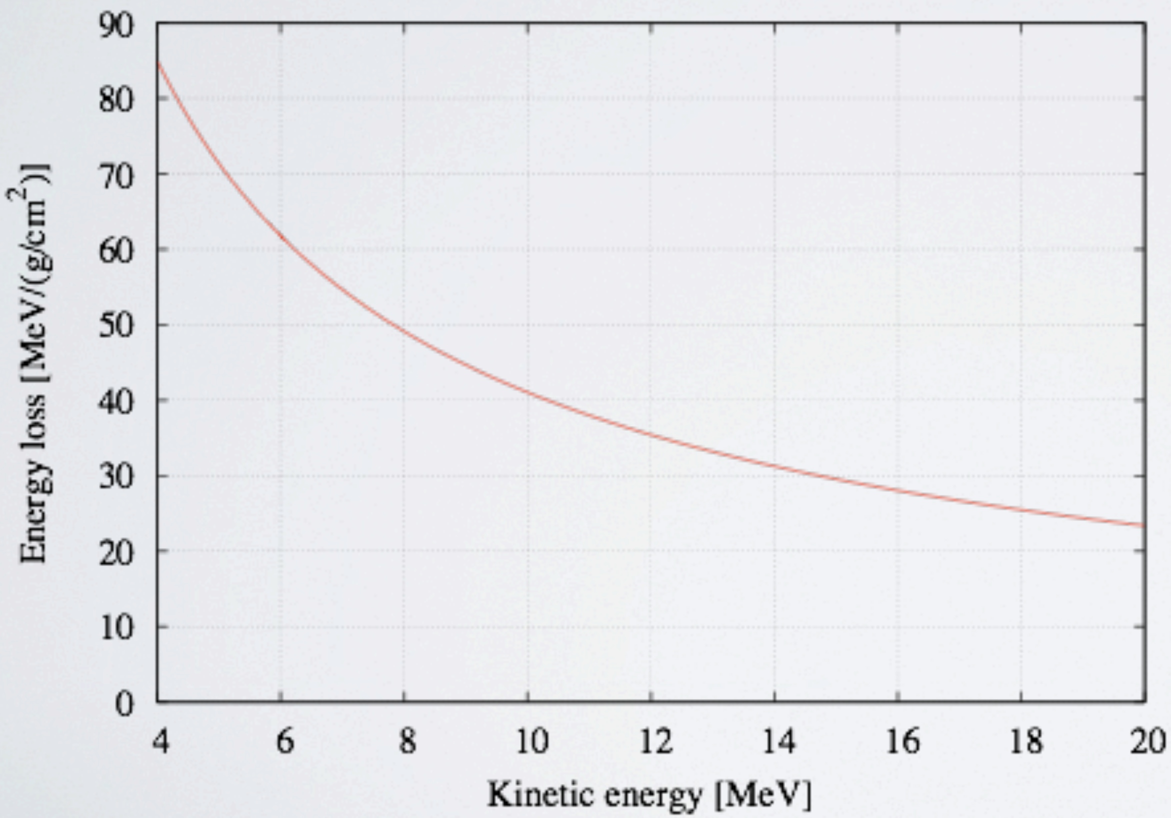
Mechanism for Foil Change



- 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 μg/cm² : 760eV
  10 μg/cm² : 380eV
- Bucket height
- RF voltage : 2kV
- (sync. phase = 23 deg)
- ΔE = 120keV

Emittance Blow up(1)

Longitudinal

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

Horizontal

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

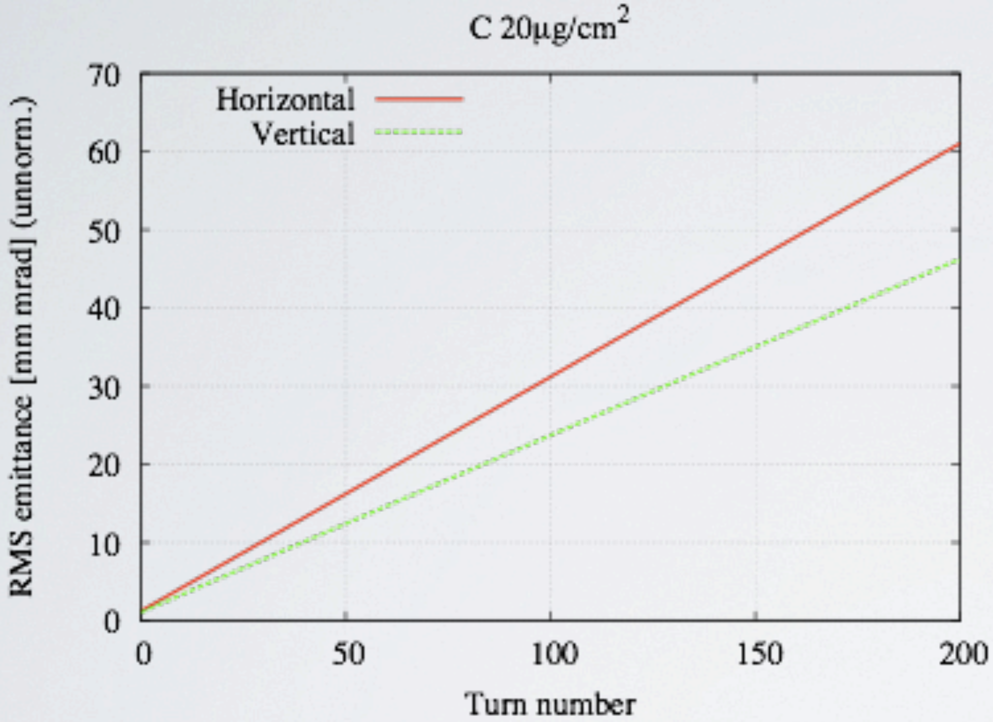
Vertical

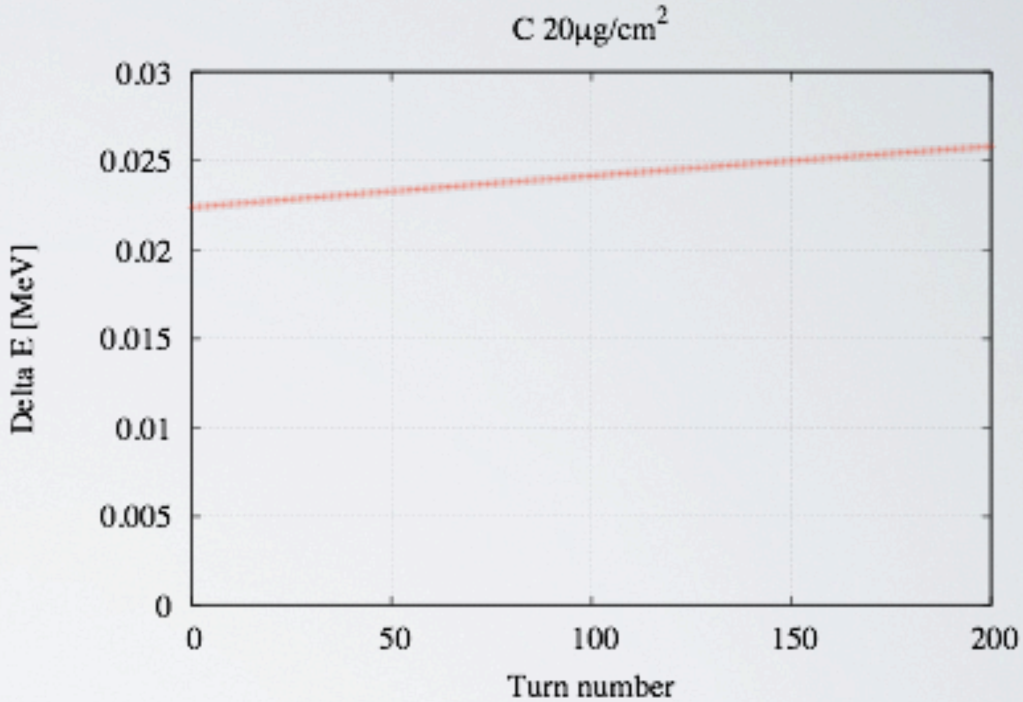
$$\frac{d\varepsilon_y}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_y + \frac{\beta_y E_s{}^2}{2\beta^3 m_p c^2 L_R E}$$

Emittance growth depend upon the β function at the foil position.

Emittance Blow up(2)

Foil thickness : 20 μg/cm^2

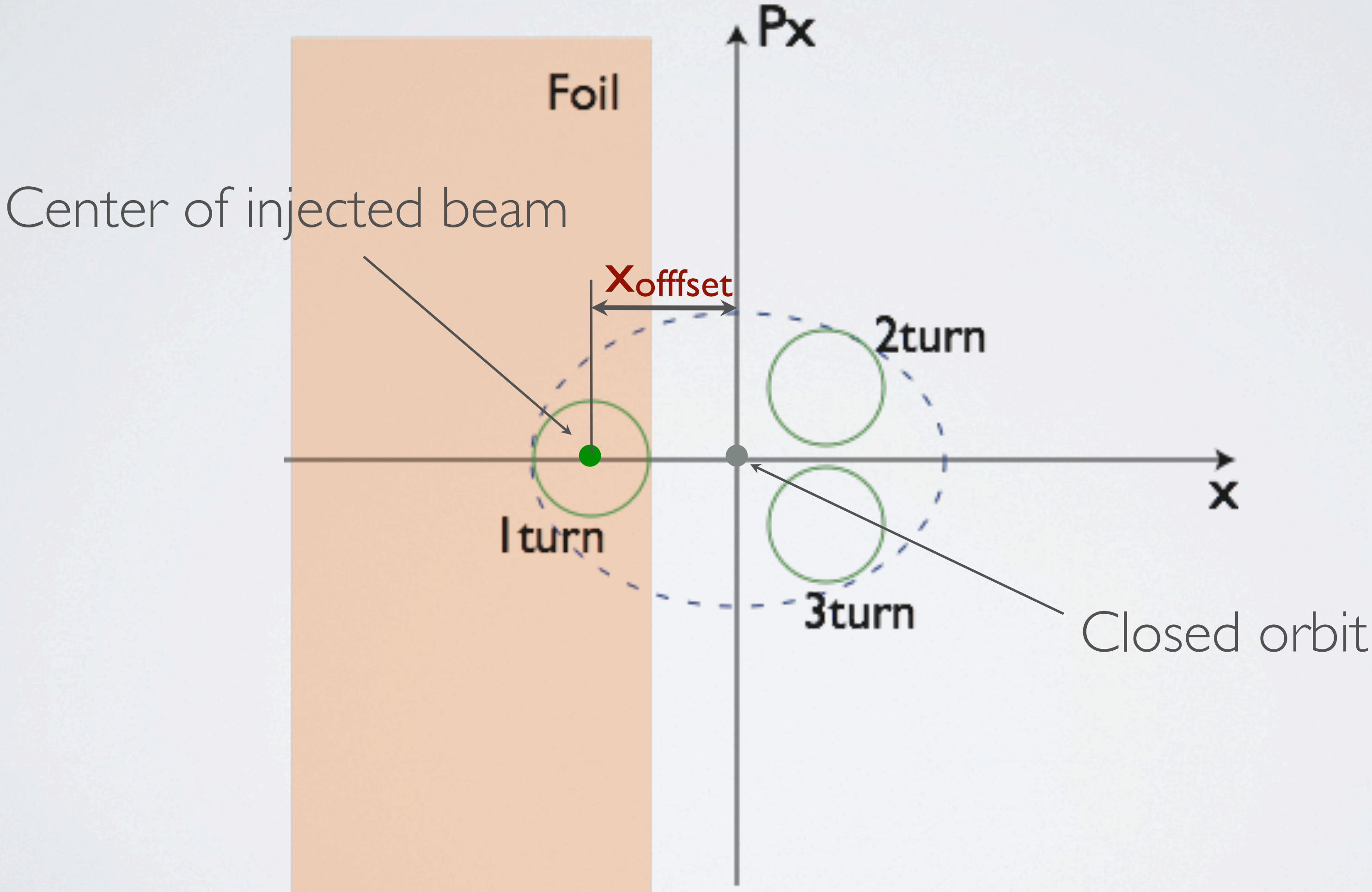




- disp. : 0.54[m]
- hori. beta : 3.31[m]@foil
- vert. beta : 2.50[m]@foil

Off-center Injection

Decrease the hitting probability

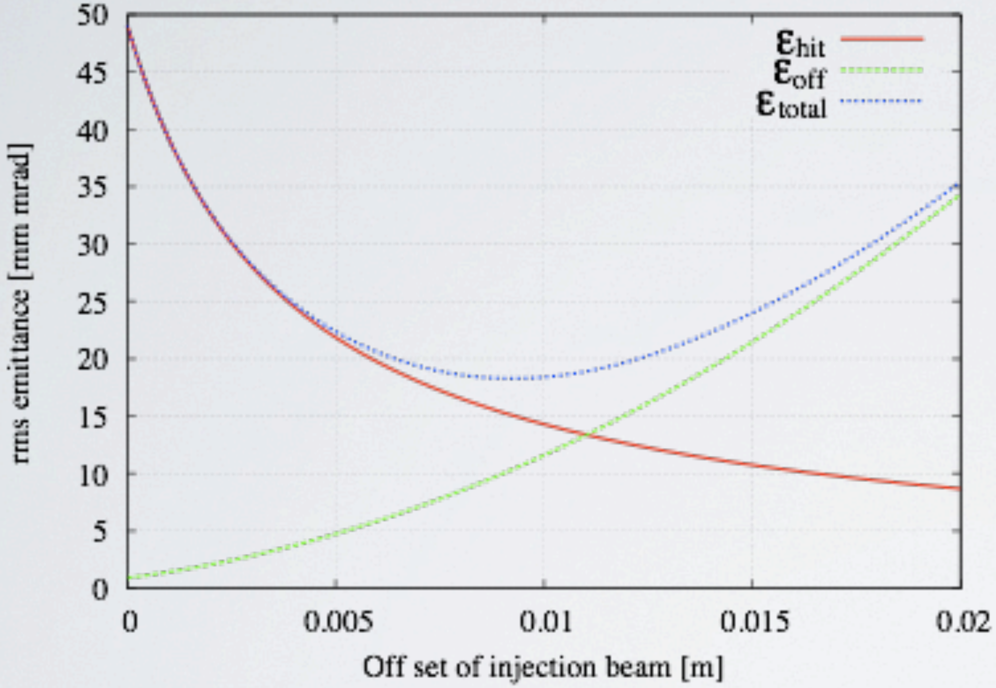


Horizontal emittance growth by injection miss-match must be taken account.

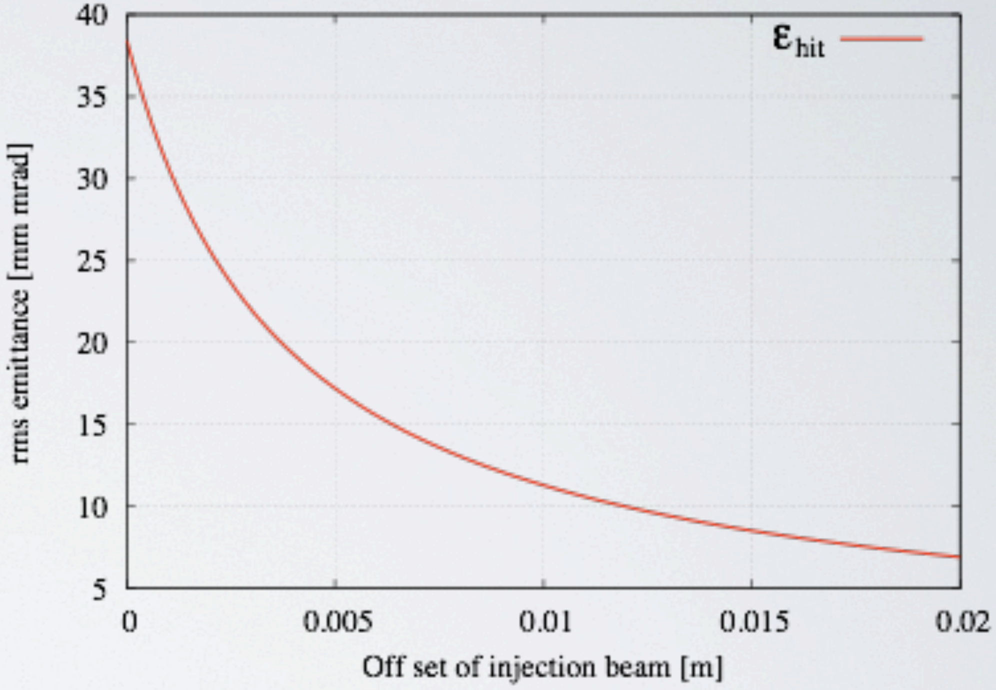
Emittance Blow up

After 160 turn

Horizontal



Vertical



off set ~9mm $(\varepsilon_{total}^2 \sim \varepsilon_{off}^2 + \varepsilon_{hit}^2)$

$\varepsilon_x \sim 18$ mm mrad
$2\sigma_x = 15.4$mm

$\varepsilon_y \sim 12$ mm mrad
$2\sigma_y = 11.0$mm

Turn Separation by RF acceleration

- Dispersion : 0.54[m]
- RF voltage : 2kV(4kV)
- Energy loss : 760eV (20 μg/cm²)

sync. phase = 23 deg@2kV(11deg@4kV)

	V_{rf} = 2kV				V_{rf} = 4kV	
acceleration phase[deg]	0	20	40	50	20	40
sync. phase[deg]	23	43	63	73	31	51
bucket height[keV]	120	75	33	17	146	81
energy gain[keV]	0	0.60	1.00	1.2	1.3	2.4
orbit shift / turn[mm]	**0**	**0.015**	**0.025**	**0.028**	**0.032**	**0.059**

Turn Number required for 10mm Shift

V_{rf} = 2kV(+23deg)

Acceleration phase[deg]	20	40	50
bucket height[keV]	75	33	17
turn number[mm]	**666**	**400**	**357**

V_{rf} = 4kV(+11deg)

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

Temperature of Stripping Foil

Pi(heating) = Po(radiation)

Energy loss ΔE: 800eV

Injection area S: 1cm^2

Pi(heating) = $\Delta E \cdot t \cdot I$

Po(radiation) = $\sigma \cdot S \cdot T^4$ (σ=5.67e-8)

Beam current(I) 1 μA

Pi(200turn) = 1e-6*800*200 = 16×10^{-2}W

T = 110 °C

Beam current (I) 10 μA

Pi(200turn) = 1e-6*800*200 = 16×10^{-1}W

T = 348°C

Foil life time(1 μA) ~ 8 hours×3 months

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 μA.(11 turn injection)
  - Maximum current is 15 μA 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 μg/cm^2
  - 10 μg/cm^2 foil is very fragile and hard to handling. 20 μg/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 mm・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.
- **Foil temperature and life time**
  - Beam current 1μA(10μA) : $T_{average}$ = 110 ℃ (348℃)
  - Foil life time (1μA) ～ 8 hours × 3 months

Problems to be solved

- Methods of orbit shift to escape the stripping foil (RF acceleration , Fast orbit bump)
- Precise design of injection beam line($\pi/2$ & π section steering magnets)
- Fabrication of carbon foil , Instruments and tools
- Energy variation
- Beam scraper to decrease residual radio activity