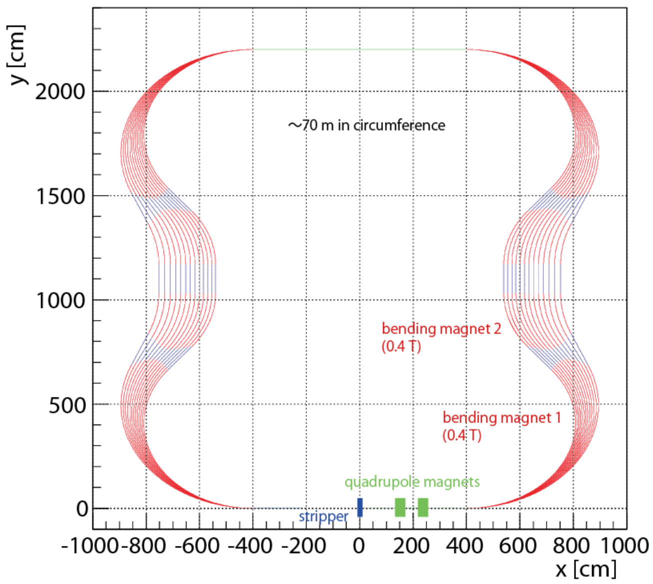
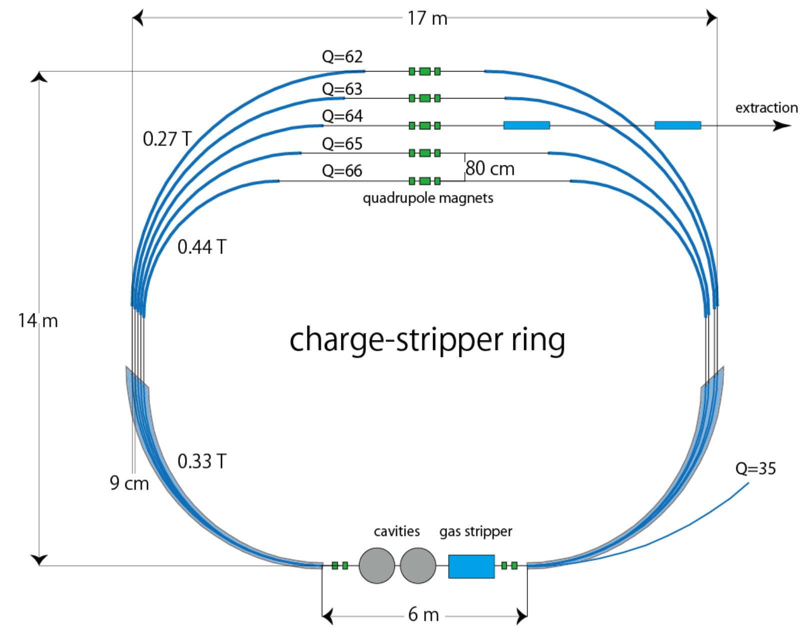
CHARGE STRIPPER RING FOR CYCLOTRON CASCADE





H. Imao, O. Kamigaito, H. Okuno, N. Fukunishi,

K. Suda, N. Sakamoto, K. Yamada, Y. Yano

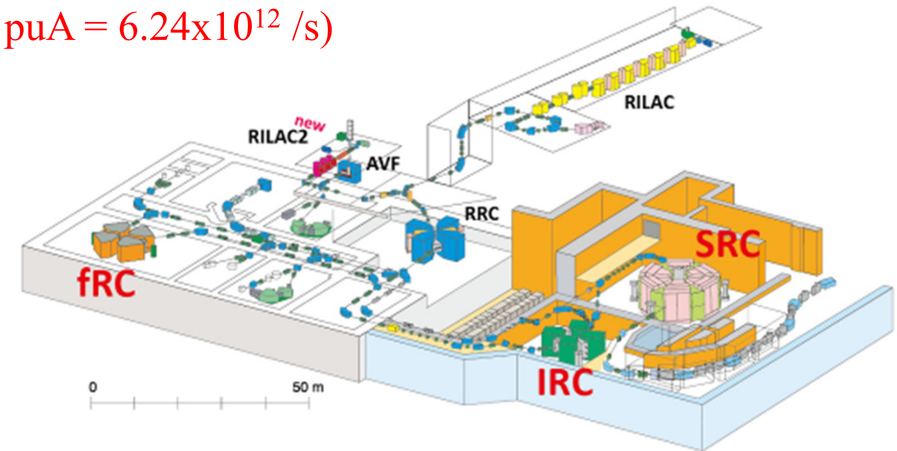
Intensity upgrade of U beams at RIBF

Riken RI Beam Factory (RIBF)

Cyclotron-based heavy-ion accelerator complex

Accelerate the whole mass range of heavy ions up to 350-400 MeV/u with a goal intensity of **1 puA**†

(† 1 puA = 6.24x10^{12} /s)

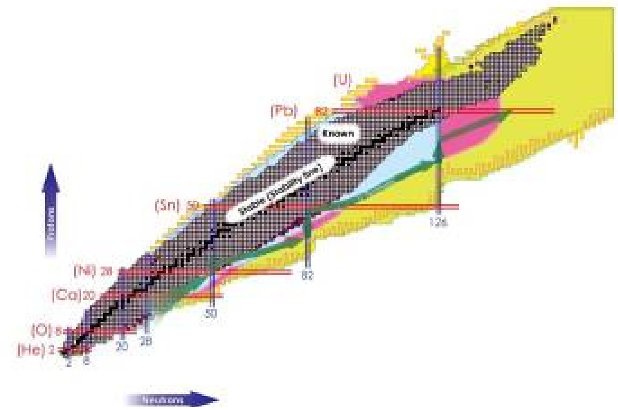


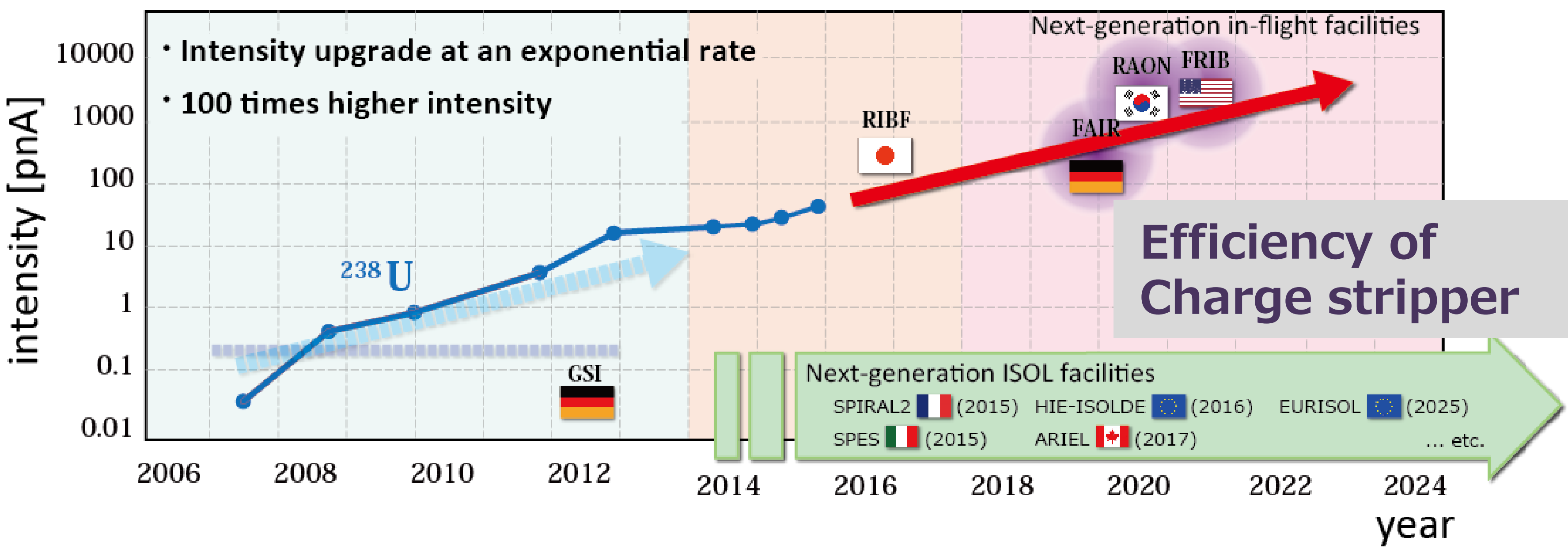
Upgrading of ^{238}U intensity

RI beams via in-flight fission

Expansion of nuclear chart

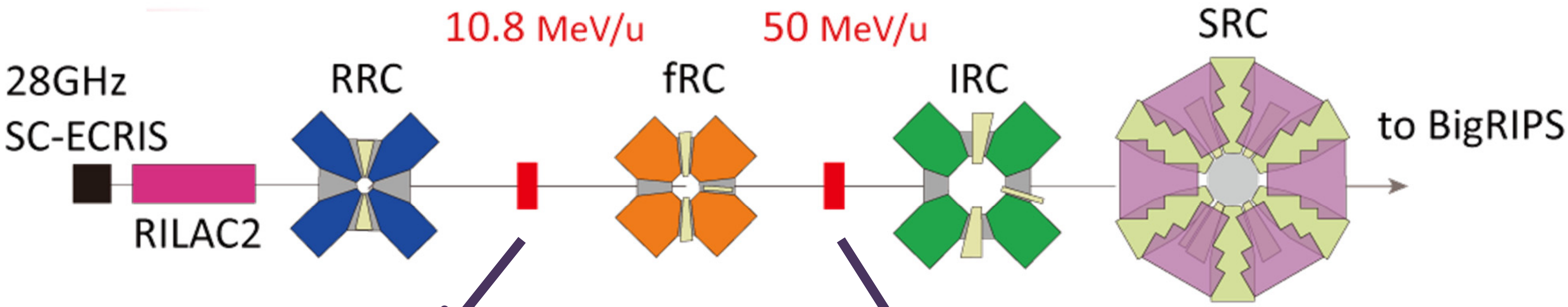
⇒**create a few thousands new RI**





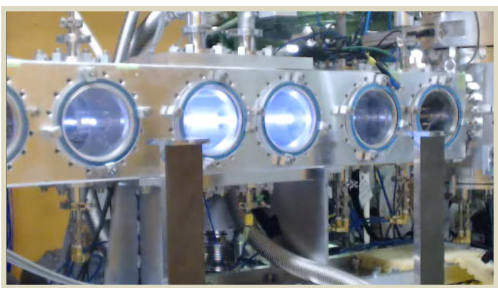
Efficiency of Charge stripper

Acceleration scheme of U



1． He gas stripper

35+⇒64+ (20%)

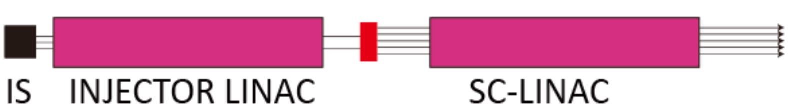


2． Rotating C-disk stripper

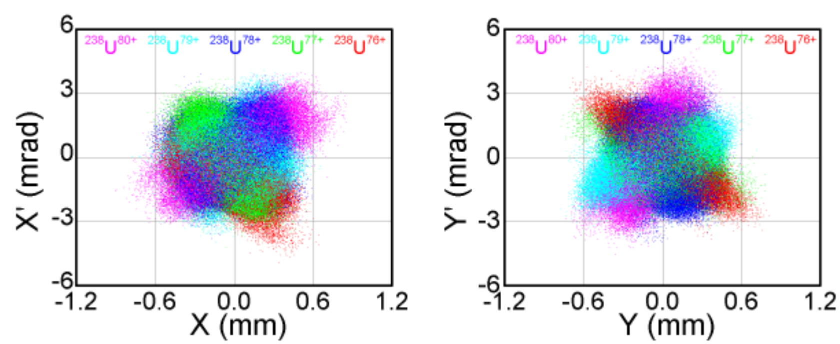
64+⇒86+ (30%)

Total charge conversion efficiency < **6%**

FRIB uses multi-charge acc.



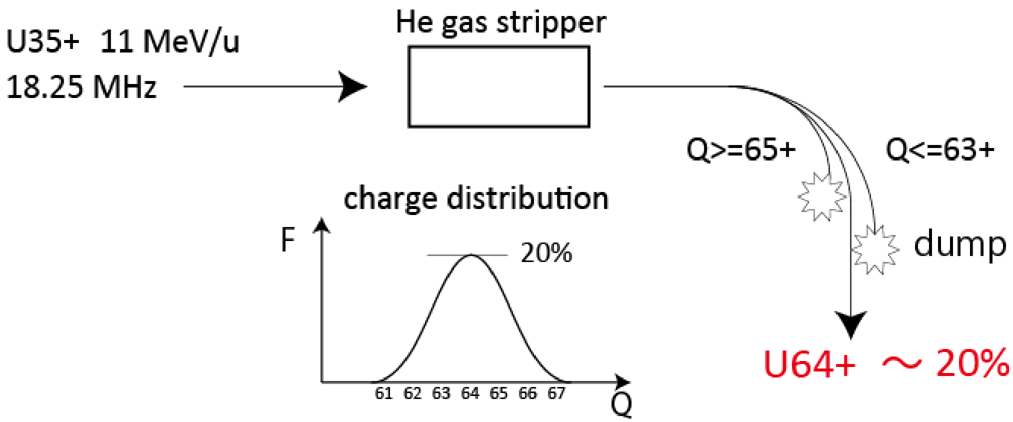
➡ 85% effectively



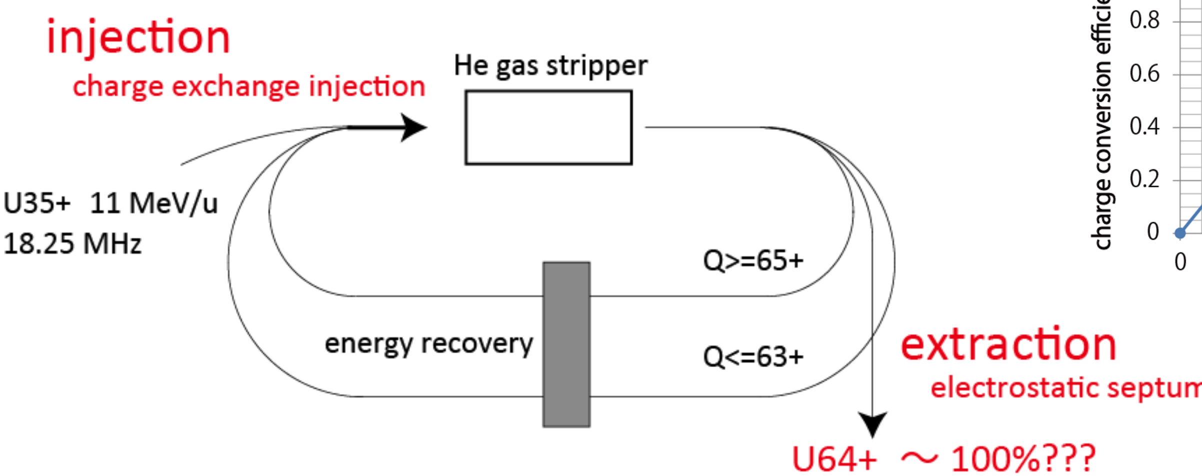
Q. Zhao, HB2014

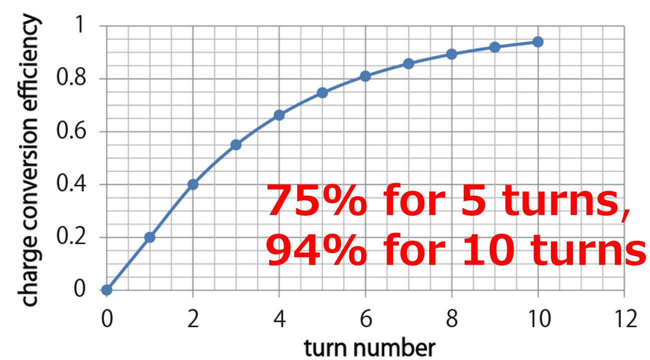
Concept of stripper ring

Present scheme at RIBF (conventional)



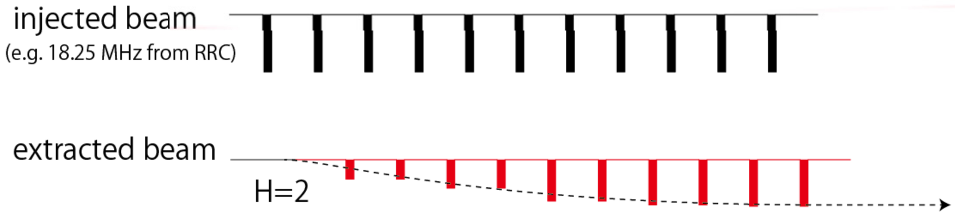
Stripper-ring scheme

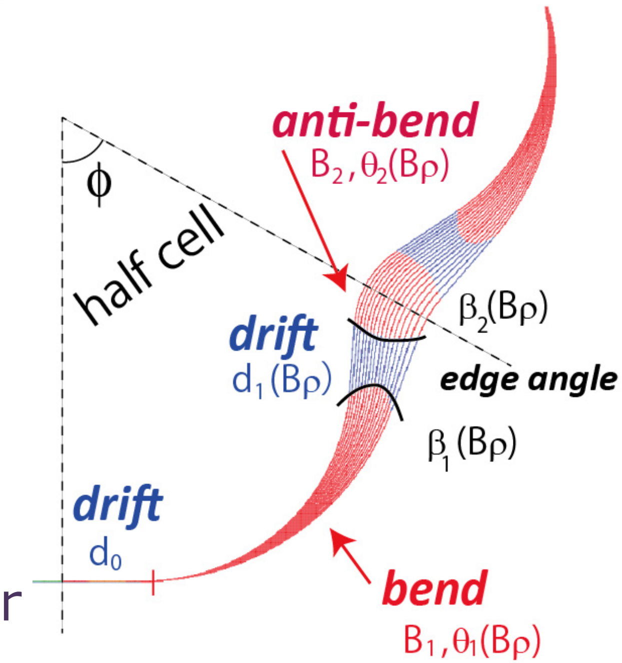




The **bunch structure must be preserved** to match to acceptance of the subsequent cyclotrons (e.g., 18.25 MHz at RIBF).

Isometric ring





To hold bunch structure;

Isometric ring to any magnetic rigidities

(**momentum compaction factor $\alpha=0$**)

Harmonics number H should be integer

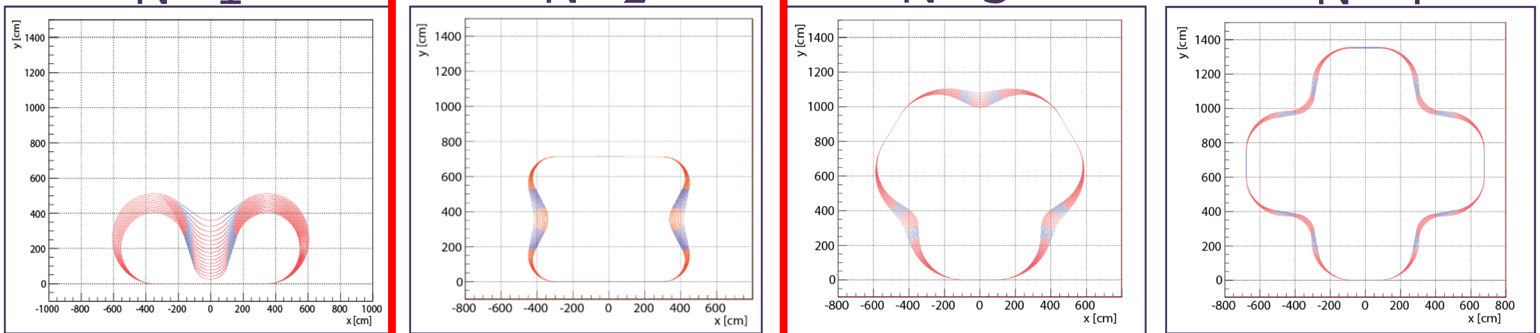
Conditions to be satisfied by half-cell;

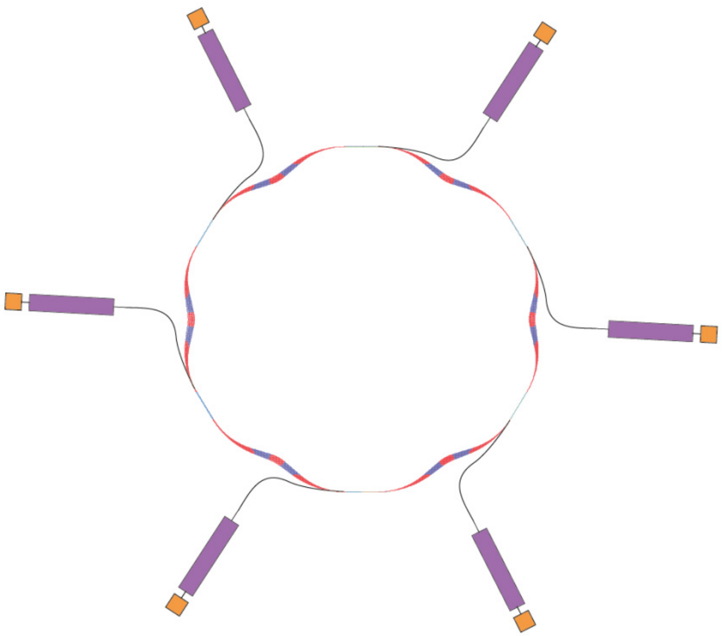
1. Deflection angles ($\phi=2\pi/2\mathbf{N}=\theta_1-\theta_2$) are constant with $B\rho$
2. Orbit lengths ($d_0+r_1\theta_1+d_1+r_2\theta_2$) are constant with $B\rho$
3. Endpoints of the orbits are collinear for all $B\rho$

The **edge angles of dipoles** are automatically determined

Number of symmetry

N=1 N=2 N=3 N=4





N=6

➡ **6 injectors acceptable**

Beam accumulation keeping bunch structure and beam energy

This kind of ring have some applications

Procedure for lattice design

Beam parameters

$q_c = 64+$

$E = 10.8$ MeV/u

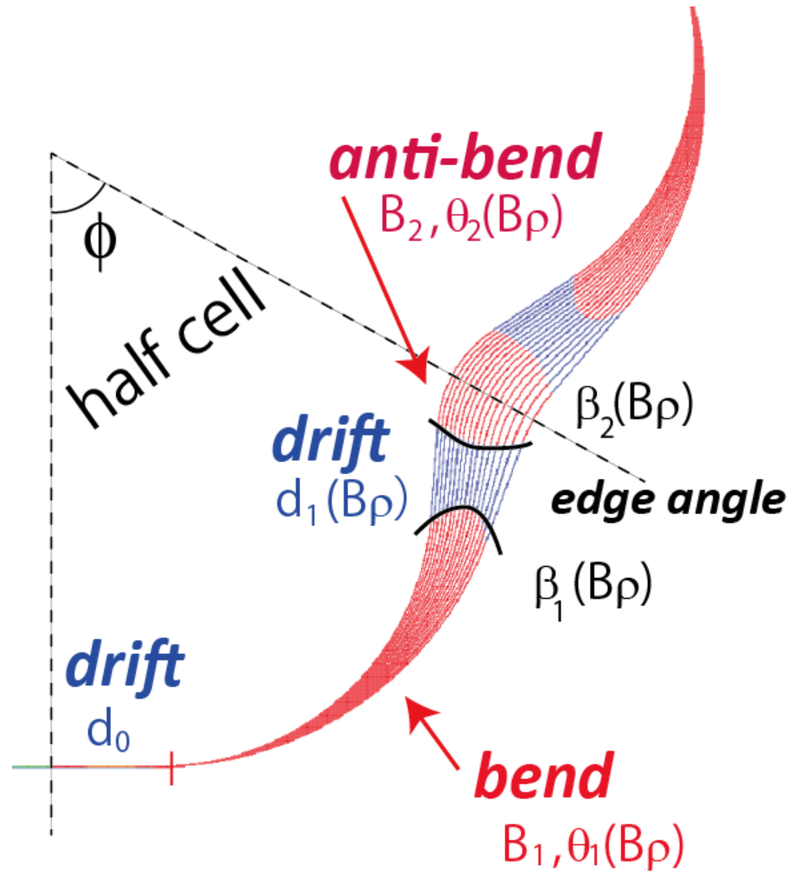
Input parameters

N= 2	symmetry
d_0	drift length
B_1, B_2	magnetic field
$\theta_1(B\rho)_0$	deflection angle for q_c

↓

Calculated parameters

$\theta_1(q)$, $\theta_2(q)$	deflection angle
$d_1(q)$	drift length
$\beta_1(q)$, $\beta_2(q)$	edge angle



↓

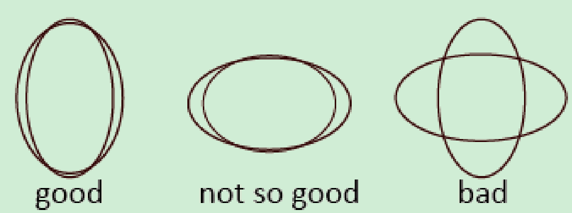
1st-order transfer matrix M(q)

$|\mathrm{Tr}\, M(q)| < 2$

eigen-ellipse (x-x′, y-y′)

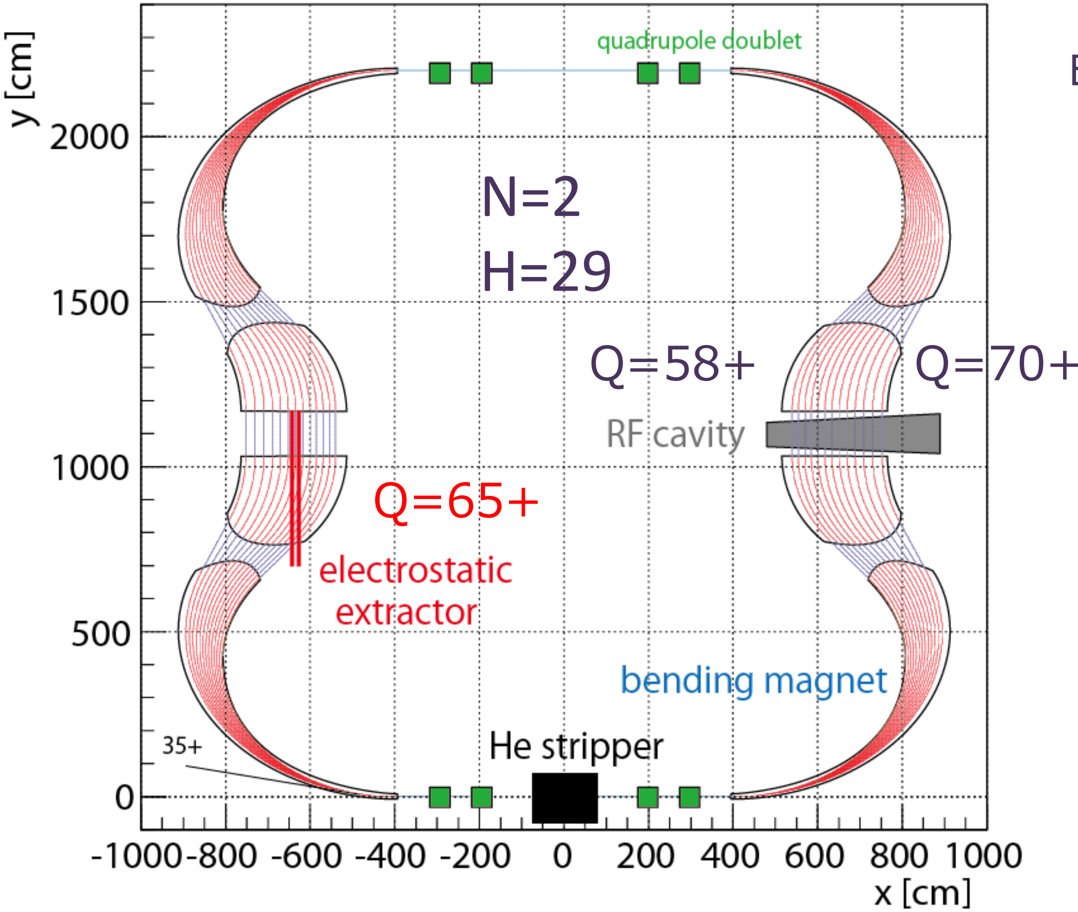
Well overlap

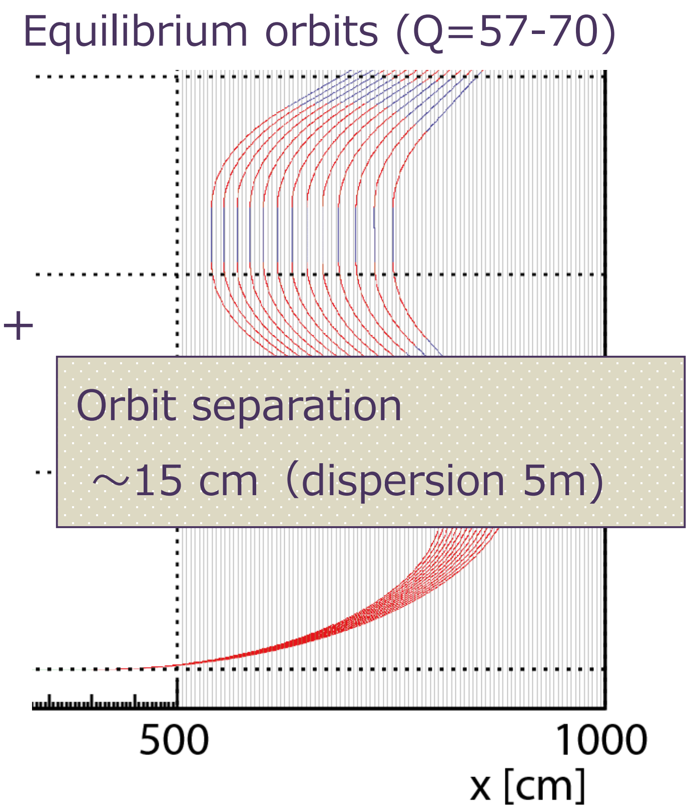
Vertically long



Demonstration of lattice design

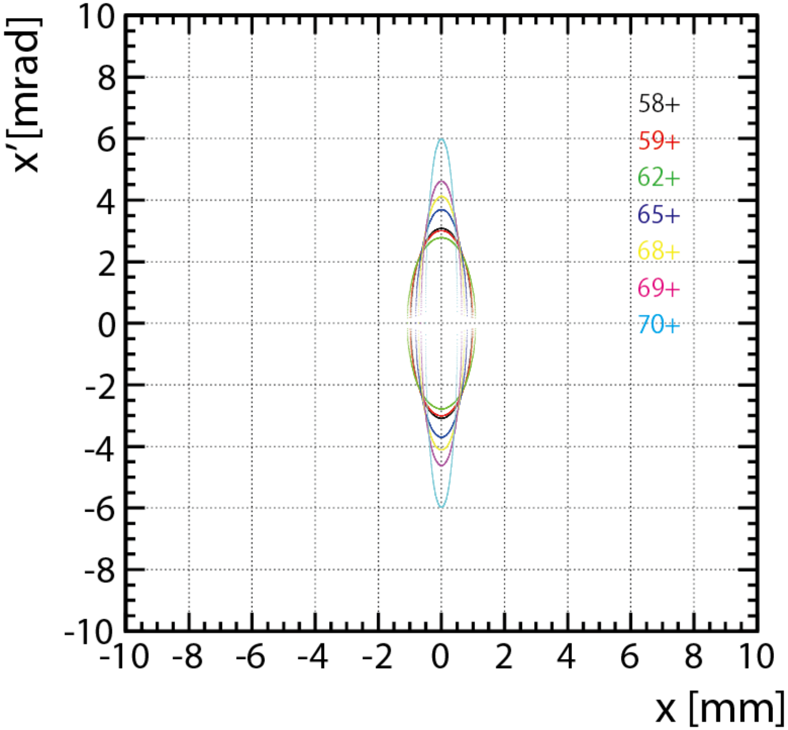
Optimized lattice for the first stripper at the RIBF

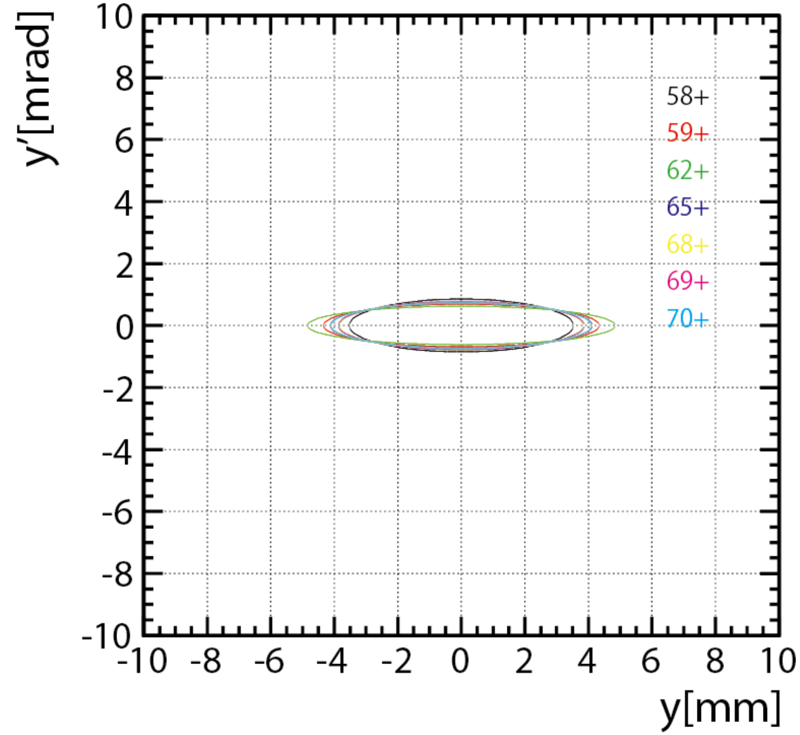


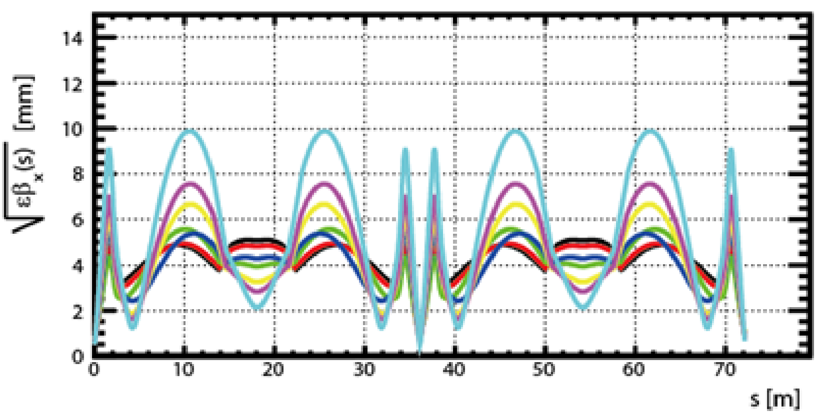


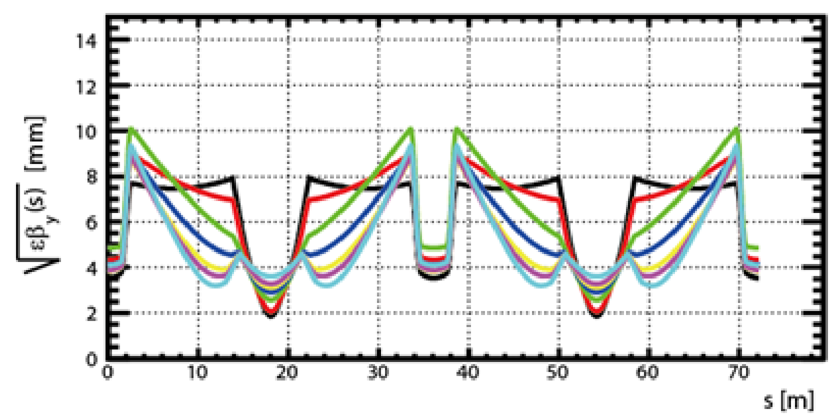
- Acceptable charge state 58-70+
- Magnetic field of 0.4 T, ～20 m square
- Orbit separation 15 cm

Eigen-ellipse and beam envelope

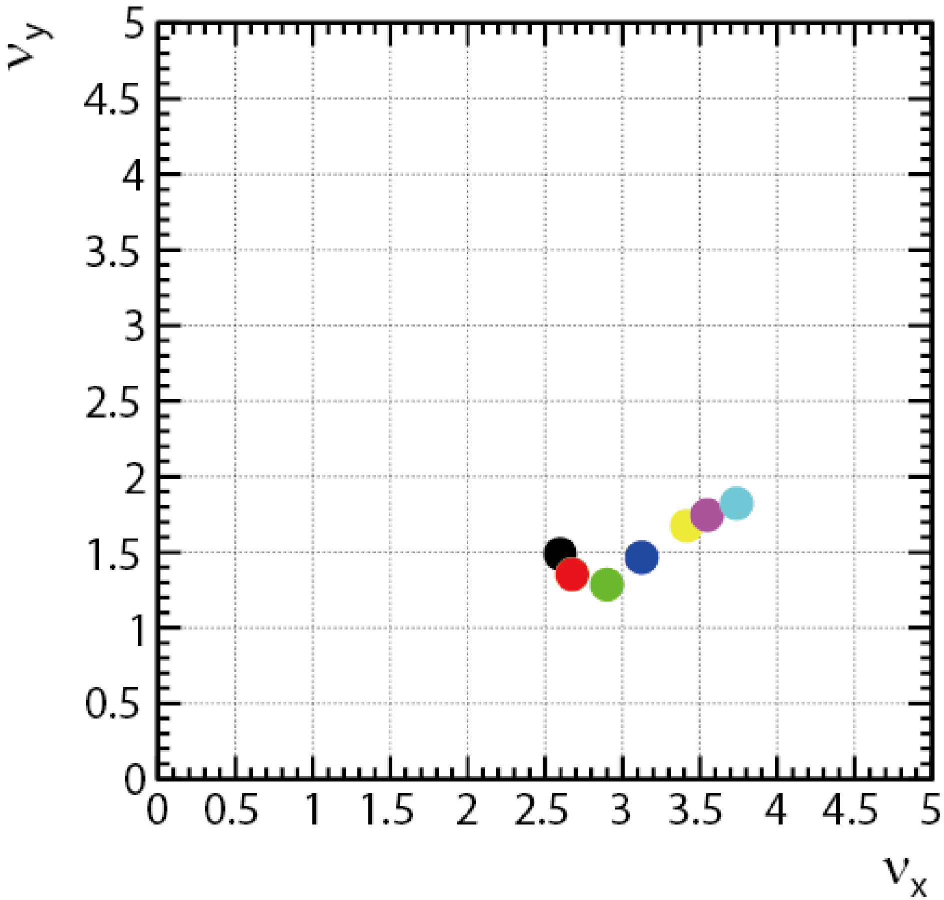








Tune diagram



Tunes also depend on the charge states

The resonance would not be problematic

- charge state is not always constant
- mean turn number is not high

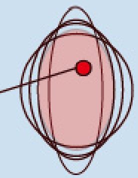
Calculation of transverse motion with the stripper

Parameters for a particle

$q_{init} = 35+$

$E_{init} = 10.8$ [MeV/u]

$(x, x')_{init}$ & $(y, y')_{init}$



Given randomly on the initial ellipse match to **the common area** of eigen ellipses

↓

Monte-Carlo calculation of the stripper

$q = q + dq$

$E = E - dE$

$x' = x' + \text{ang. strag.}$

$y' = y + \text{ang. strag.}$

↓

Energy recovery

GAIN = q*0.8 [MV]

→ IF q=65

Extraction and data aqcuisition (→ back to Parameters for a particle)

↓ IF q≠65

Transport

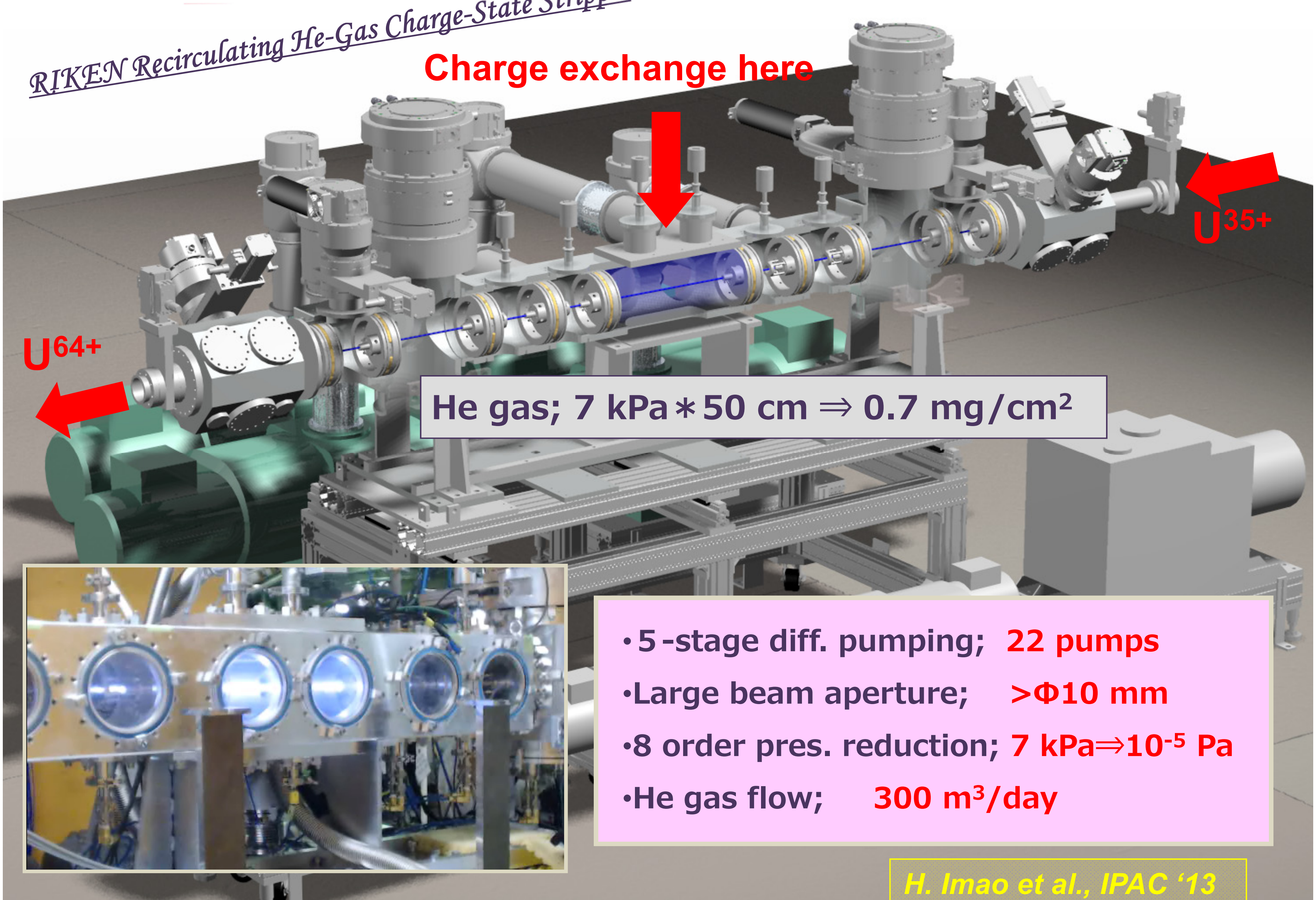
calculate M(q,E)

$X' = M(q,E)X$

(→ back to Monte-Carlo calculation of the stripper)

1st order calculation particle by particle

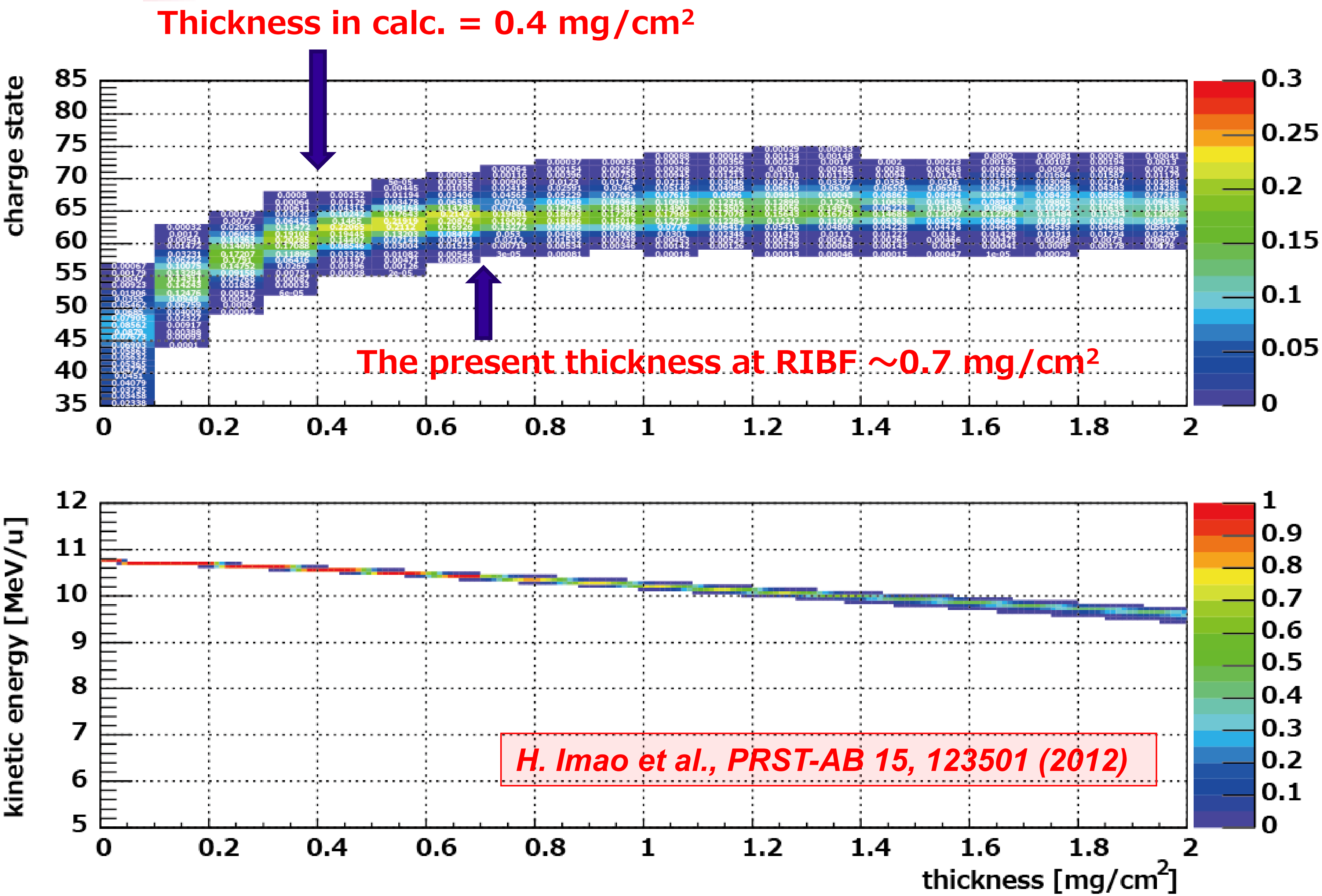
He gas stripper at RIBF



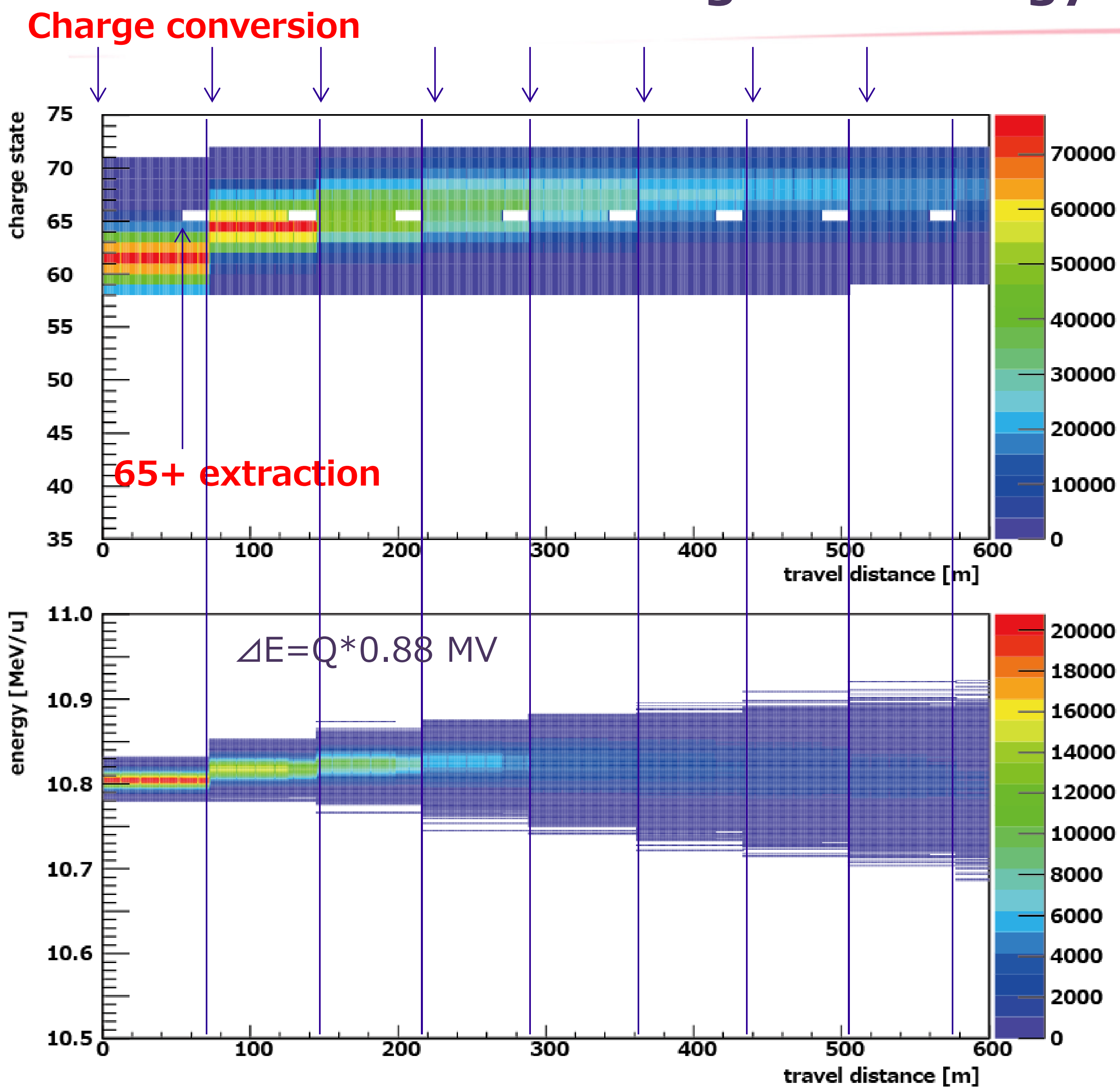
- 5-stage diff. pumping; **22 pumps**
- Large beam aperture; **>Φ10 mm**
- 8 order pres. reduction; **7 kPa⇒10^{-5} Pa**
- He gas flow; **300 m³/day**

H. Imao et al., IPAC '13

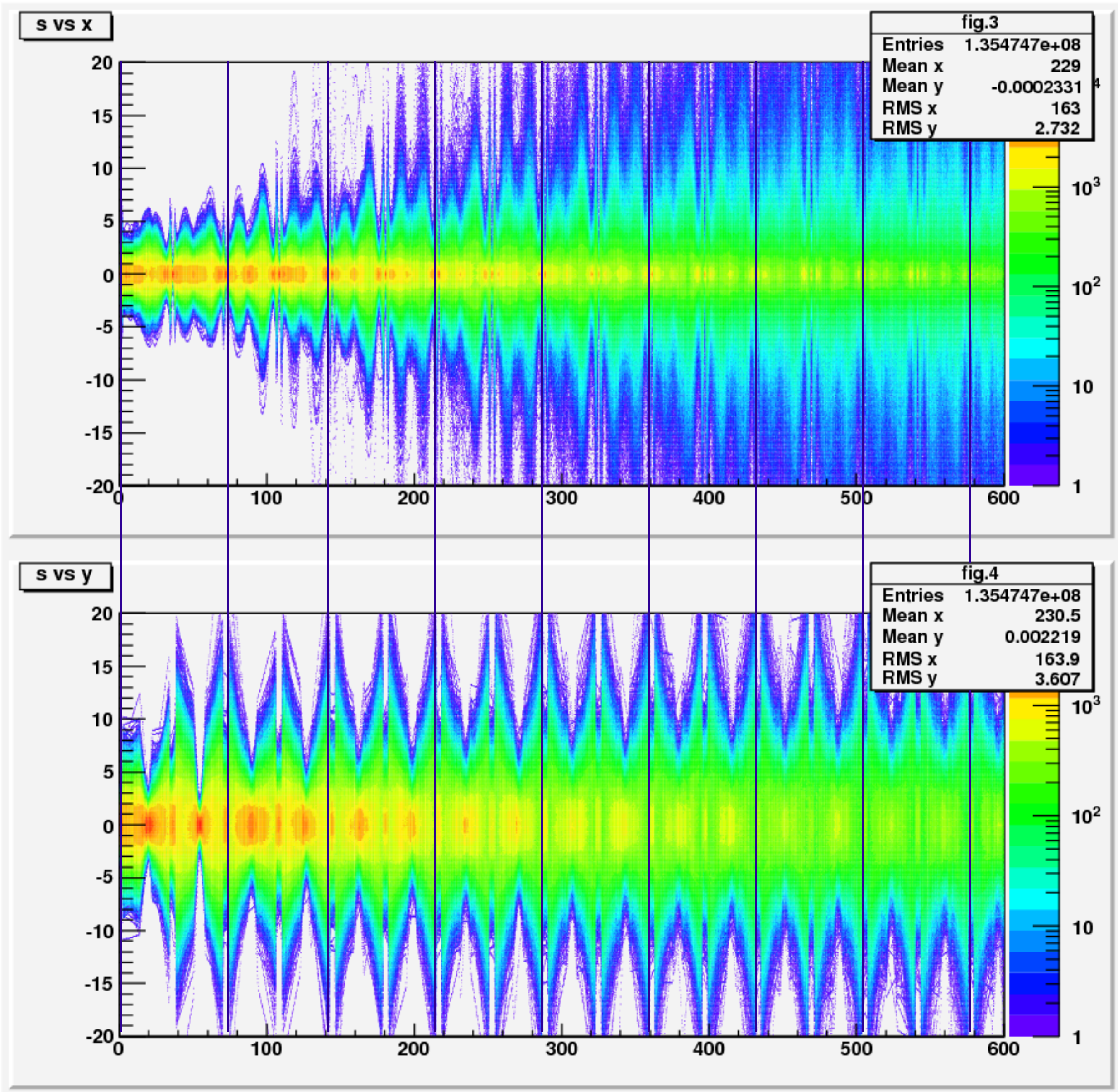
Charge evolution and energy degradation in He gas



Charge and energy evolution

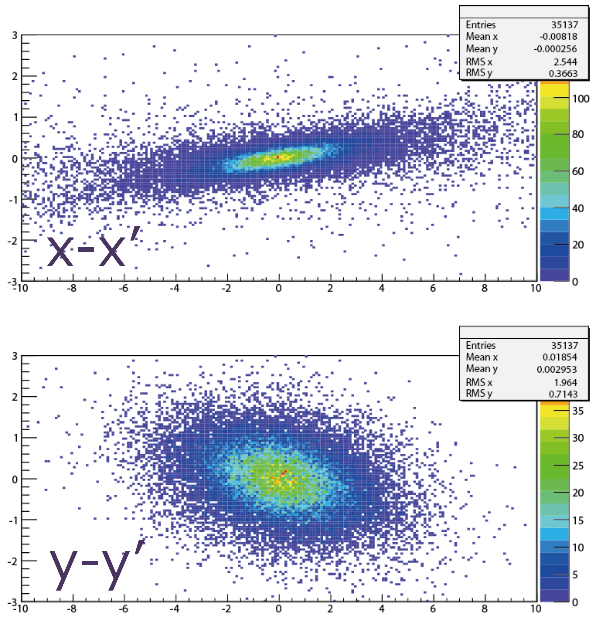


Plots of particles for transverse directions

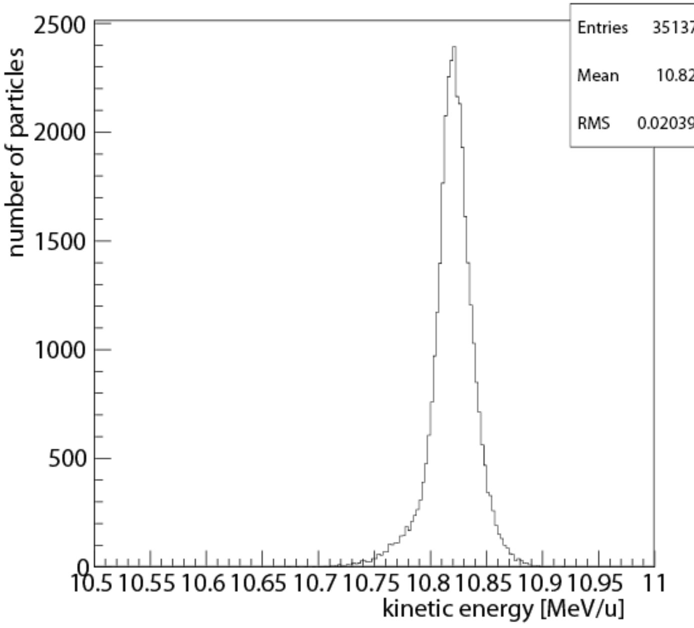


Extracted beams

Beam ellipse



Energy distribution



- 65+ are extracted with the **efficiency of 72%**

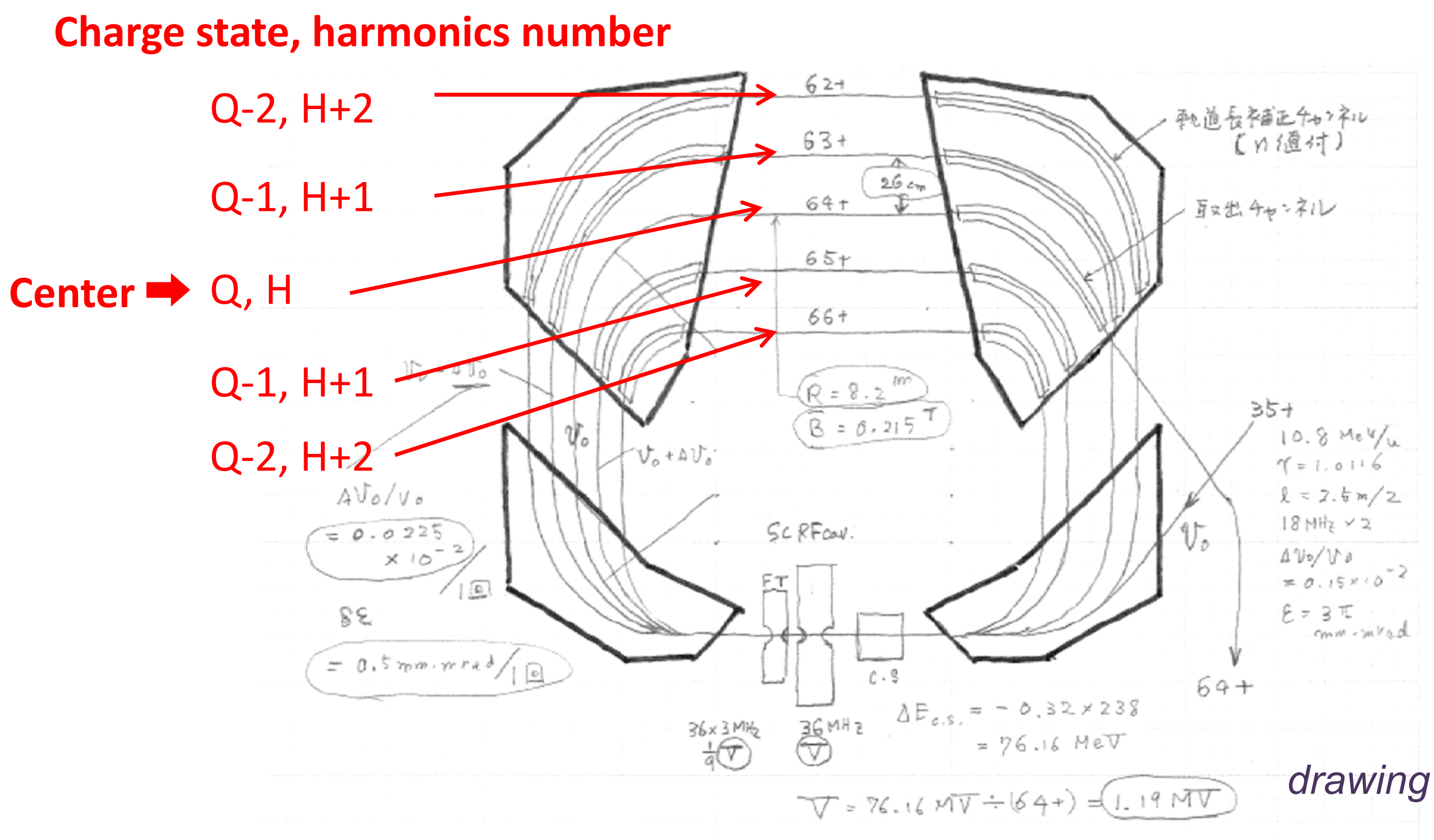
  (phys ap (>10 cm). 9%, charge(59-71) 14%, pass 5%)

- Emittance growth for transverse= x3 of the present stripper
- The energy width = x1.5 of the present stripper

Further optimization are required, but good as 1st calc.

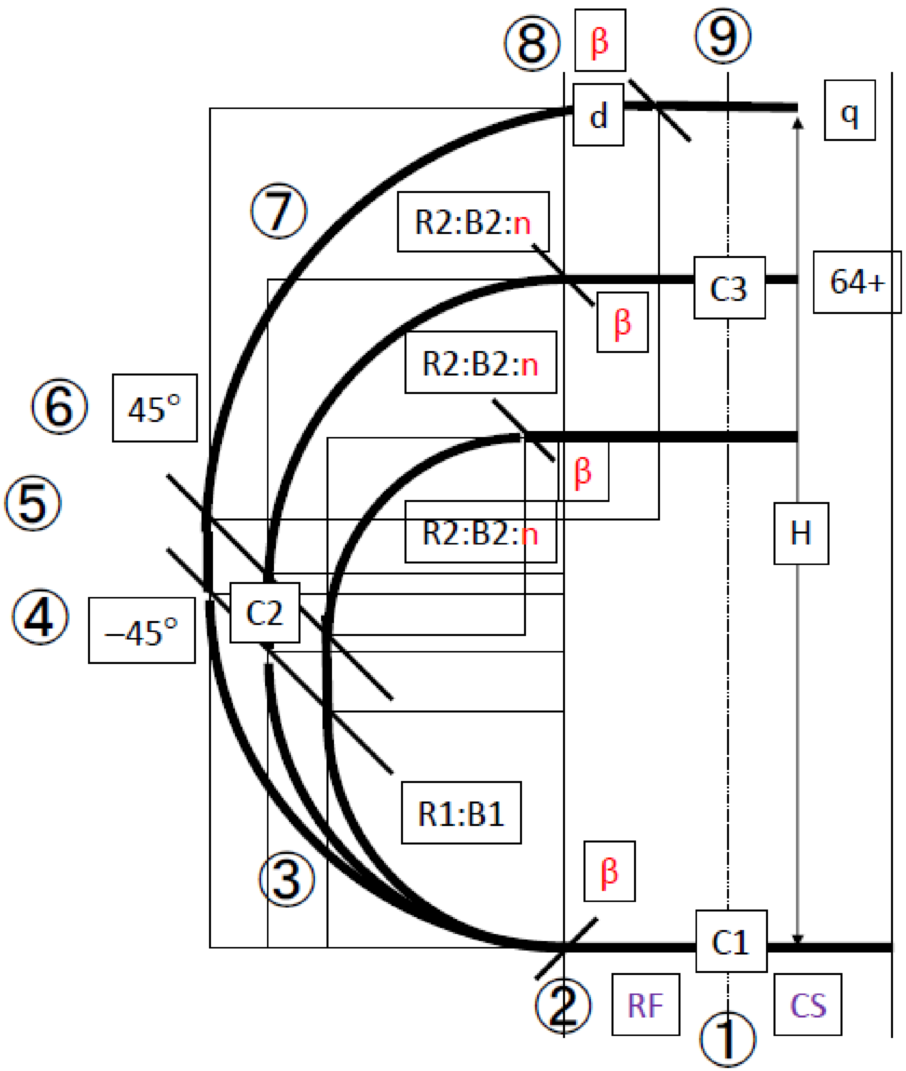
Orbit-difference adjusting ring

- The orbit difference by *q* is adjusted to match to the bunch spacing (harmonics number depends on *q*)
- Large orbit separation ➡ independent components
  easy extraction



drawing by Yano-san

Fundamental parameters for equilibrium orbit



$\mathrm{E} = 10.8\ MeV/u$ $\quad f = 36.5\ MHz$

$L = 1.25\ m$

Input parameters

$\mathrm{C}(q_0) = L \cdot h \qquad \mathrm{C}(q) = C(q_0) + L(q_0 - q)$

$$r_1(q_0) = \frac{C - 2(C_1 + C_2)}{2\pi} \qquad B_1 = \frac{P}{q_0 r_1}$$

$$r_1(q) = \frac{P}{qB_1}$$

$$r_2(q_0) = \frac{\frac{C(q)}{2} - C_1 - C_2 - (\frac{\pi}{2} + 1)r_1(q)}{(\frac{\pi}{2} - 1)}$$

$$B_2(q) = \frac{P}{qr_2(q)}$$

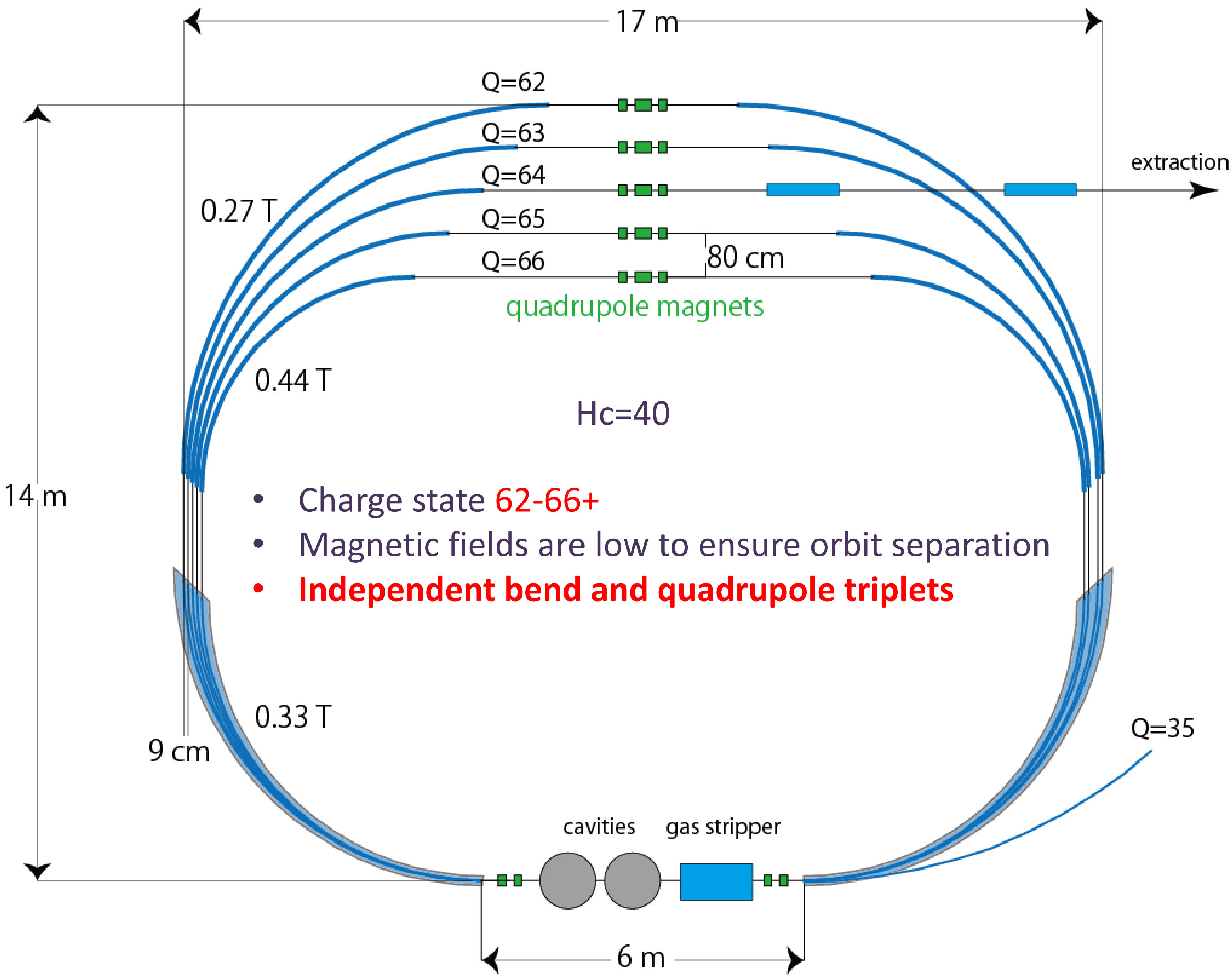
$$C_3(q) = \frac{C_1}{2} + r_1(q) - r_2(q)$$

$$H = r_1(q) + r_2(q) + C_2$$

$$d(q) = \frac{C_1}{2} - C_3$$

lattice parameters

Optimized lattice for the first stripper

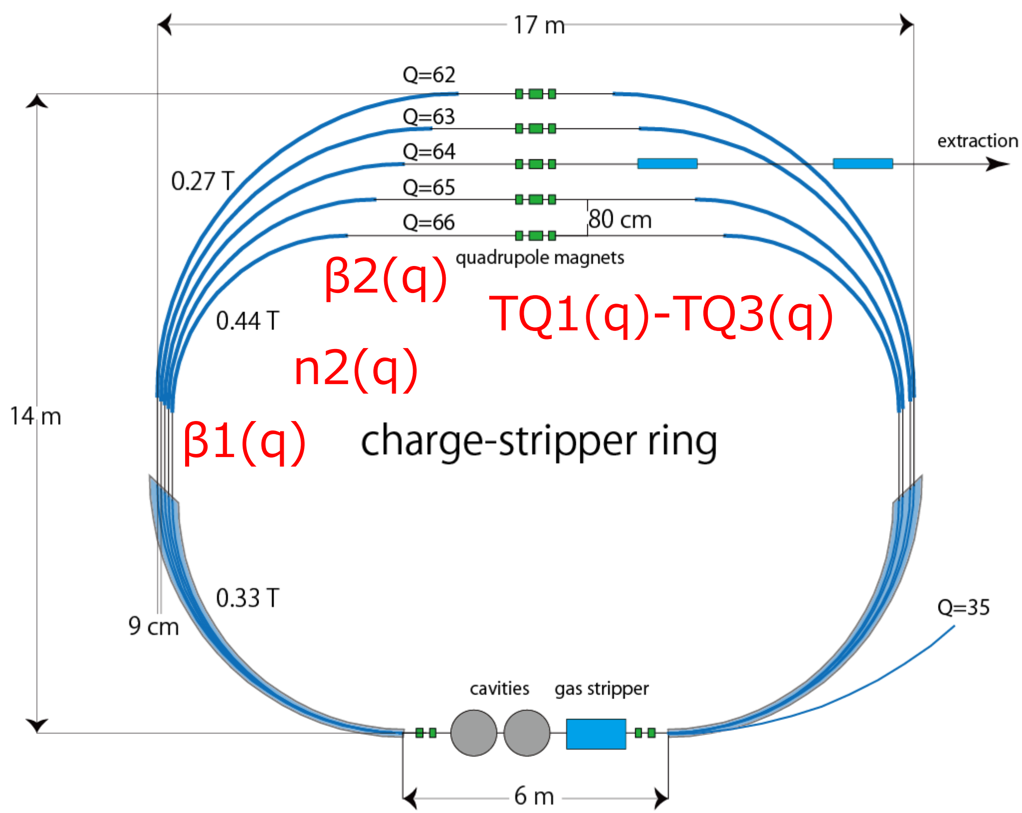


- Charge state 62-66+
- Magnetic fields are low to ensure orbit separation
- **Independent bend and quadrupole triplets**

Lattice design

- Vertically long eigen ellipses to reduce angular straggling
- Amplitude of betatron functions and dispersion should be tolerable within realistic apertures
- Achromat conditions ($R_{16}=R_{26}=0$)
- Eigen ellipses for all *q* should be **nearly uniform**

6 free parameters for each q are used

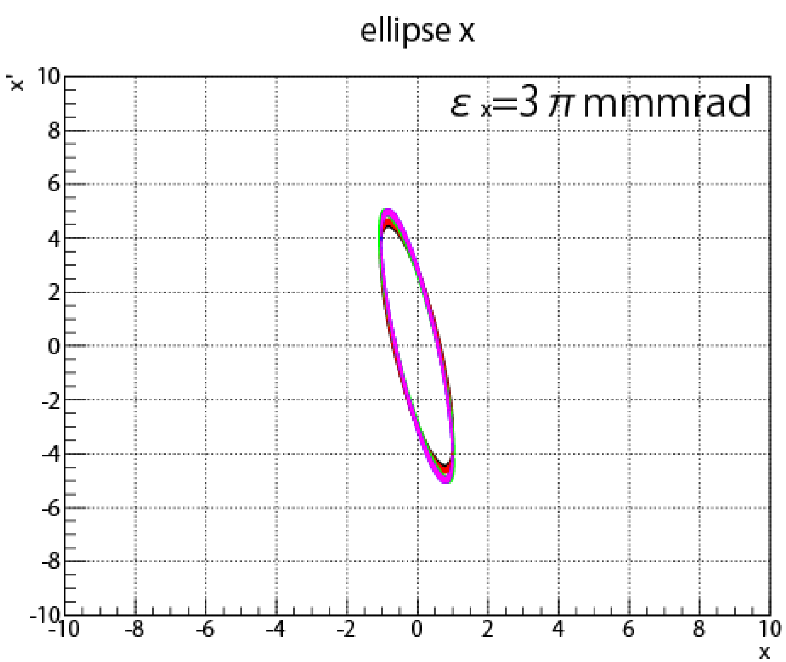


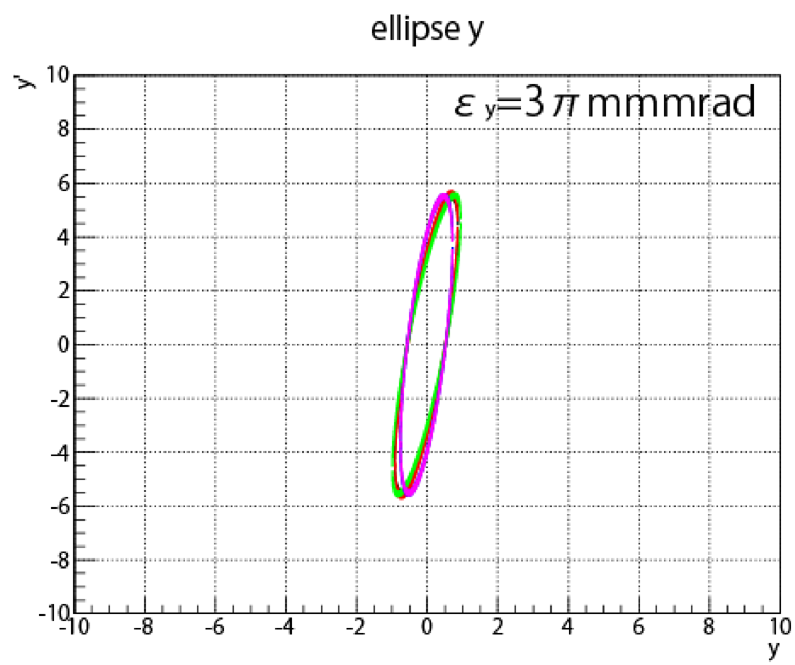
Parameter optimization

q	62	63	64	65	66
C1 [m]			6.00		
C2 [m]			2.00		
TQ1(q) [T/m]	-0.76	-0.19	5.11	1.73	4.90
TQ2(q) [T/m]	-1.19	-1.28	-3.22	4.78	0.60
TQ3(q) [T/m]	3.52	3.31	3.47	-9.81	-2.66
DQ1 [T/m]			18.23		
DQ2 [T/m]			-18.00		
DQ3 [T/m]			-17.78		
DQ4 [T/m]			17.19		
n1			-0.10		
n2(q)	-0.10	-0.10	-0.10	-0.10	-0.10
β1 [°]			-34.33		
β2 [°]			-45.00		
β1(q) [°]	-43.54	-43.54	-43.54	-43.54	-43.54
β2(q) [°]	27.58	29.49	43.54	11.72	42.36

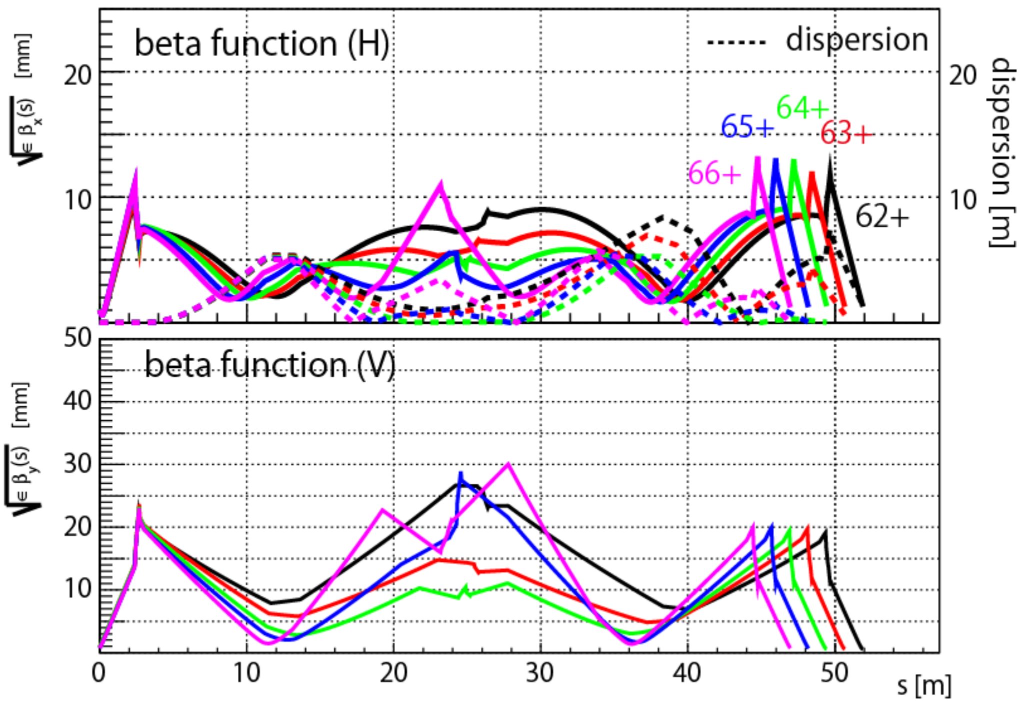
Minimization program (**MINUIT** of CERN library) was used for the optimizations of the parameters

Optimized eigen ellipses for all *q* could be **almost uniform** with 6 fitting parameters





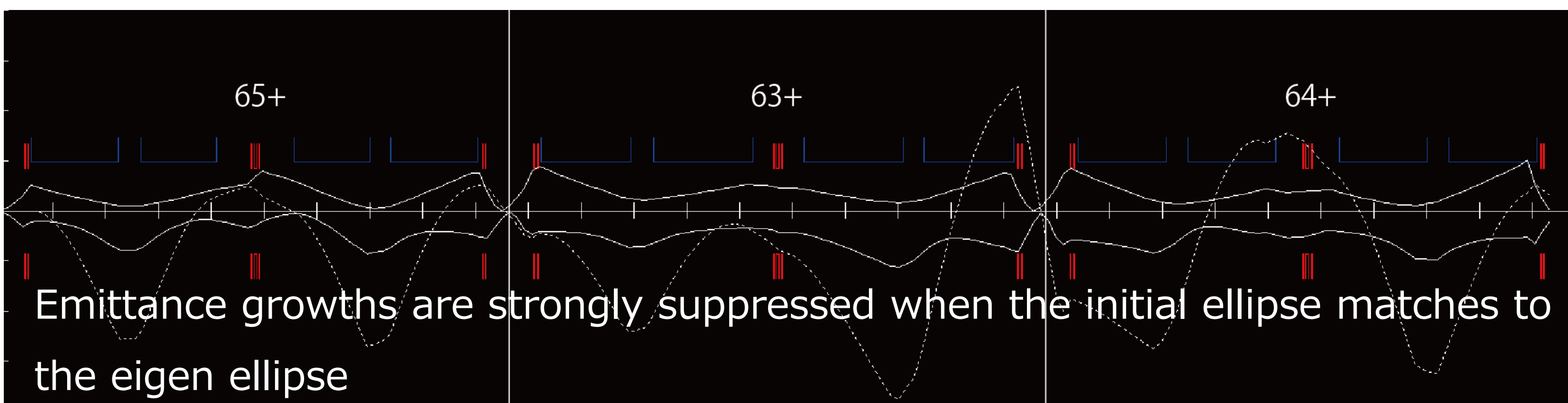
Beam envelope



⇦Beta functions and dispersion in the ring

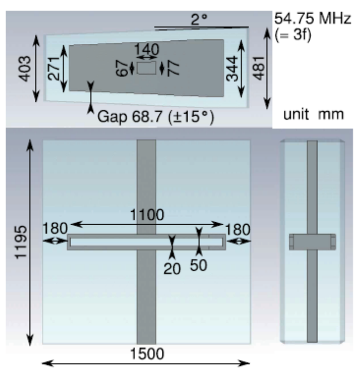
Beam envelopes when the charge state is changed as 65+➡63+ ➡ 64+ with TRANSPORT code

⇩

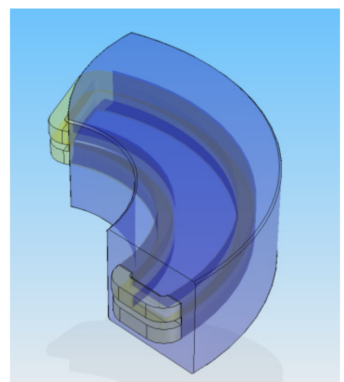


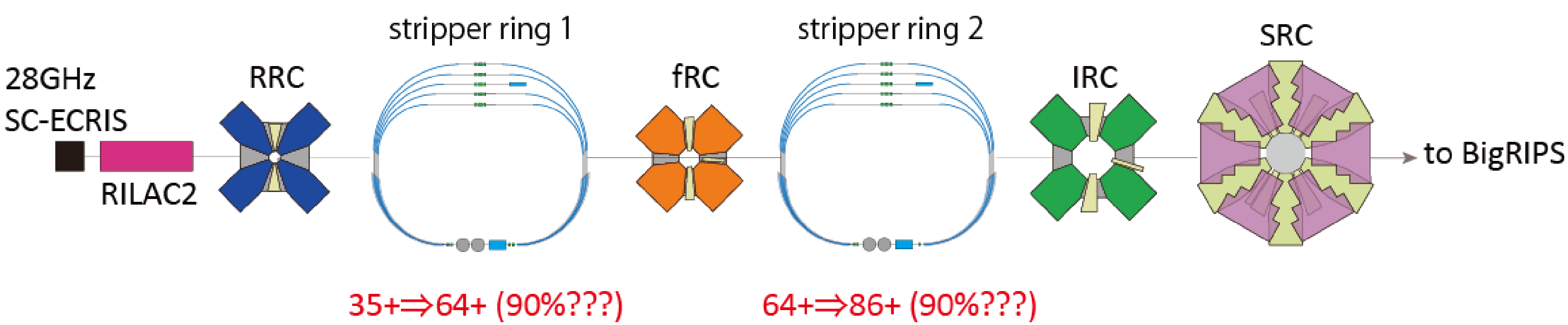
Summary and future prospects

- Two types of high-efficient charge stripper rings are proposed.
- Calculation methods for the lattice design are developed and demonstrated.
- Further optimization of lattice design and also engineering design are undergoing.
- Other applications, such as the storage ring or cooler ring, are also under consideration.



K. Suda et al. RIKEN acc. report

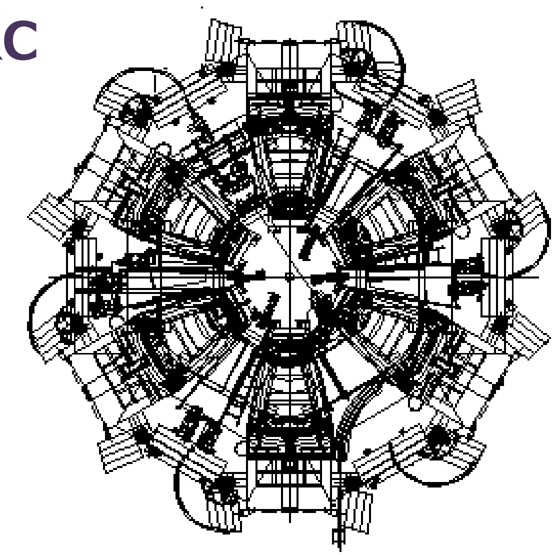




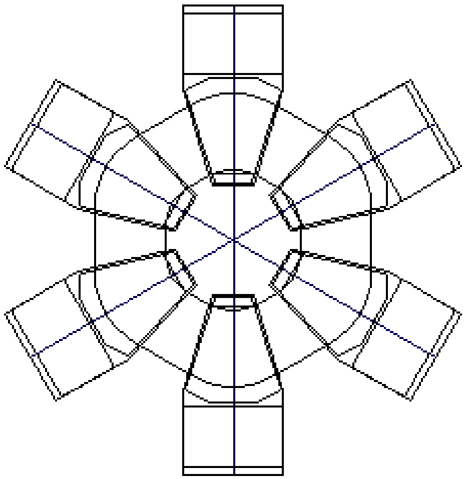
Cyclotron for 35+ acceleration

	常伝導New-fRC	SRC
K値	2230 MeV	2600 MeV
周波数	36.5 MHz	18-42 MHz
入射半径	2.76 m	3.56 m
取出し 半径	5.67 m	5.36 m
速度ゲイン	2.1	1.5
直径	19 m	18.4 m
高さ	6.6 m	7.7 m
重量	6400 t	8100 t
最大磁場	2.1 T	3.8 T
起磁力	0.175 MAT/sector	4 MAT/sector
セクター数	6	6
セクター角	34°	25°
最大電流	1460 A	5000 A

SRC



New-fRC (same scale)

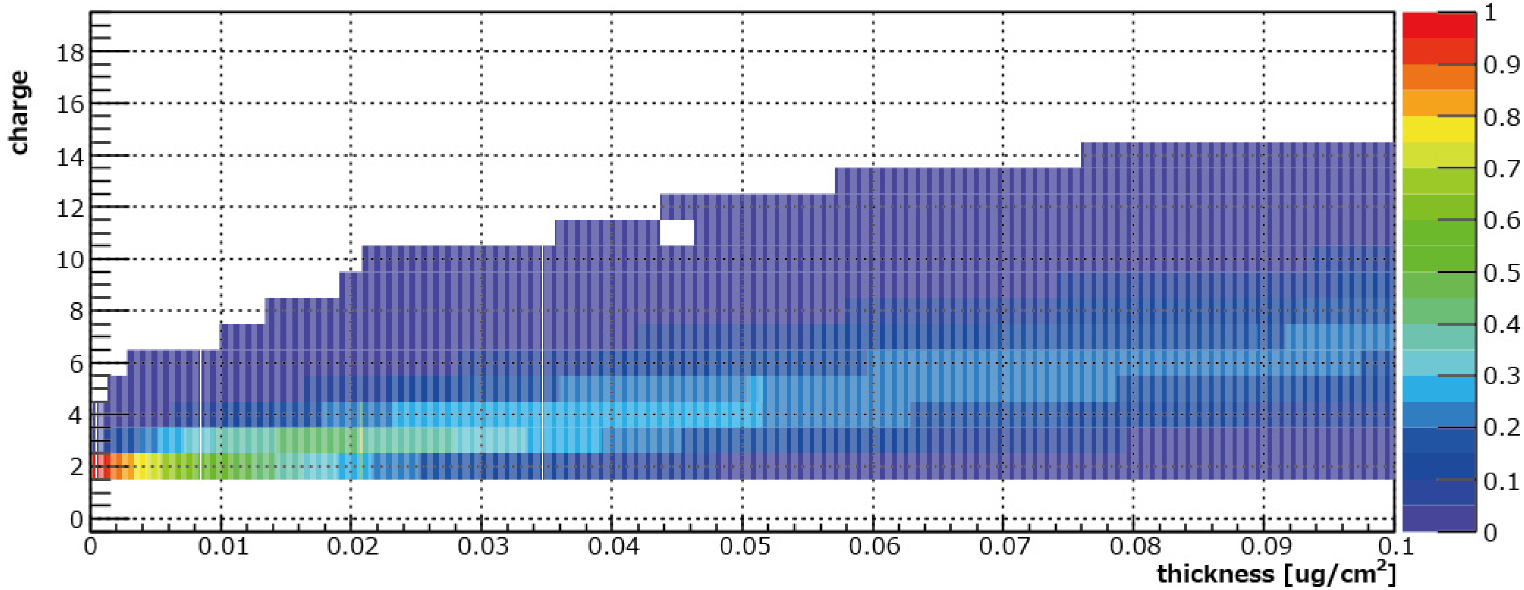


Largest cyclotron in the world ???

Sure way, but further optimization is required

Cooler ring or accumulation ring

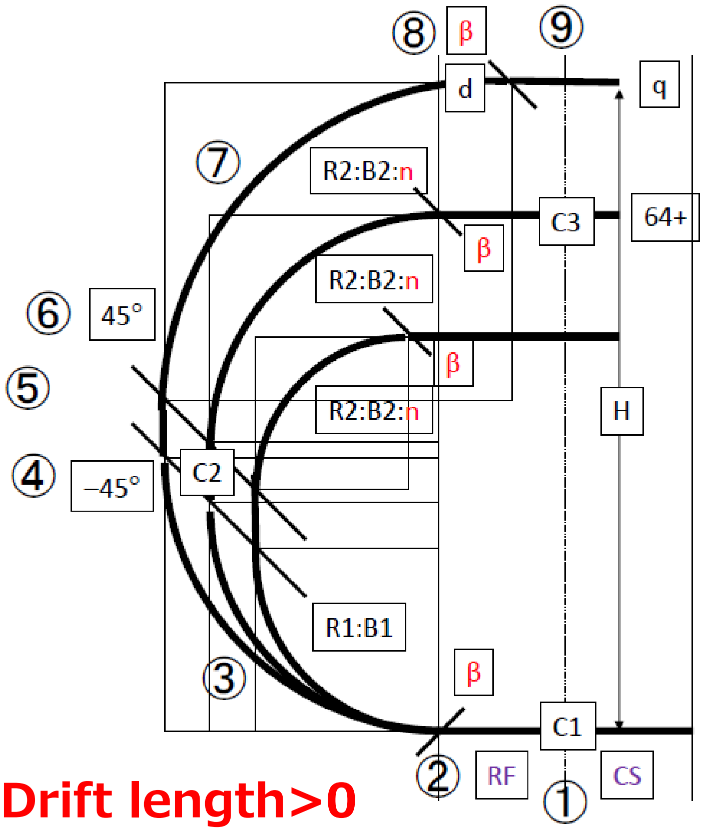
1. Thin stripper with some cooling method（ionization cooling & stochastic cooling）
2. Plasma stripper or gas jet stripper



U2+ w/ He 50 ng/cm2, circulate 4-70+

U2+ w/ He 300 ng/cm2, circulate 15-70+

Equilibrium orbits



fRF	36.50	[MHz]
L	1.24	[m]
H	25	

q0	64	
C	30.93	[m]
C1	4.00	[m]
C2	1.00	[m]
r1	3.33	[m]
B1	0.53	[T]
H	7.66	[m]
W	10.66	[m]

Drift length>0

Magnetic field

q	61	62	63	64	65	66	67
r1(q)	3.49	3.44	3.38	3.33	3.28	3.23	3.18
C(q)	34.64	33.40	32.16	30.93	29.69	28.45	27.21
r2(q)	5.84	5.01	4.18	3.33	2.48	1.62	0.75
B2	0.32	0.36	0.43	0.53	0.70	1.06	2.24
C3	-0.35	0.42	1.21	2.00	2.80	3.61	4.43
H	10.34	9.45	8.56	7.66	6.76	5.85	4.93
W	10.99	10.88	10.77	10.66	10.56	10.46	10.36
d	2.35	1.58	0.79	0.00	-0.80	-1.61	-2.43

Low-Z gas stripper

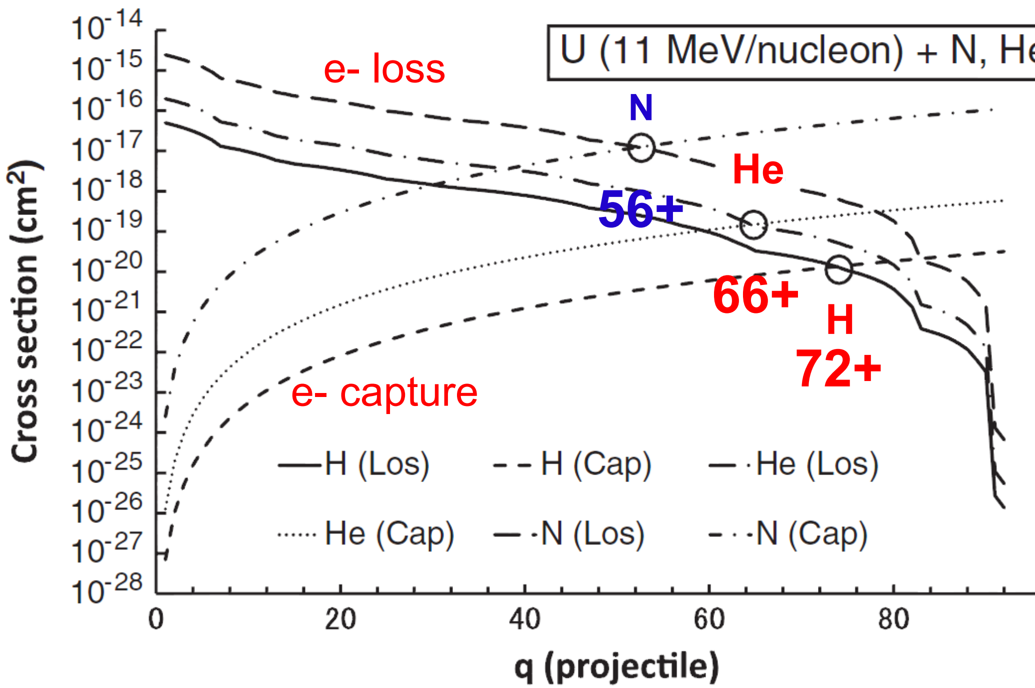
Low-Z gas（H_2・He)

- **Non destructive & uniform thickness**
- **High charge state equilibrium**

  slow electron velocity ($v_{1s} \propto Zc/137$)

  ⇒suppression of e- capture

Calculation



H. Okuno et al., PRST-AB 14, 033503 (2011)

Fundamental data and strategy

•Charge evolution

mean charge state 65+ for H_2 and He

acceptable state in fRC 69+ （C 71+、N2～56+)

•Energy spread

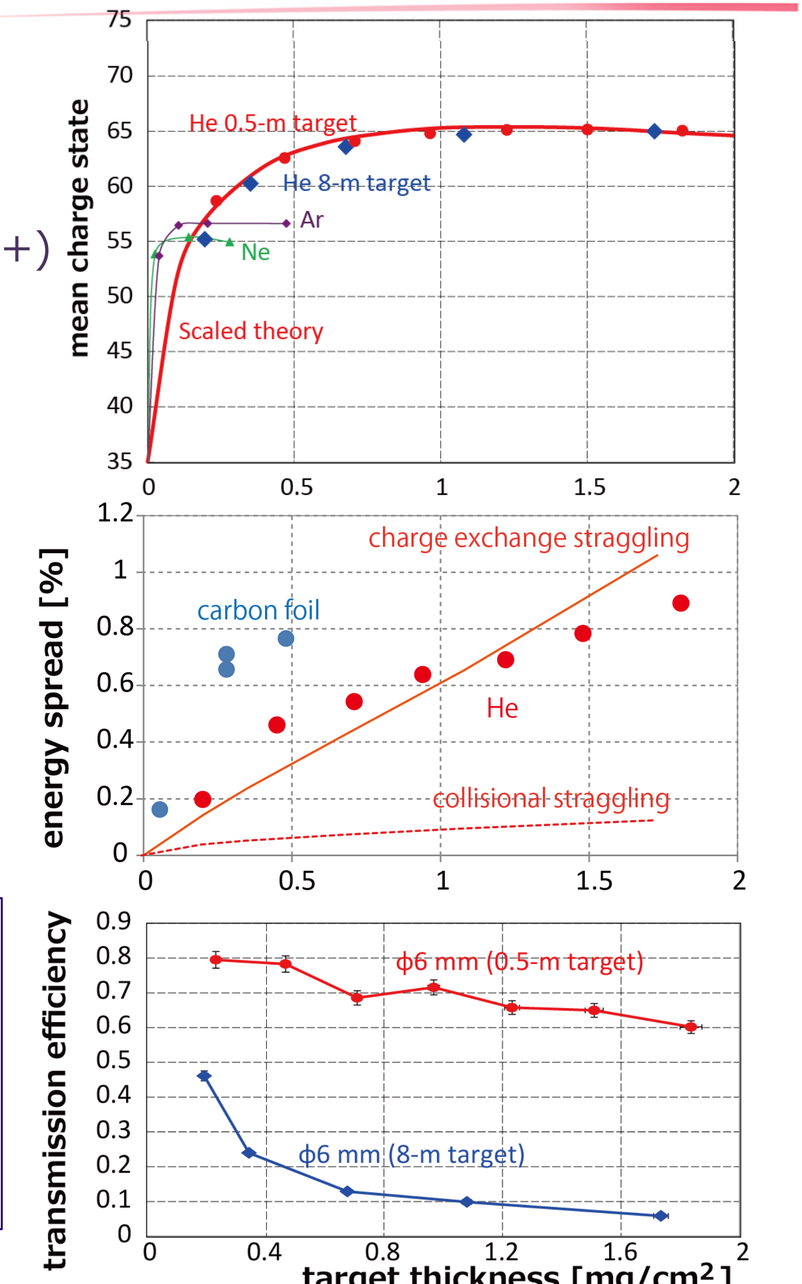
Time distribution measured w/ scinti.

Half of spread for C-foil（thickness uniformity)

•Transmission

50cm target, φ6mm aperture ⇒70%

H. Imao et al., PRST-AB 15, 123501 (2012)



Strategies for practical stripper

- **64+ acceleration w/ fRC modification**
- target thickness reduced (**0.5-0.7 mg/cm²**)
- beam orifice enlarged (Φ6mm⇒**Φ10mm**)