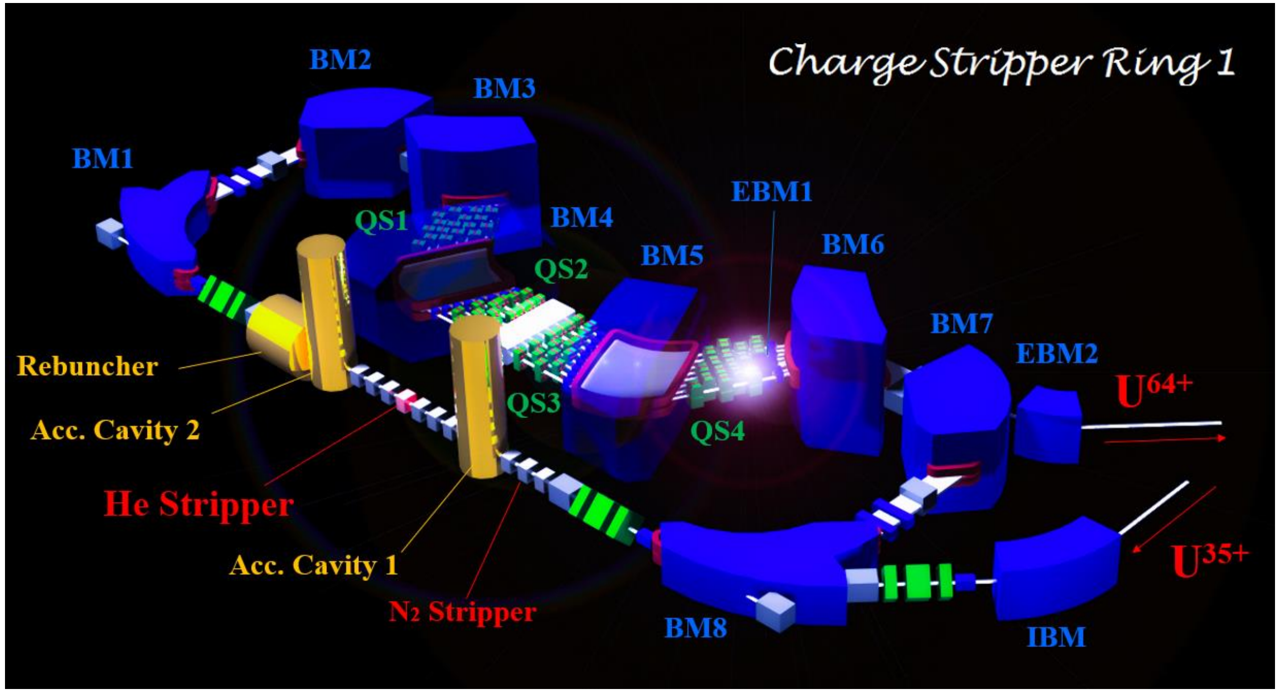
Present Status and Future Plan with Charge Stripper Ring at RIKEN RIBF



RIKEN Nishina accelerator based science center

Hiroshi Imao

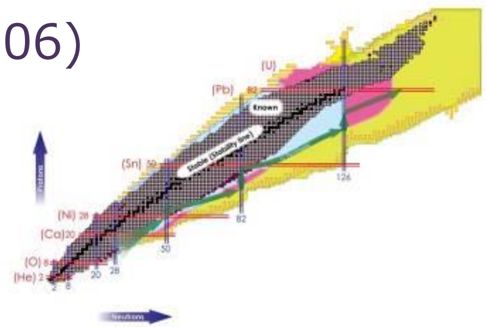
Outline

1. Recent upgrade of RIBF
    - Intensity upgrade of ^{238}U
    - Charge strippers of ^{238}U
2. Charge stripper ring（CSR)
    - Concept
    - Design of CSR1 for ^{238}U
    - CSR extension
3. Summary and future prospects

RIKEN RI beam factory (RIBF)

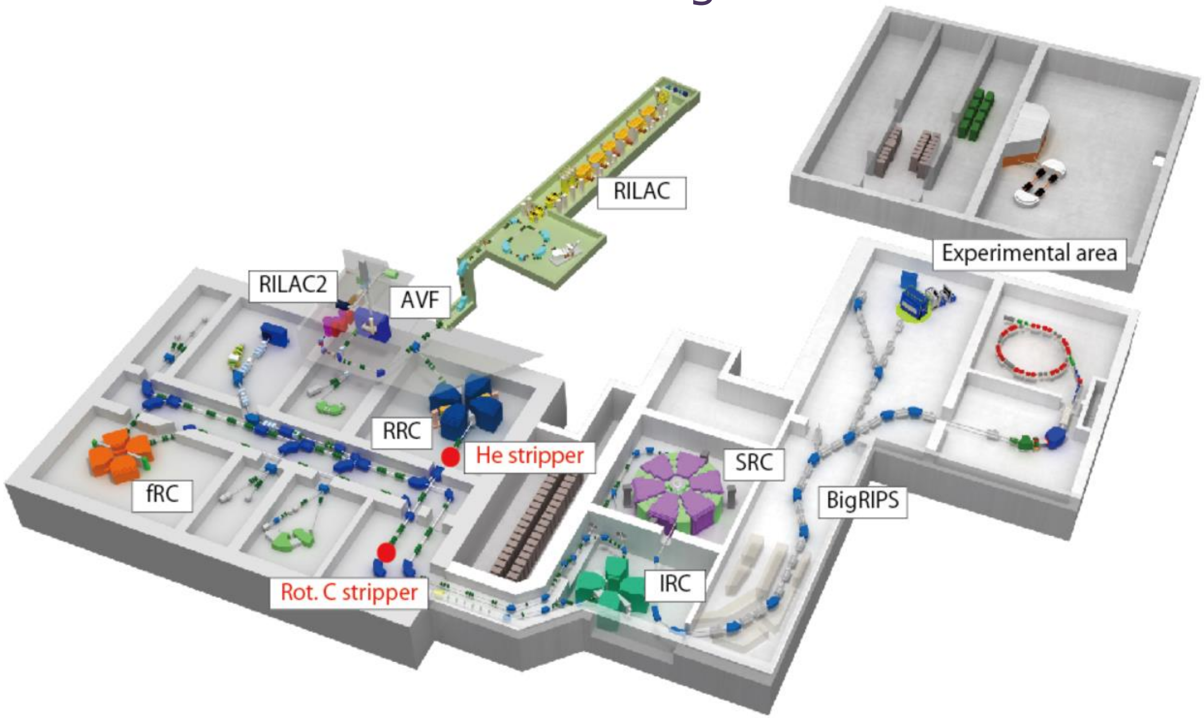
RIBF

- **Cyclotron**-based Heavy-ion accelerator for in-flight RI beams (since 2006)
- Super conducting ring cyclotron (SRC) is a main device.
- Acceleration of **ALL** ions up to 345 MeV/u (70% of c) in **CW** mode



Intensity upgrade of ^{238}U

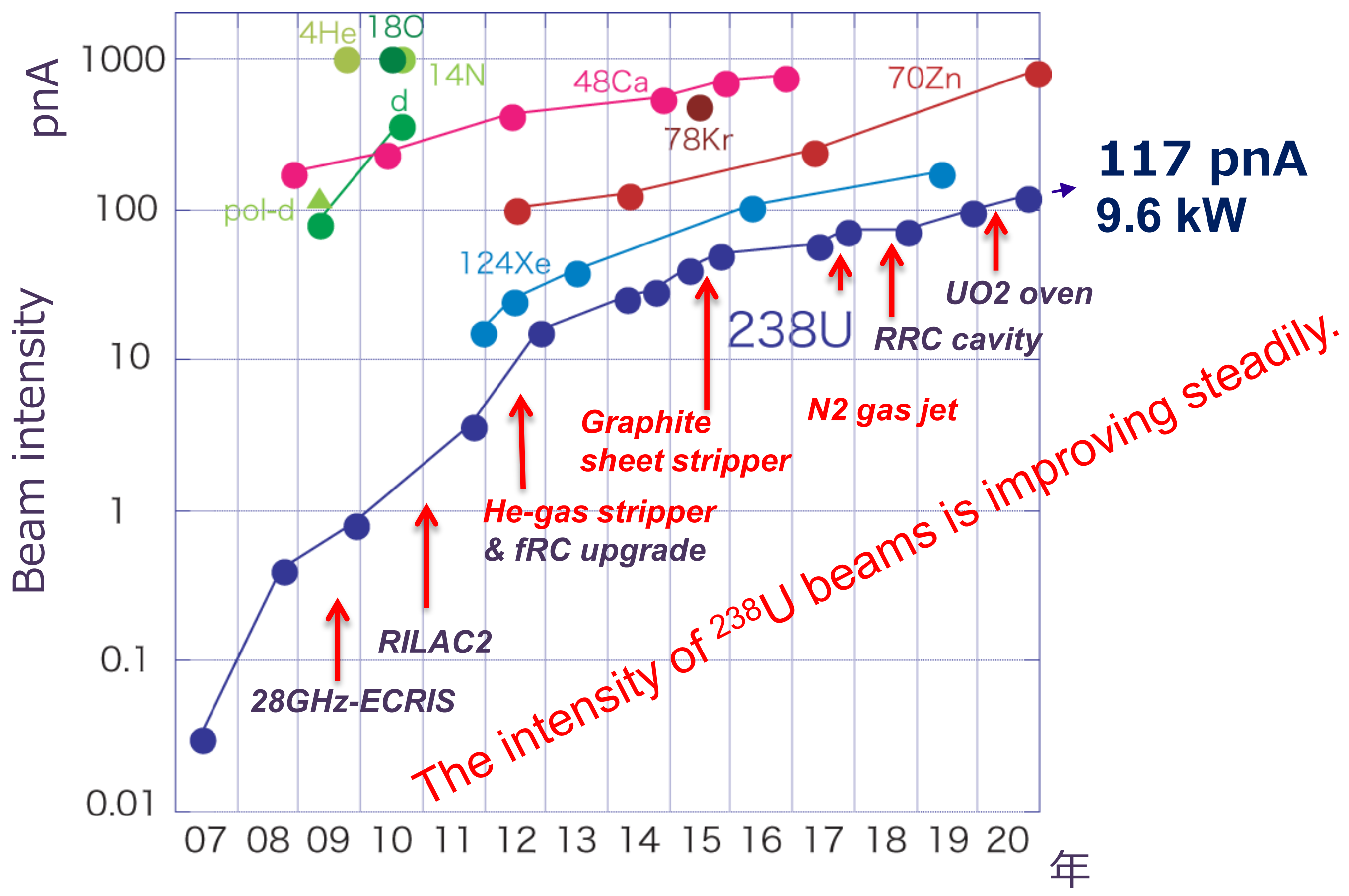
- Generation of in-flight **fission** RI beams (A~100) for elucidation of elemental synthesis
- **Only 0.1% of the goal intensity 1 puA** (ion sources, strippers, space charge effects)
- Construction of next-generation facilities worldwide (FRIB, FAIR, RAON, HIAF…)



Congratulation of successful launch of FRIB project !!!

	RRC	fRC	IRC	SRC
K value [MeV]	540	570	980	2600
number of sectors	4	4	4	6
velocity gain	4	2.1	1.5	1.5
frequency range [MHz]	18-38	54.75	18-38	18-38
weight [ton]	2300	1500	2700	8300

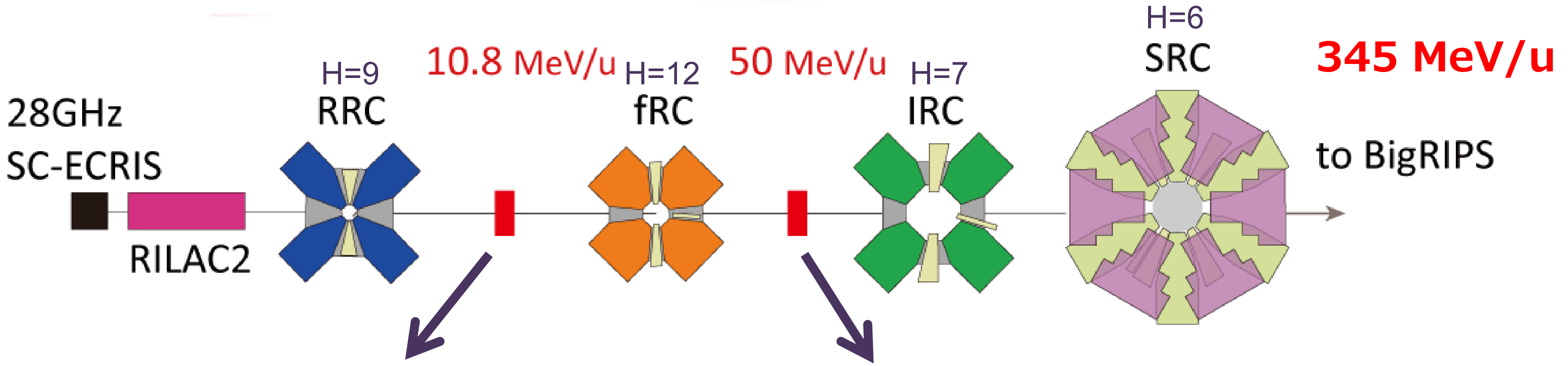
Intensity upgrade of ^{238}U



240-fold increase in beam intensity of ^{238}U since 2008

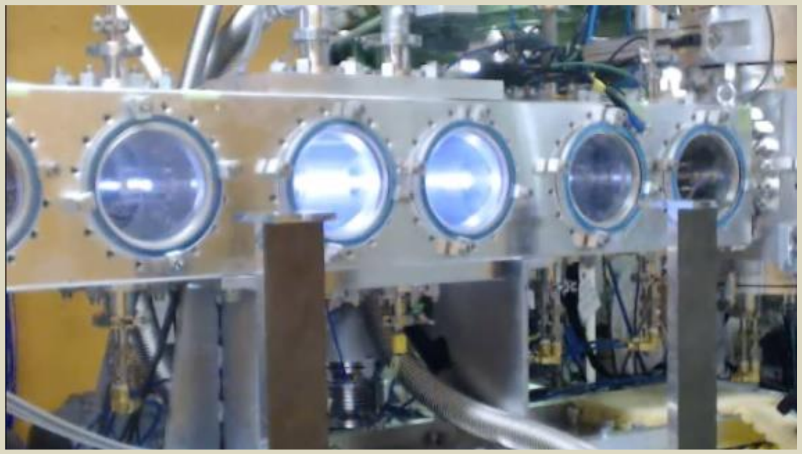
- Improvements of 28GHz-ECRIS and injector (RILAC2)
- **He gas stripper and graphite disk stripper (lifetime problem)**
- Refinement of accelerator operation techniques
- RF cavities upgrade for RRC (space charge problem)

Acceleration scheme of ^{238}U at RIBF



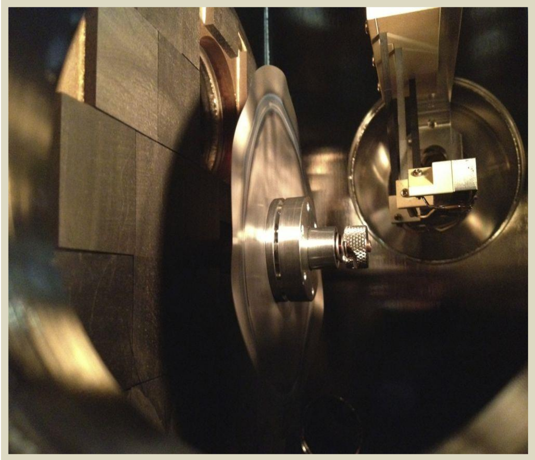
1. He gas stripper (since 2012)

35+⇒64+ (20%)



2. Rotating disk stripper (since 2012)

64+⇒86+ (25%)



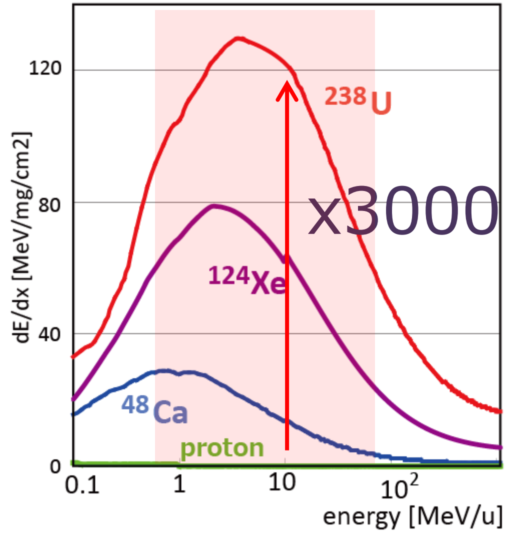
Conventional carbon foil strippers cannot be applied for U acceleration

Application limit of fixed C foil

Huge dE/dx of heavy ions on C foils

Heat load: sublimation

Radiation damage : lattice modification

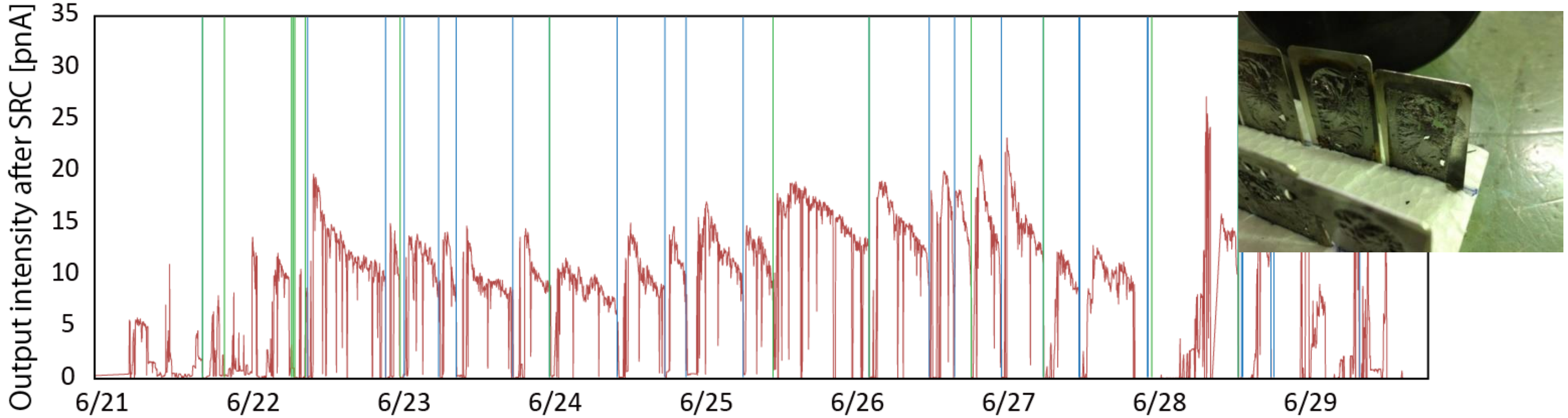


Application limit (rough estimation)

~10^{11}/s for ^{238}U at intermediate energies

Example…

Xe-MT（6/16-7/5 in 2012 at RIBF） variation of output intensities w/ time



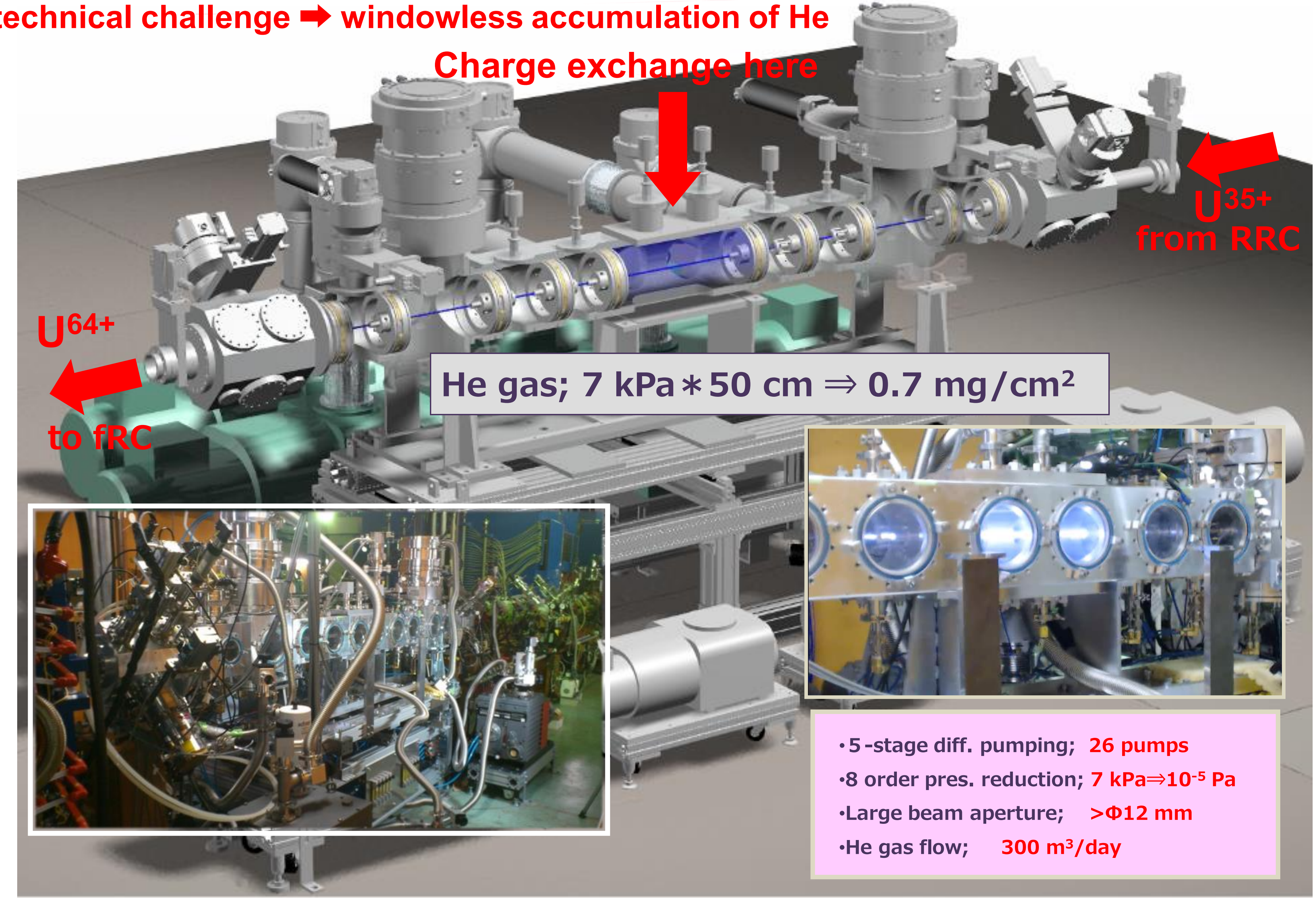
Green : 1st stripper replacement　（~50 times, 5 h for **6×10^{12}/s** at 11 MeV/u）

Blue : 2nd stripper replacement　（~20 times, 12 h for **6×10^{11}/s** at 51 MeV/u）

The He gas stripper and rotating graphite disk stripper solved this lifetime problem

He gas stripper

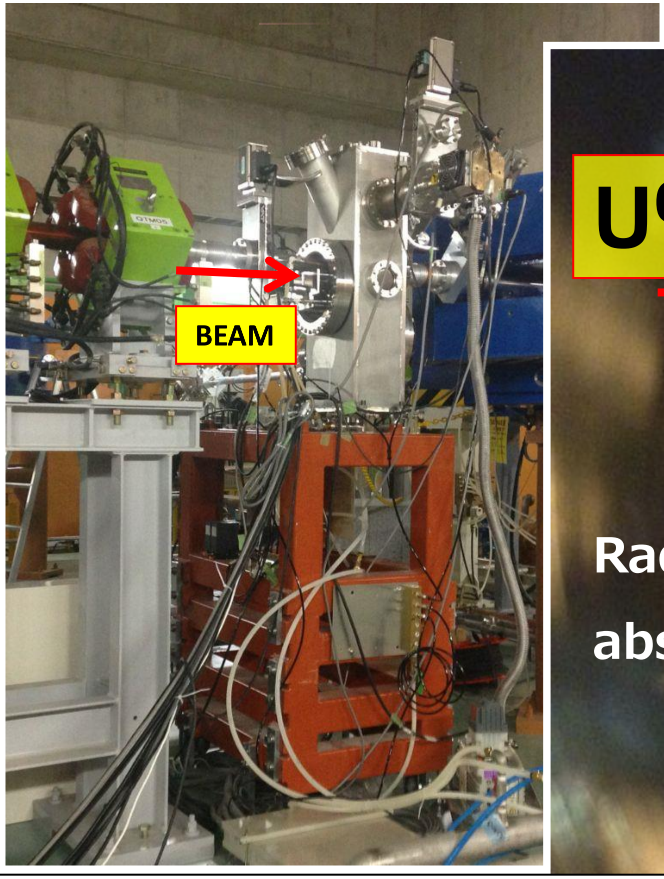
Primary technical challenge ➡ windowless accumulation of He

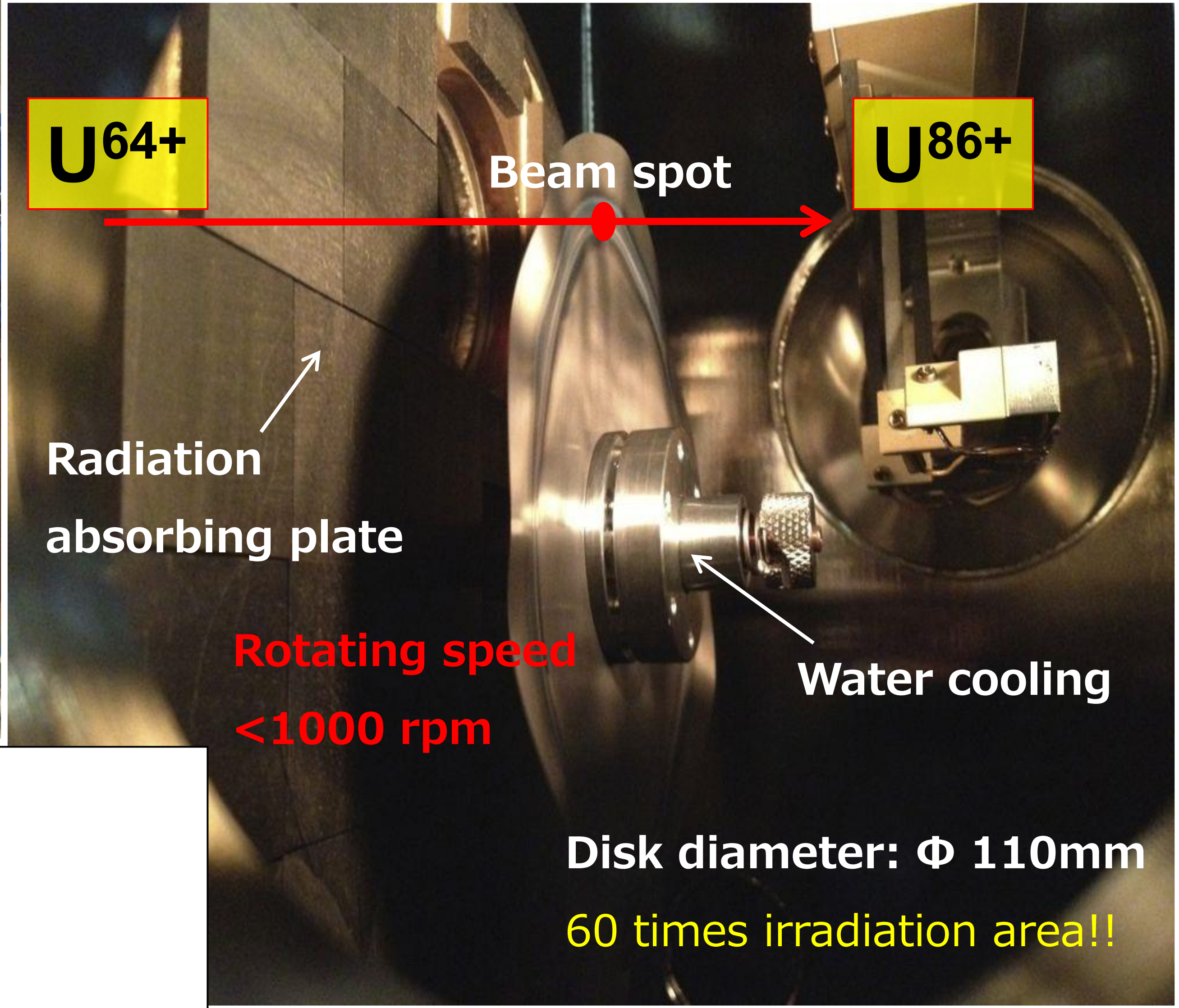


He gas; 7 kPa∗50 cm ⇒ 0.7 mg/cm²

- 5-stage diff. pumping; 26 pumps
- 8 order pres. reduction; 7 kPa⇒10^{-5} Pa
- Large beam aperture; >Φ12 mm
- He gas flow; 300 m^3/day

Rotating graphite disk stripper





2nd stripper at 50 MeV/u

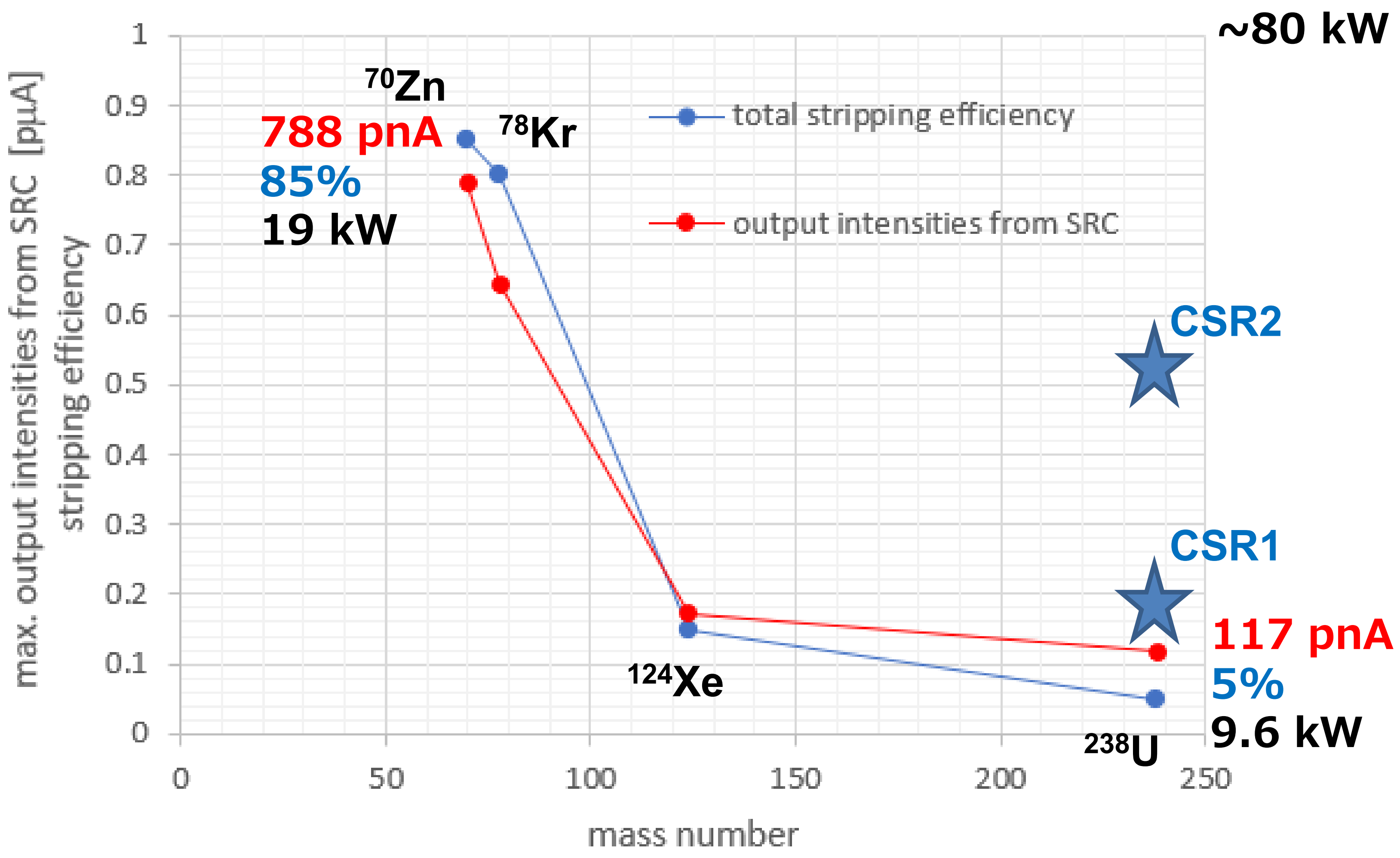
- 2011: fixed carbon foil
- 2012-14: Be disk
- 2015-: KNEKA GC

Axial thermal conductivity (~1500 W/mm2)

Courtesy of H. Hasebe (RIKEN)

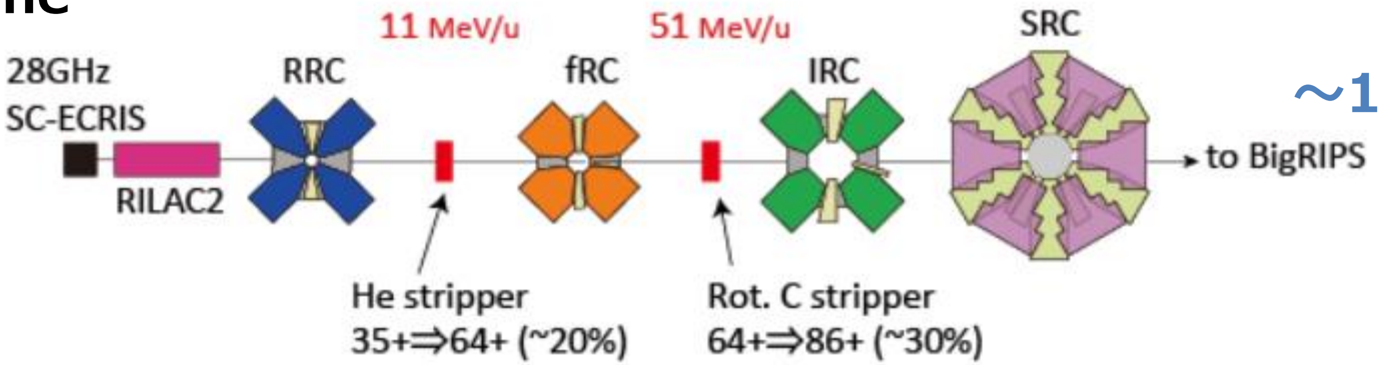
Dependence of total charge stripping efficiency on mass

Low total charge stripping efficiency for uranium of about 5% (20% x 25%) is a bottleneck for further intensity upgrade



Future upgrade plan with Charge Stripper Ring (CSR)

Present scheme



~100 pnA

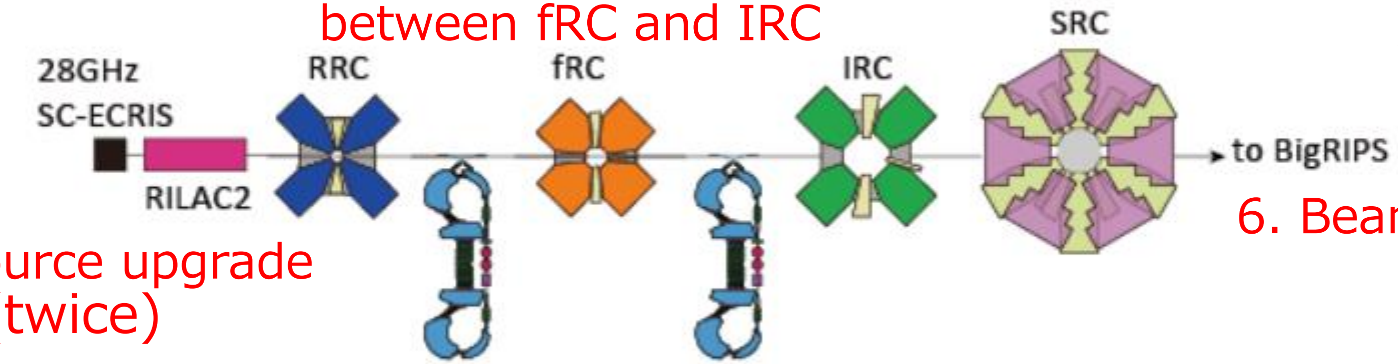
total 5%

New scheme w/ CSRs

2. Cyclotron modification for energy matching between fRC and IRC

3. RF system upgrade of SRC

x ~20 times
2000 pnA



6. Beam dump upgrade

1. Ion source upgrade (twice)

4. CSR1

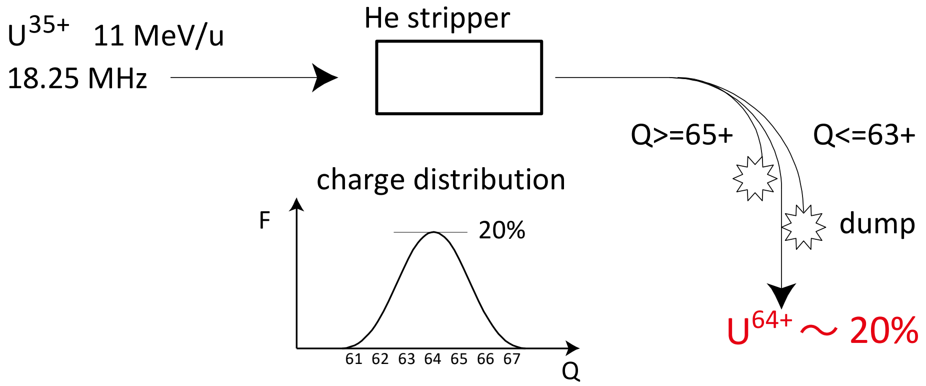
5. CSR2

total ~50%
(tenfold)

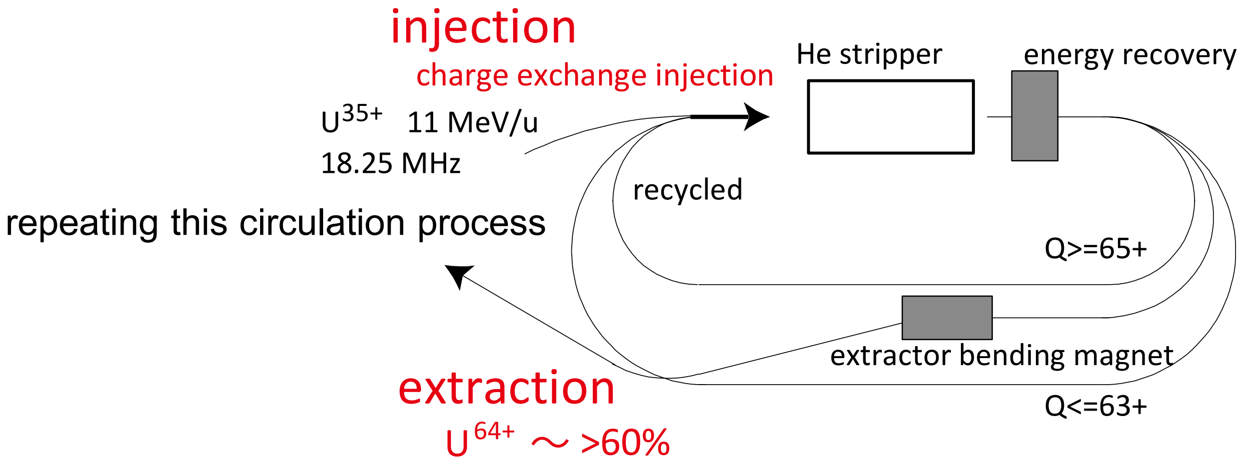
10-year plan after budgeting (Not yet budgeted)
$100M in total estimated cost

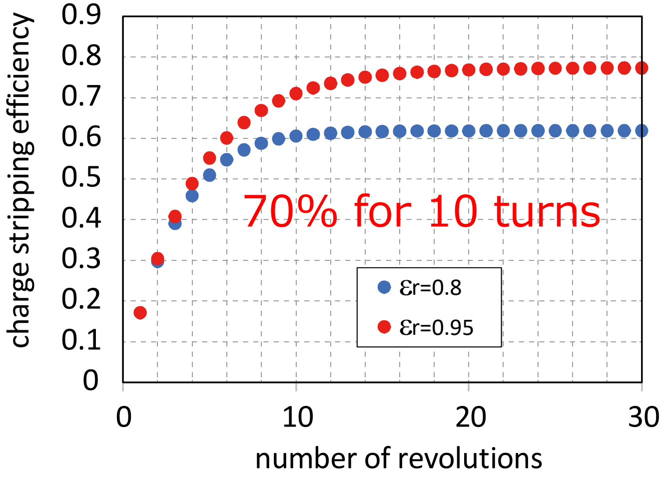
Concept of CSR

present scheme



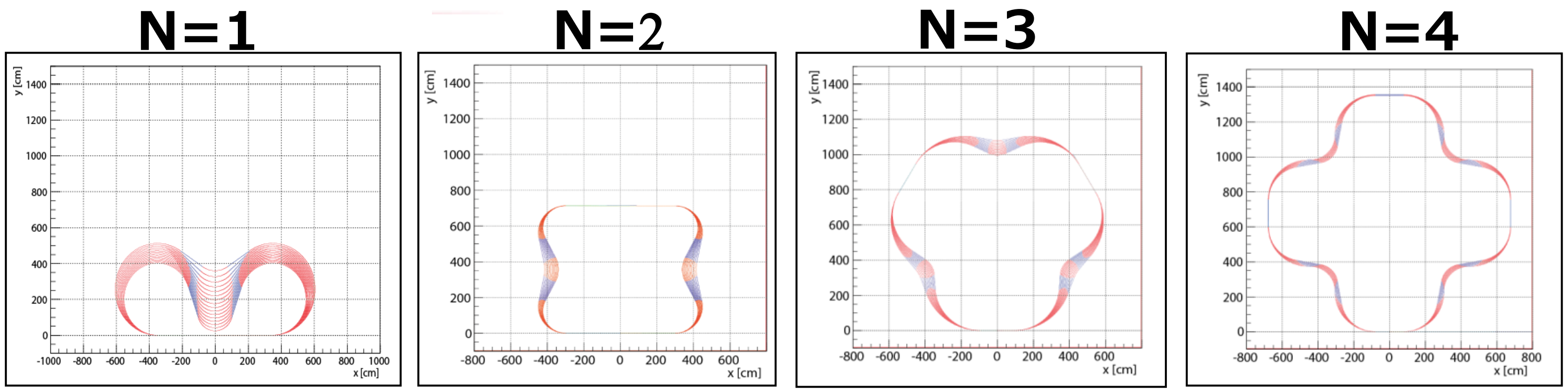
CSR scheme



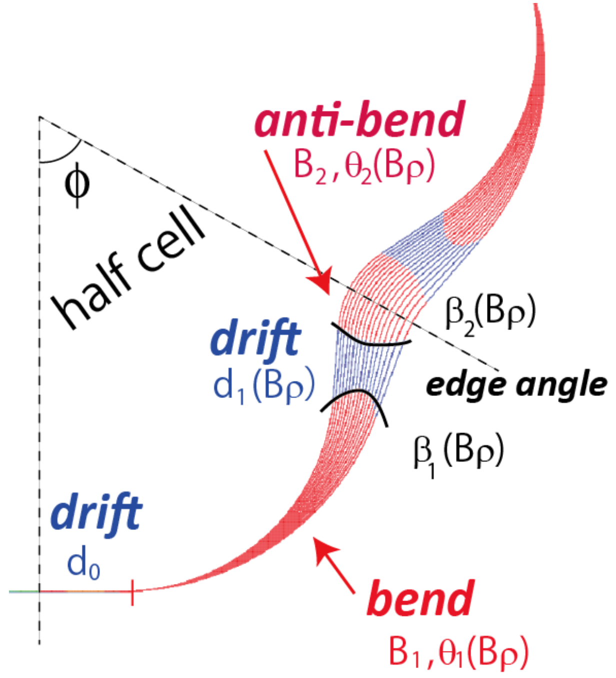


The bunch structure should be preserved to match to acceptance of the subsequent cyclotrons (e.g., 18.25 MHz at RIBF).

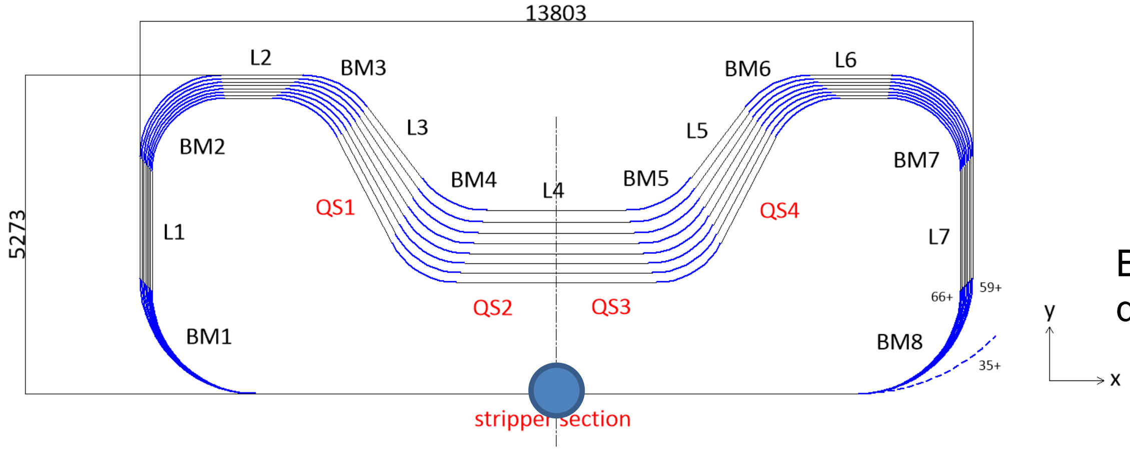
Isometric ring



Isometric rings of various symmetries



Isometric orbits of CSR1 for U^{59+}-U^{66+}



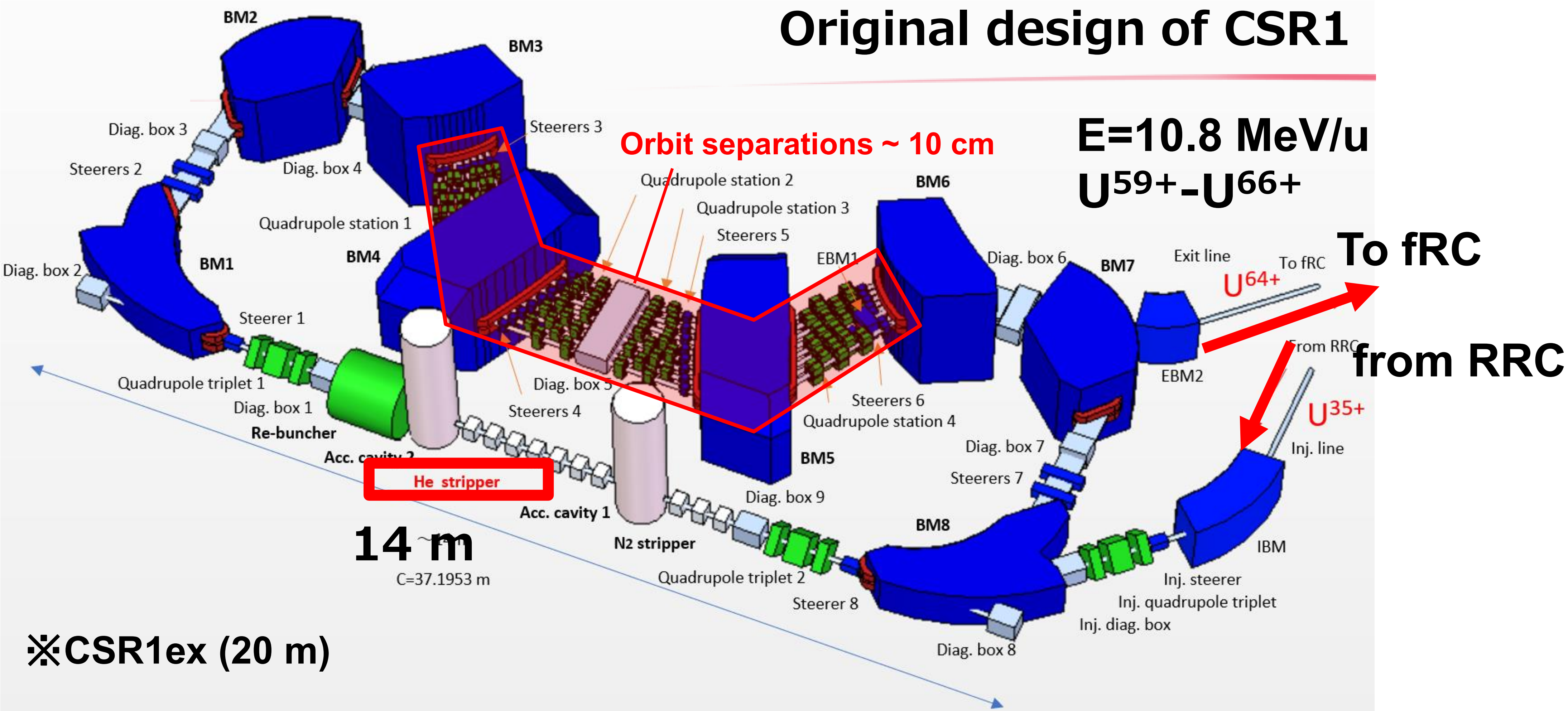
Beams of all charge states have the same defined transverse shape at the stripper

Charge stripper should be placed at achromat section

Eigen ellipses for all charge states should be matched to suppress emittance growth

→charge independent focusing

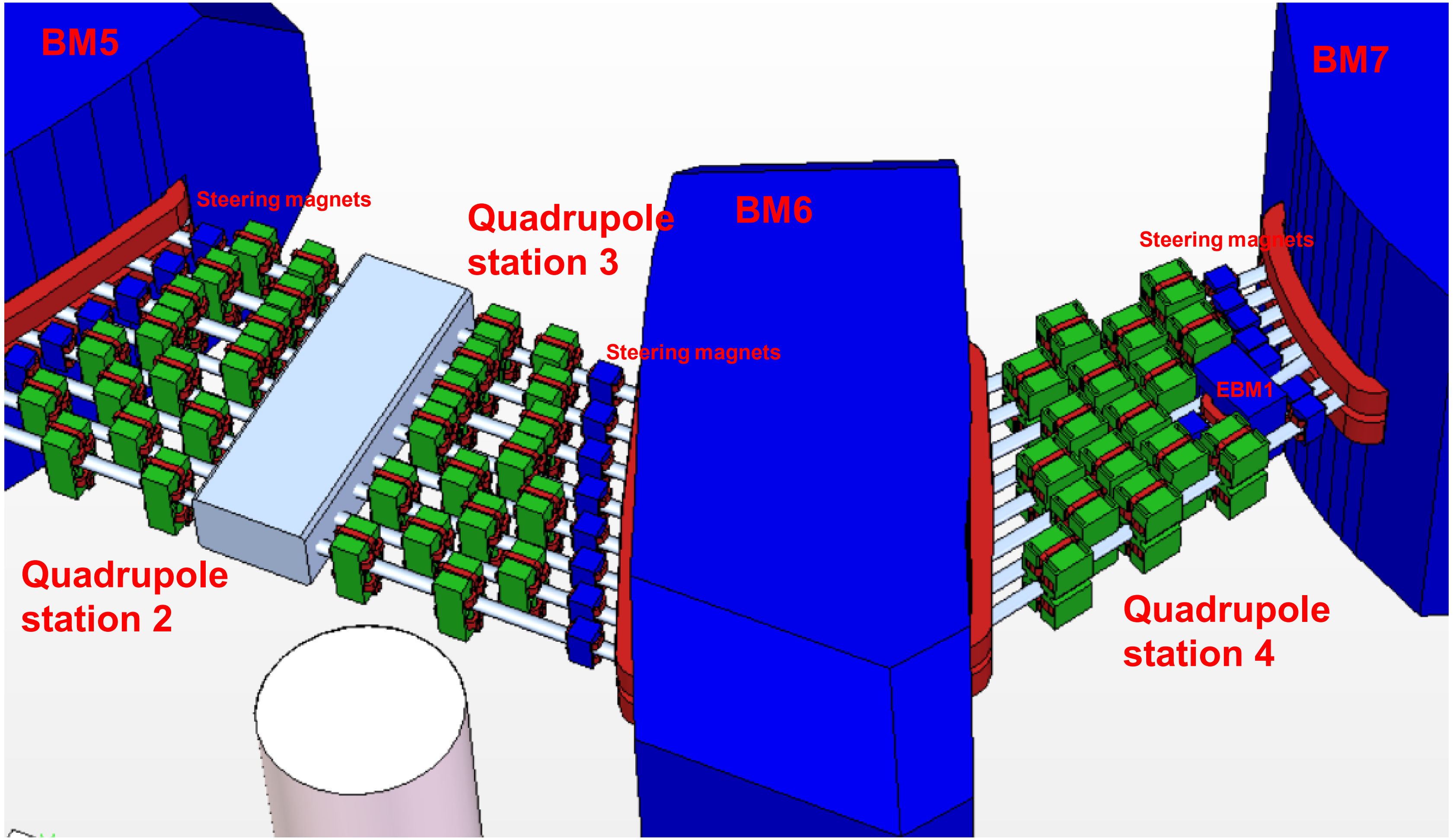
Original design of CSR1



Recycle by circling the beams with other than selective charge

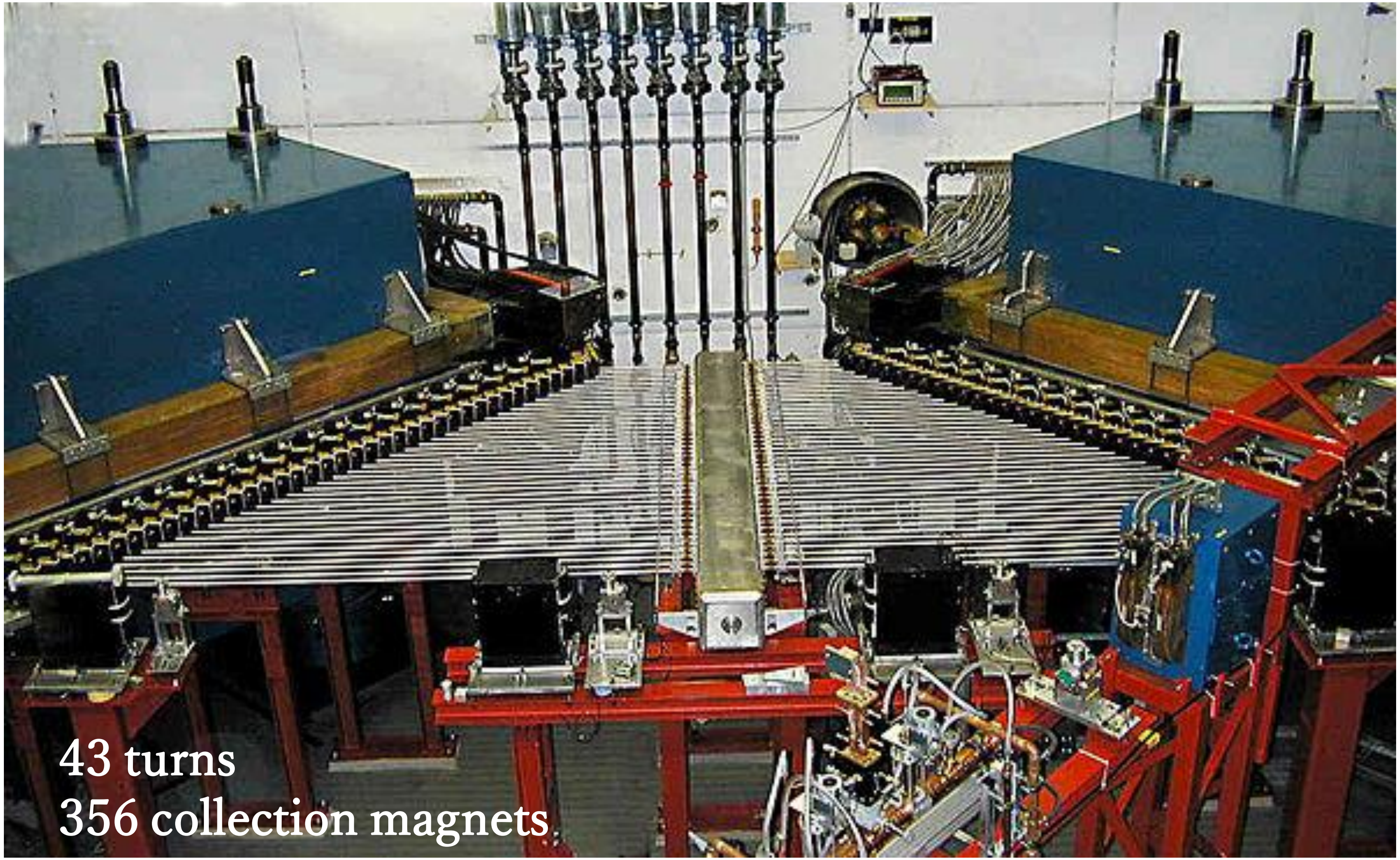
- Isometric ring → 8 bending magnets (BM1-8)
- Same energy → 2 energy recovery cavities
- Same transverse shape → 66 quadrupoles

Close-up view of quadrupole station



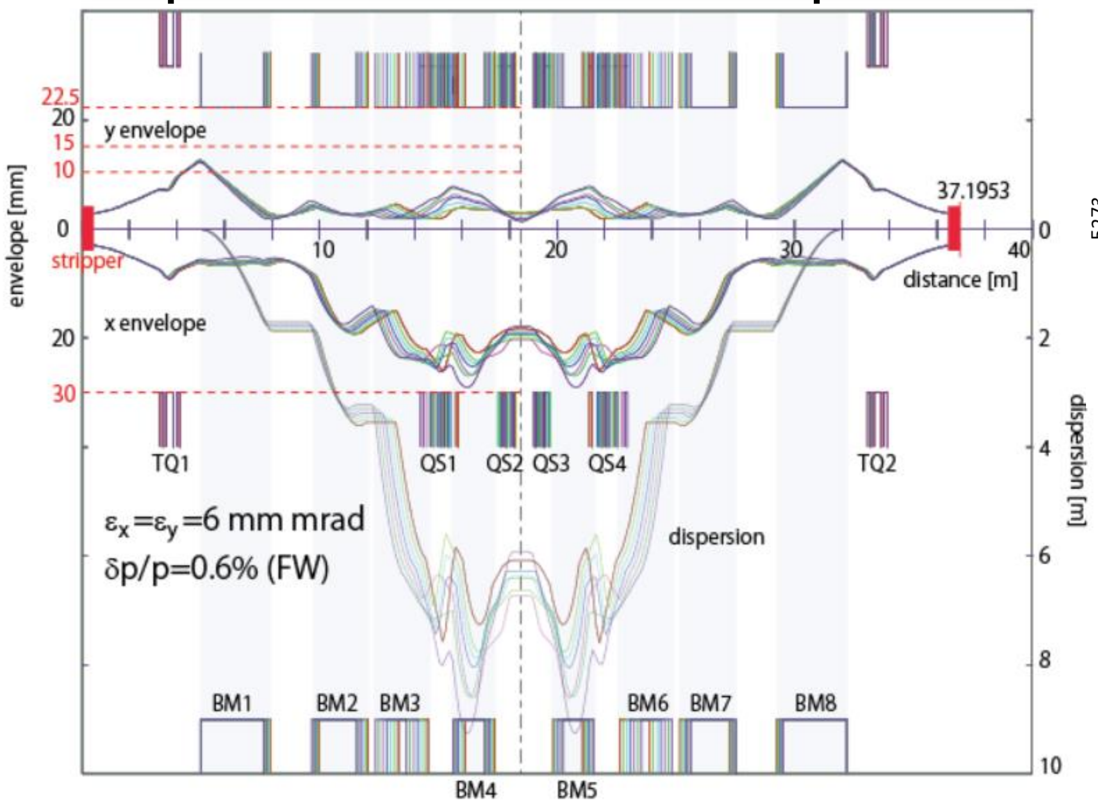
crowded quadrupoles in parallel beamlines

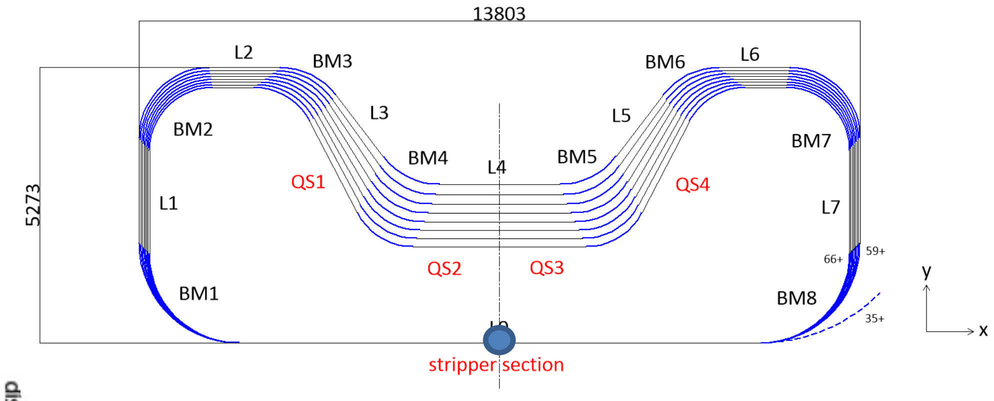
MAMI C (Microtron HDSM at Mainz univ.)



Linear calculations

Overlap of the calculated beam envelopes in CSR1





	Q1 [T/m]	Q2 [T/m]	Q3 [T/m]	Q4 [T/m]	Q5 [T/m]
q=59	13.1	-11.9	N/A	-0.2	-2.4
60	13.1	$\boxed{-13.4}$	N/A	-1.4	-0.6
61	10.9	-11.3	N/A	0.5	-1.6
62	10.1	-10.3	N/A	1.6	-3.0
63	8.1	-7.4	N/A	2.0	-3.7
64	3.7	-2.4	N/A	0.8	-2.0
65	1.3	1.3	N/A	-0.8	-1.7
66	0.6	-3.3	5.6	1.0	-4.7

<13.4 T/m

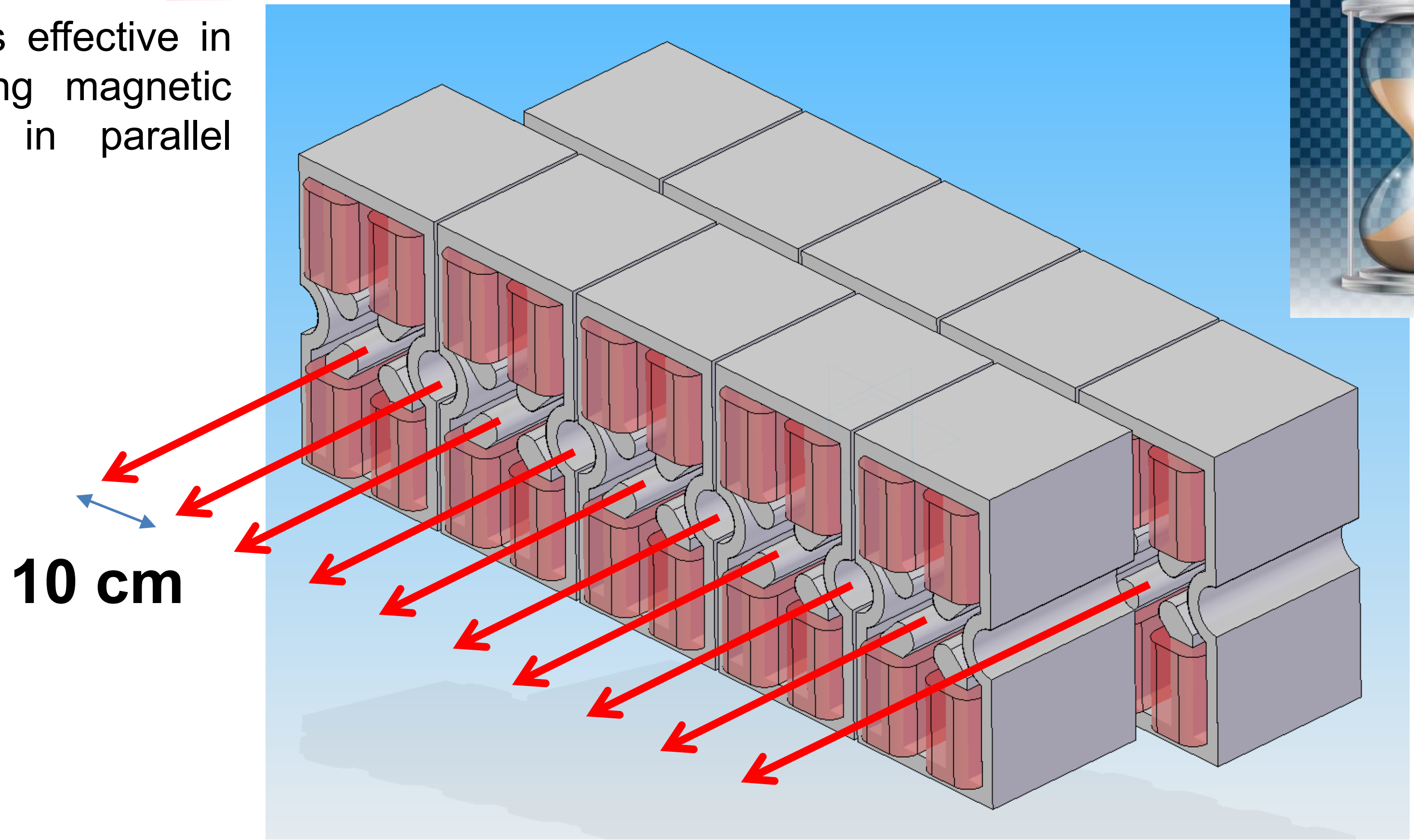
Linear orbit calculations to determine the quadrupole's specification

Beams are doubly achromat and eigen ellipses are match on all charge states at the He stripper.

Design of compact and powerful Q magnets is a key for CSR

Conceptual design of ``Hourglass-shaped" quadrupoles

The geometry is effective in generating strong magnetic fields gradient in parallel beamlines.



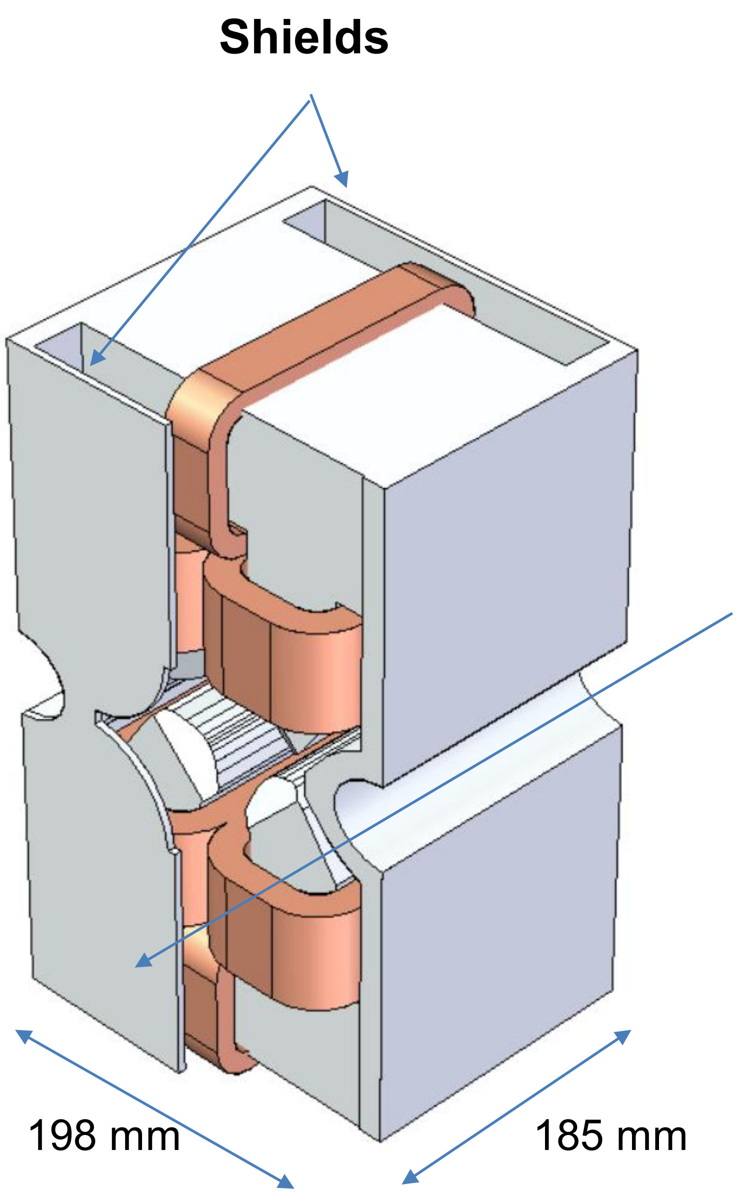
bore [mm]	φ53
pole length [mm]	120
magnet length	185
magnetmotive force	350A x 15 turns

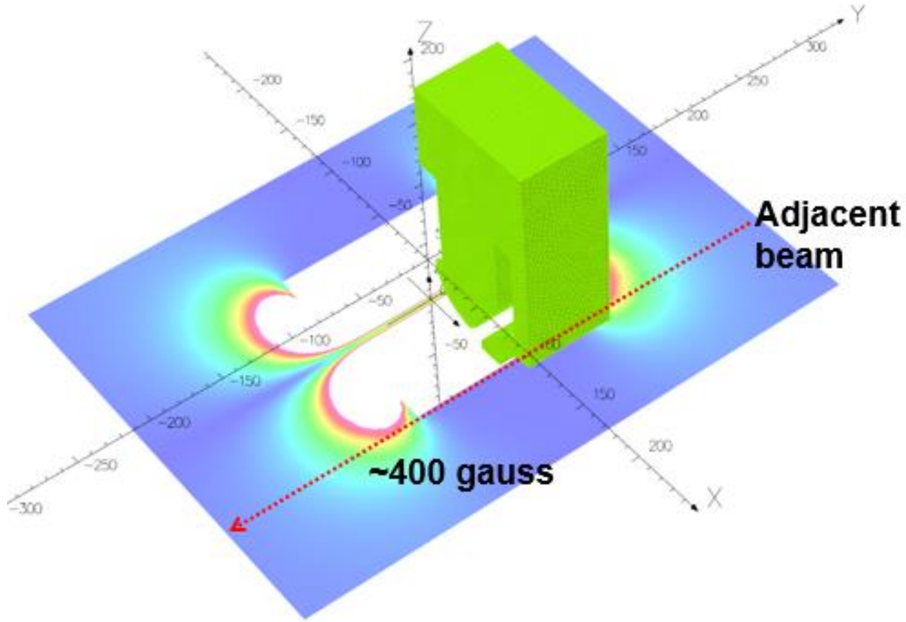
Bent poles and the coils in a straight neck of a pole

The waisted side yokes reduce leakage field on the adjacent path

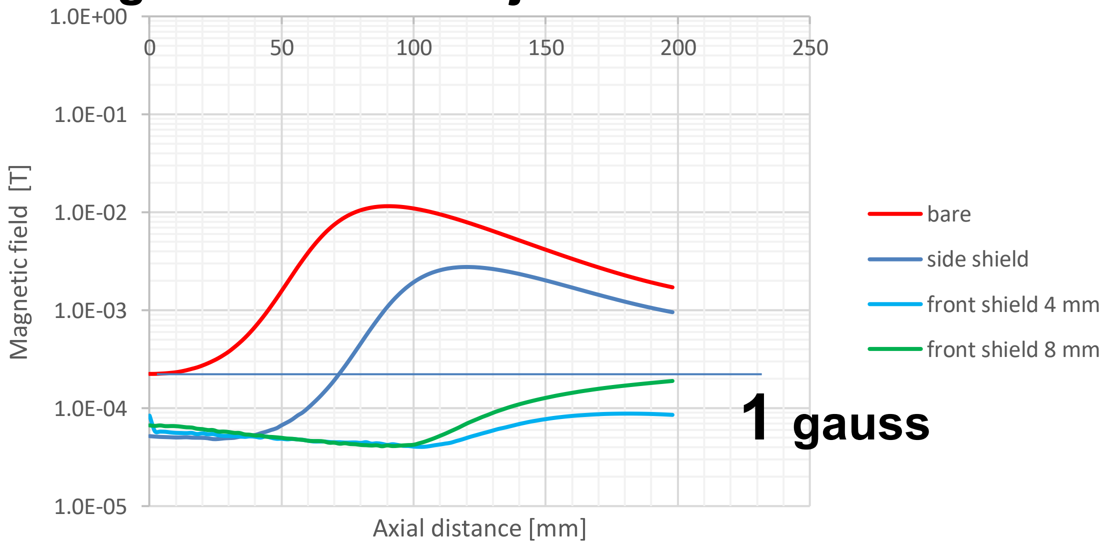
Patent for the unique shape was applied by RIKEN and HITACHI Engineering Co., Ltd. (application number JP2020-056540 in Japan).

Shield to reduce axial leakage field

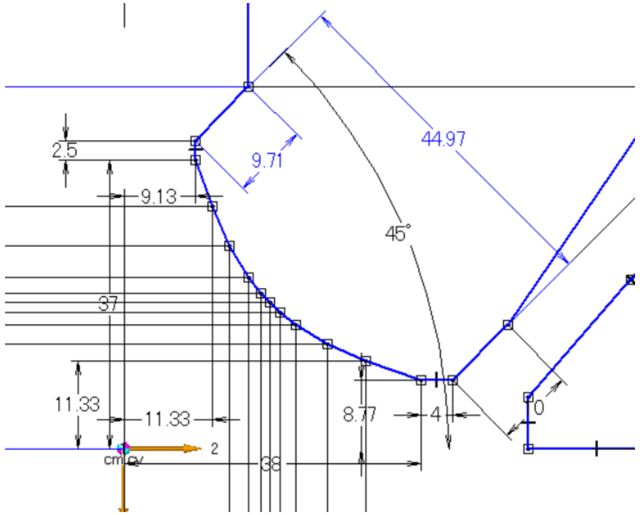


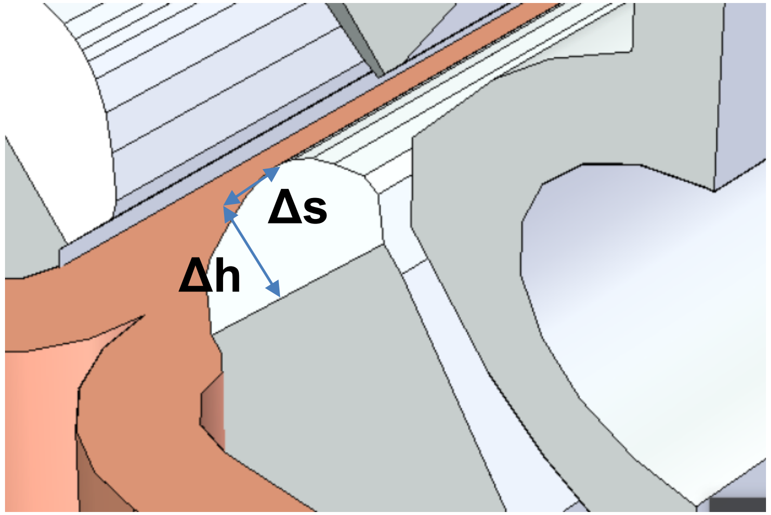


Leakage field on the adjacent beam line



Optimization of pole shape





r=20 mm

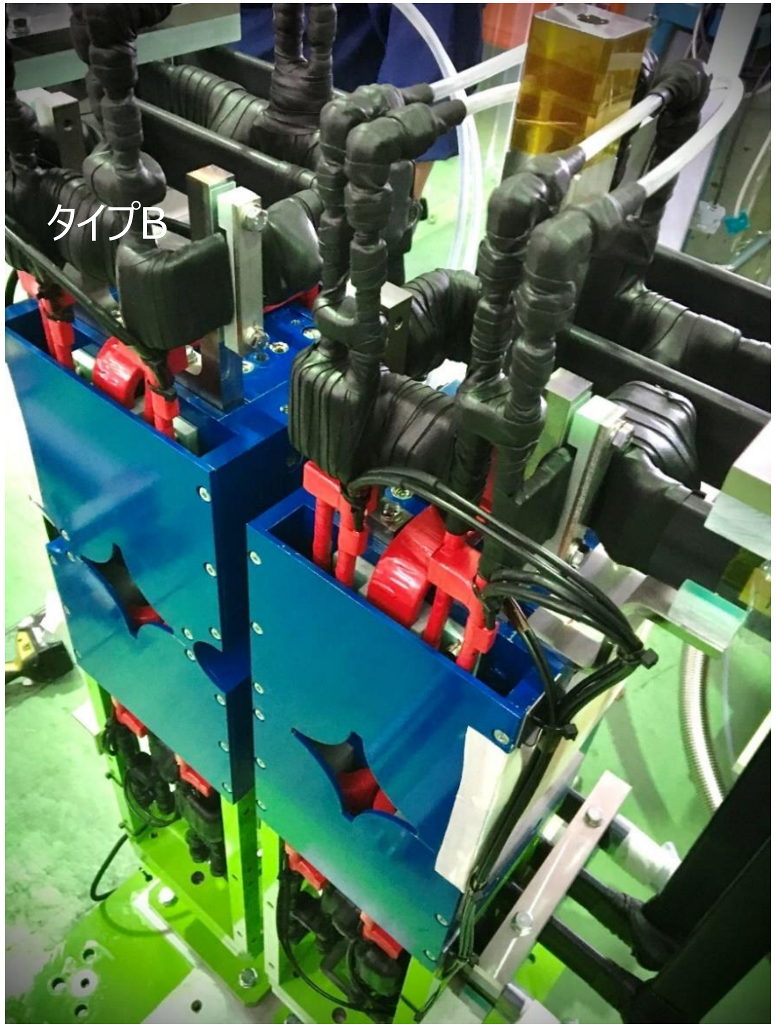
	no chamfer	(Δs, Δh)=(8, 15)	pole adjusted	
Integrated field	0.046	0.044	0.044	[T・m]
B4/B2	8.413	12.087	5.936	[x10-4]
B8/B2	1.011	0.650	-1.749	[x10-4]
B6/B2	-27.971	1.956	-0.762	[x10-4]
B10/B2	5.330	3.889	3.210	[x10-4]

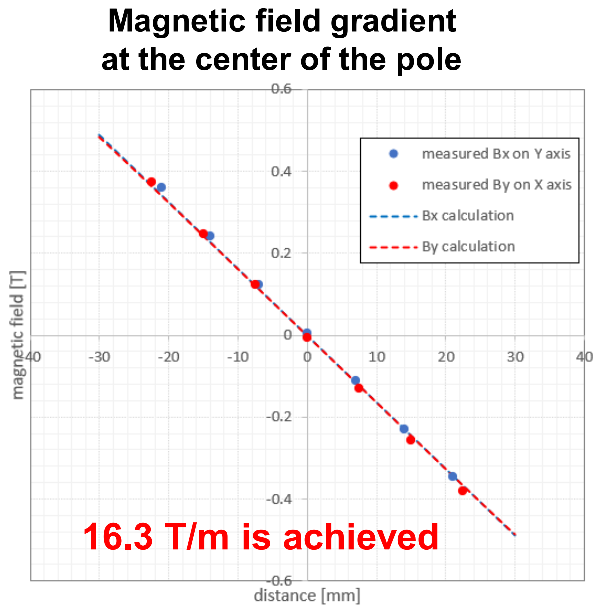
➡**18.3 T/m (12 cm)**

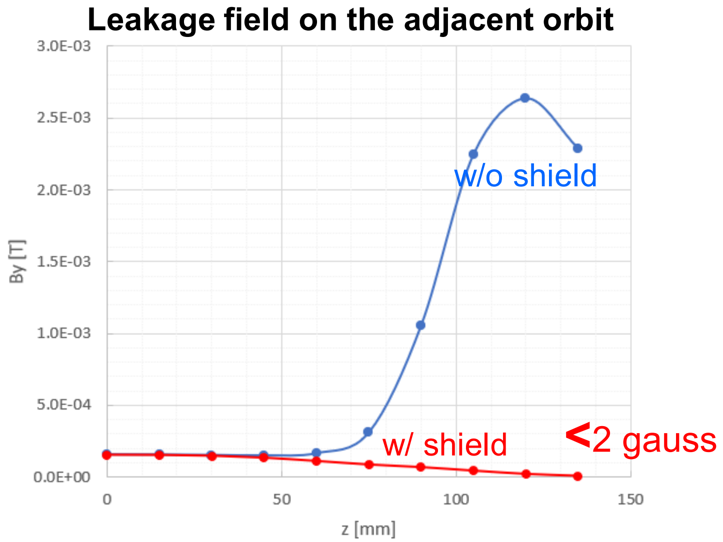
$\int B4\,dz / \int B2\,dz$ and $\int B6\,dz / \int B2\,dz < 10^{-3}$

Minimize multipole components due to XY asymmetry and deviation from hyperbolas w/ 3D calculations using OPERA

Prototype production and magnetic field measurements

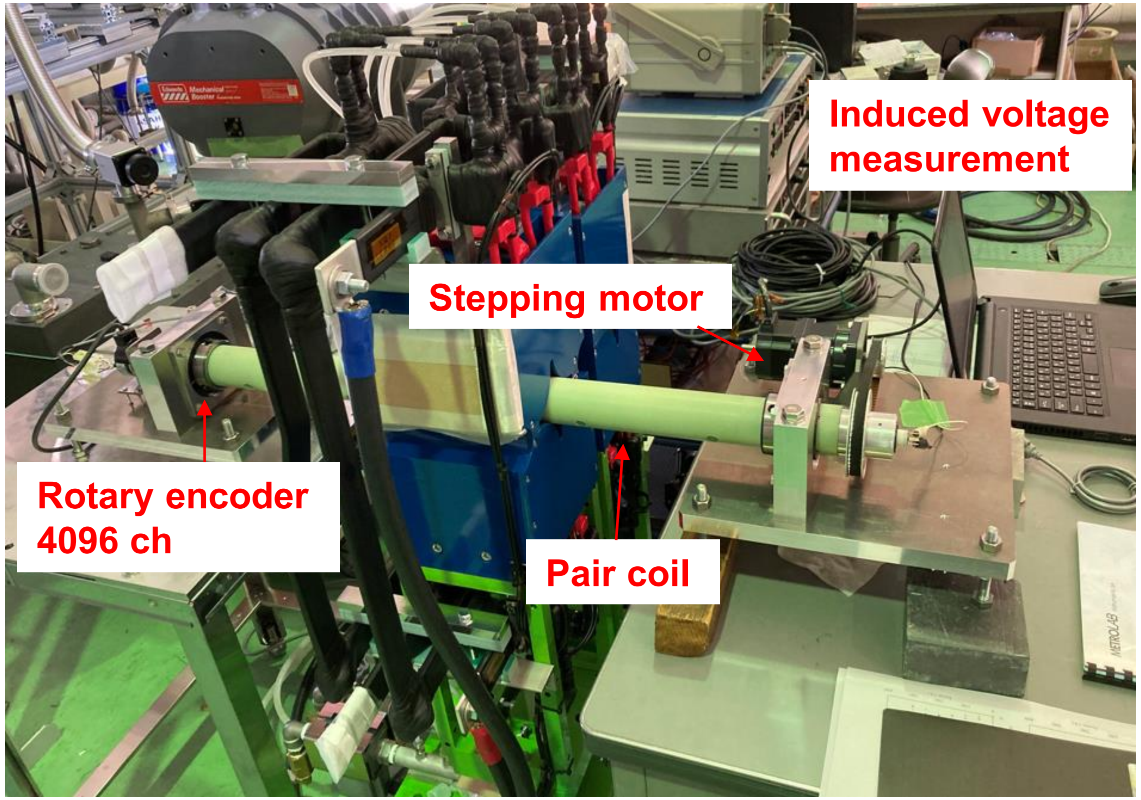






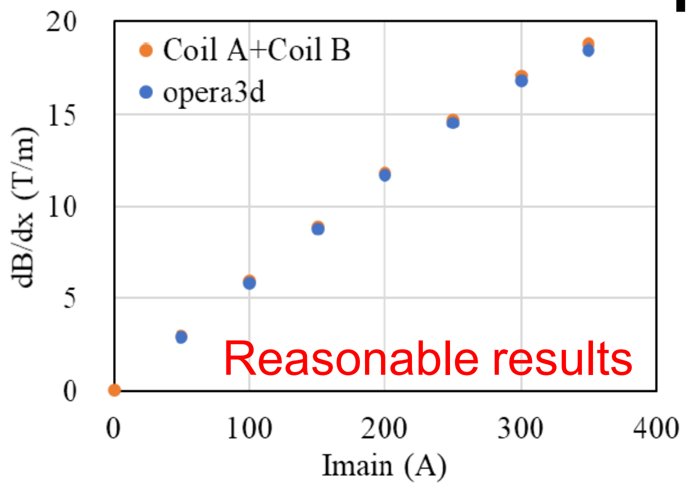
The desired magnetic field gradient was obtained
The leakage field was sufficiently small as calculated

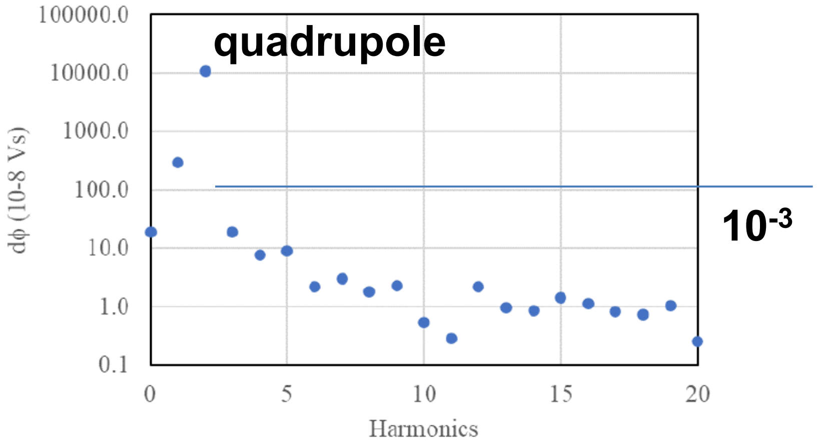
Harmonic coil method

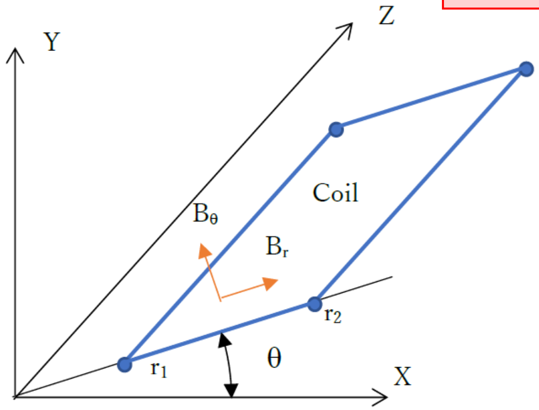


Developed by J. Ohnishi (RIKEN)

~18 T/m







$$\emptyset = \int dz \int_{r_1}^{r_2} dr B_\theta$$

$$V = -\frac{d\emptyset}{dt}$$

$$\int V dt = \emptyset_{\theta=\theta_a} - \emptyset_{\theta=\theta_b}$$

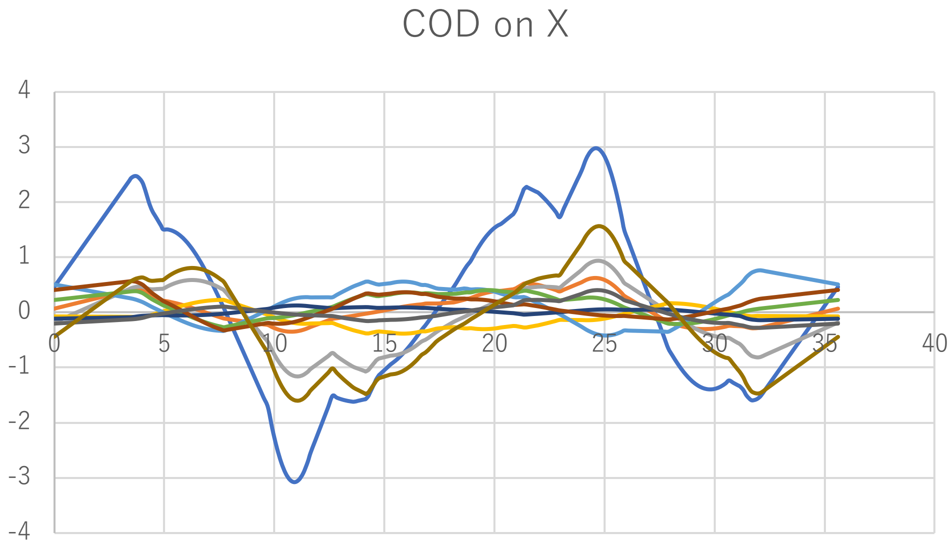
Integrated field gradient and multipole components are measured with harmonic coil method

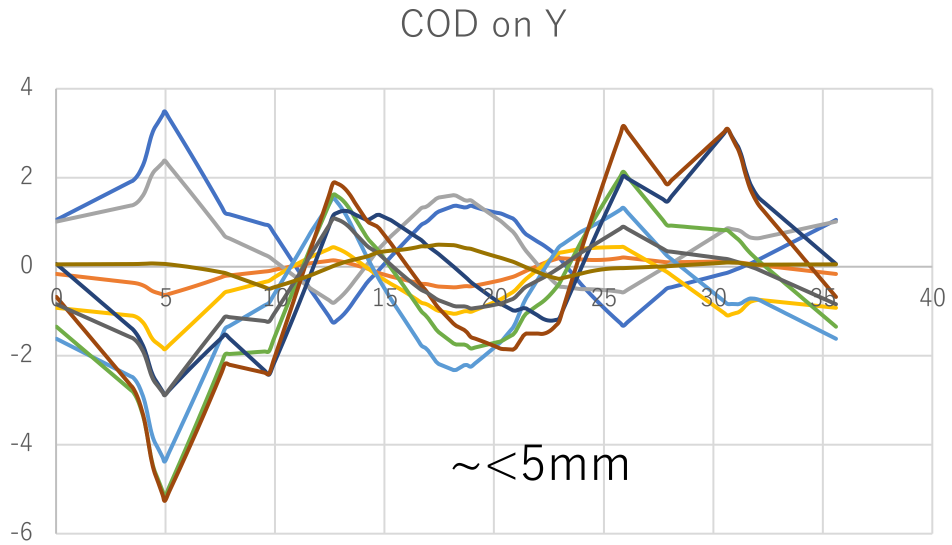
Effective for inspection during mass production of 66 quadrupoles

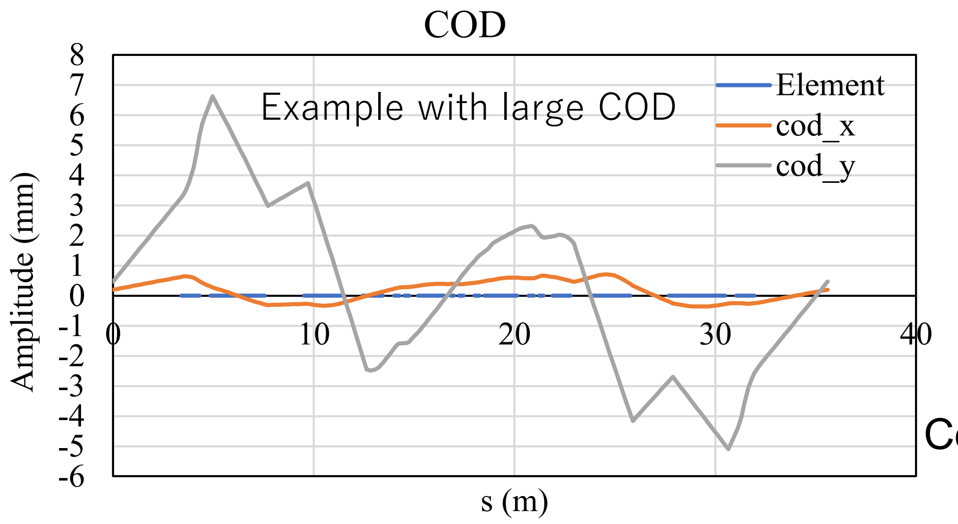
COD correction

$y(s)=\int G(s,s_0)\theta(s_0)\,ds_0$

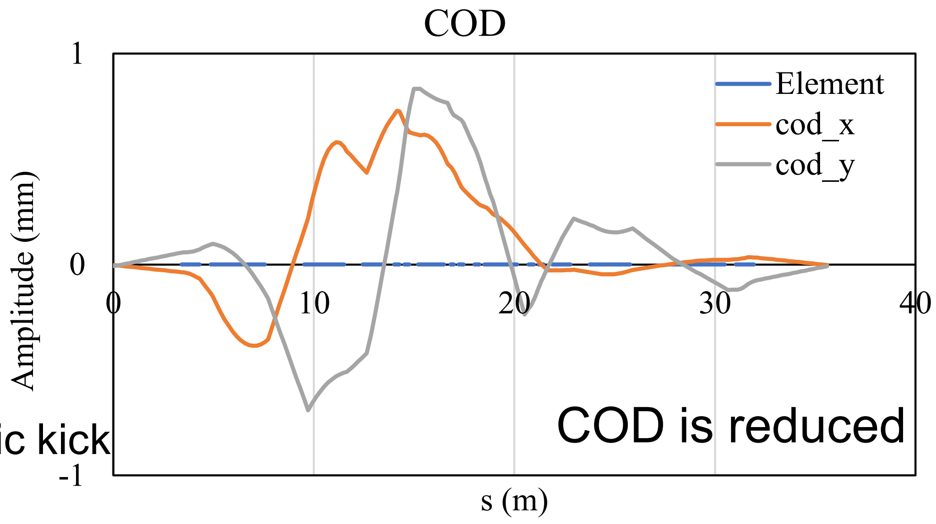
Q misalignment 0.1 mm
BM rotation 0.1°







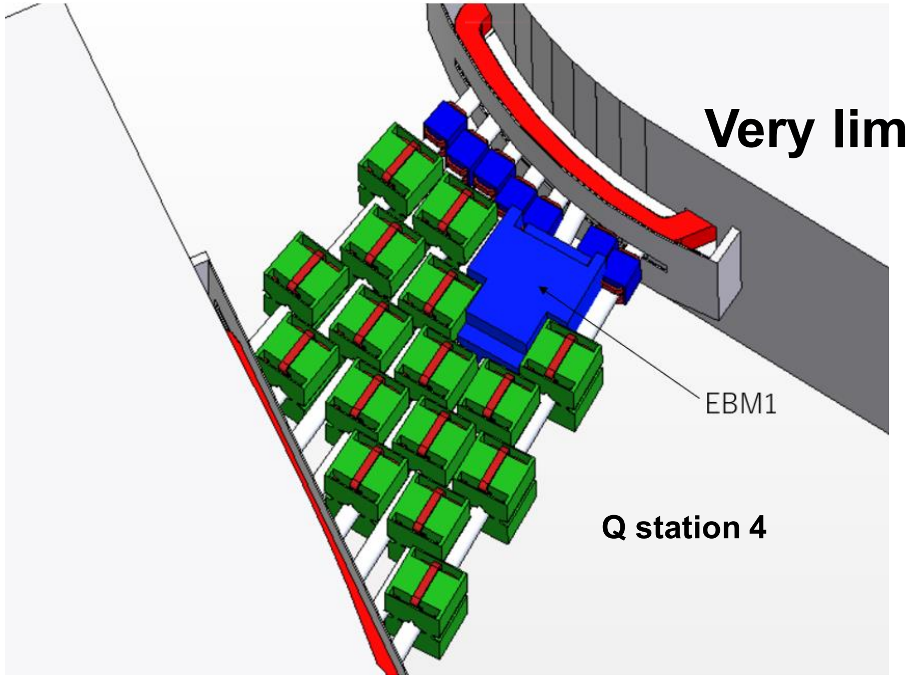
Correction w/ magnetic kick
X1 -1.5 Gauss
X2 7 Gauss
Y1 -67 Gauss
Y2 81 Gauss



CODs can be corrected by small magnetic kicks of off-center quadrupoles

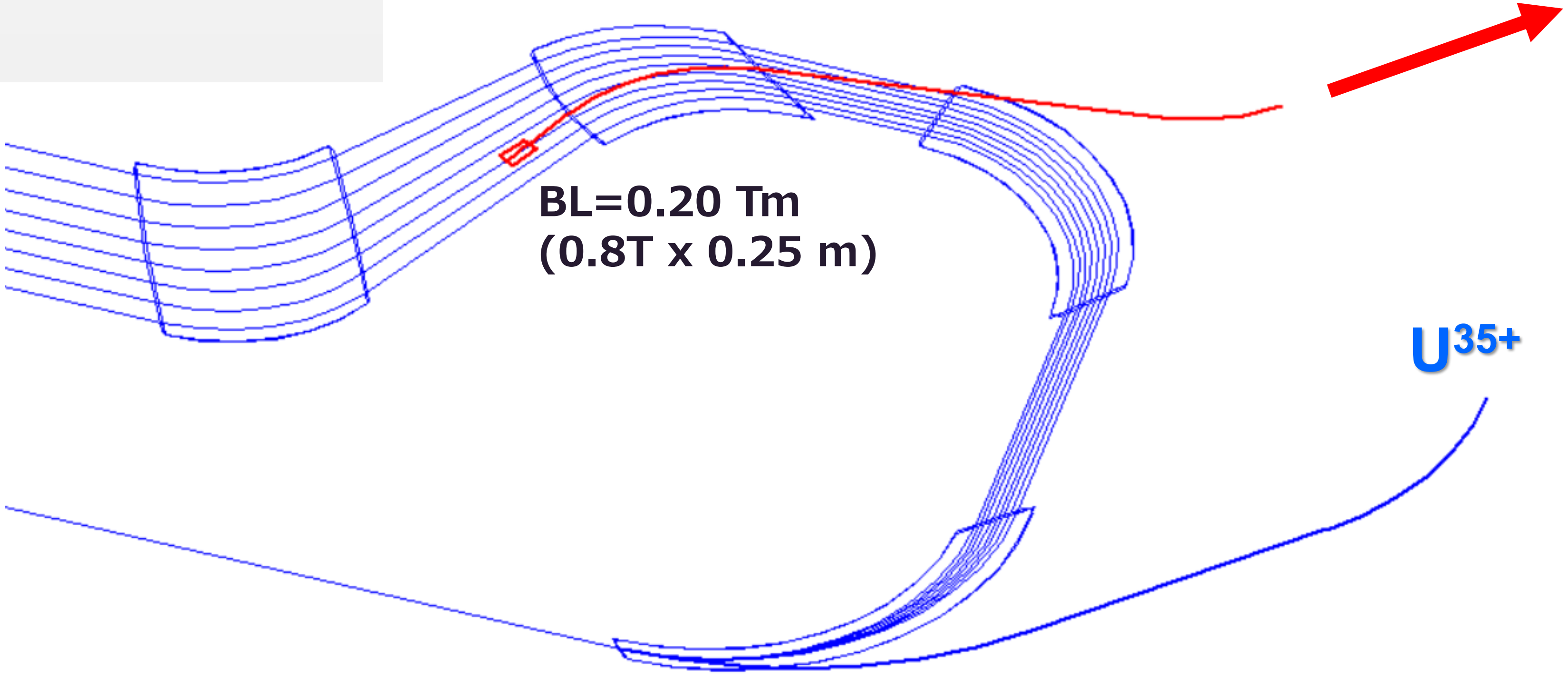
Magnet for beam extraction (EBM1)

Installation site of EBM1

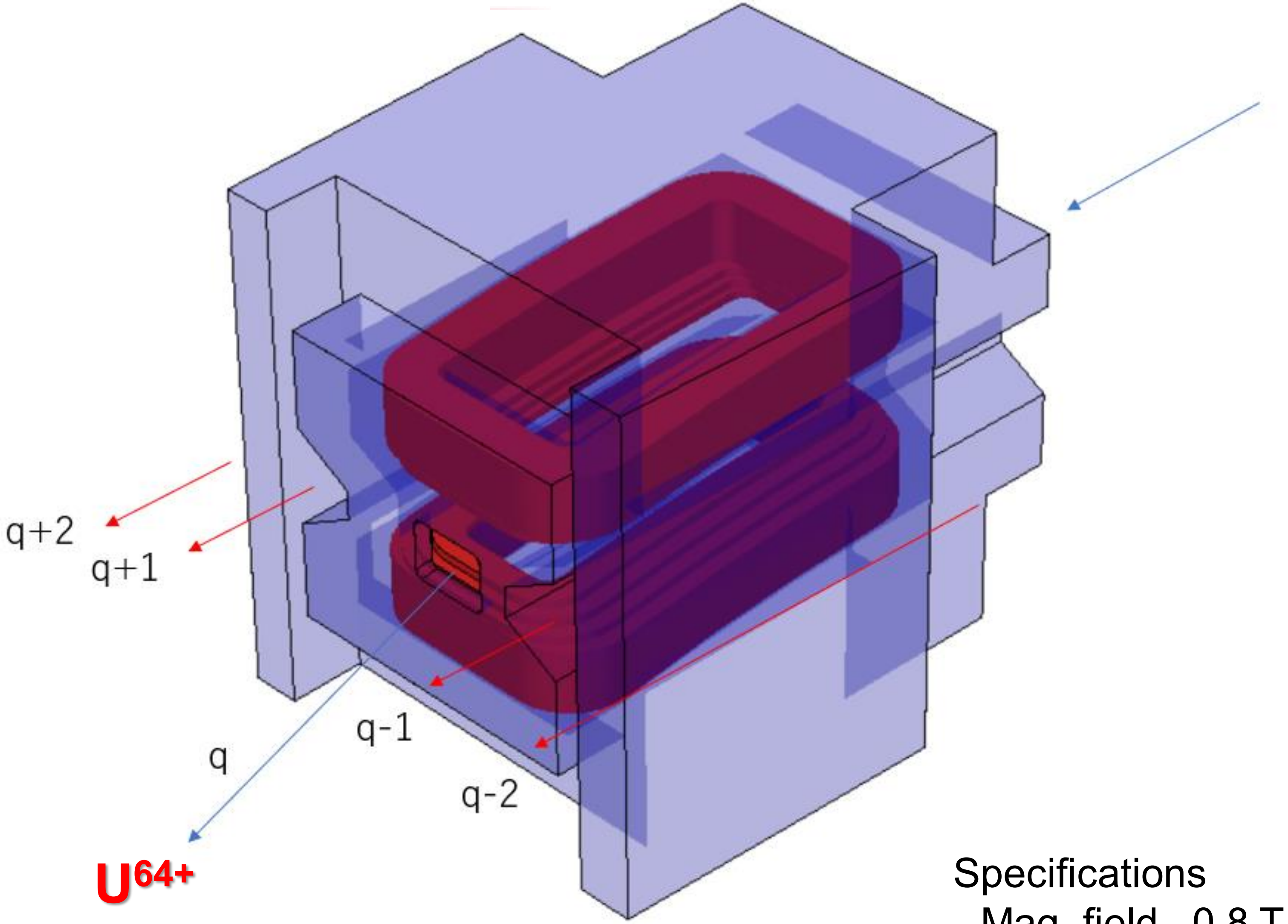


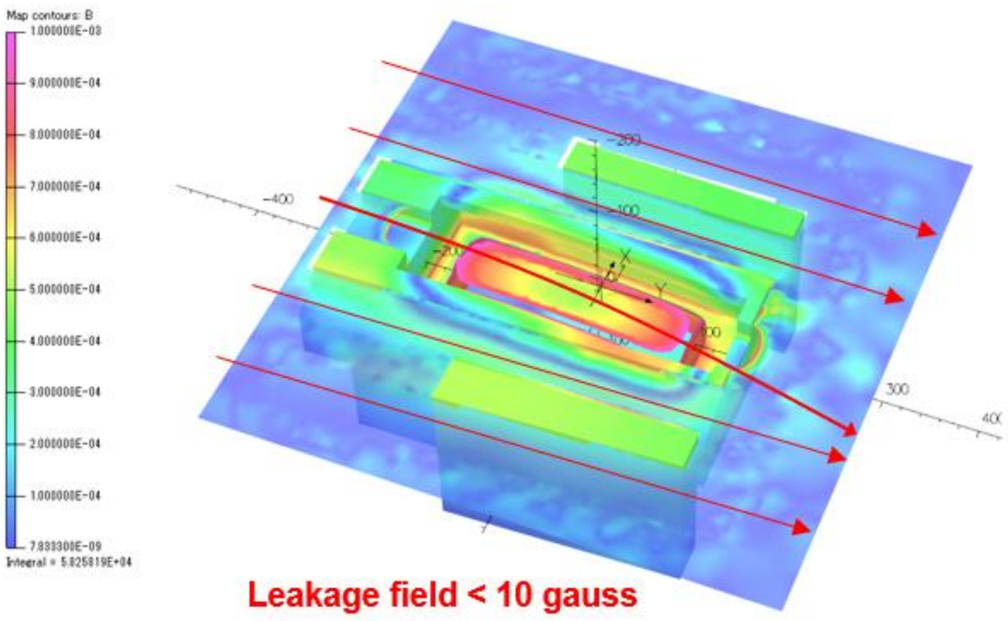
Very limited space for EBM1

continuous extraction with static magnetic field of EBM1



Design of EBM1

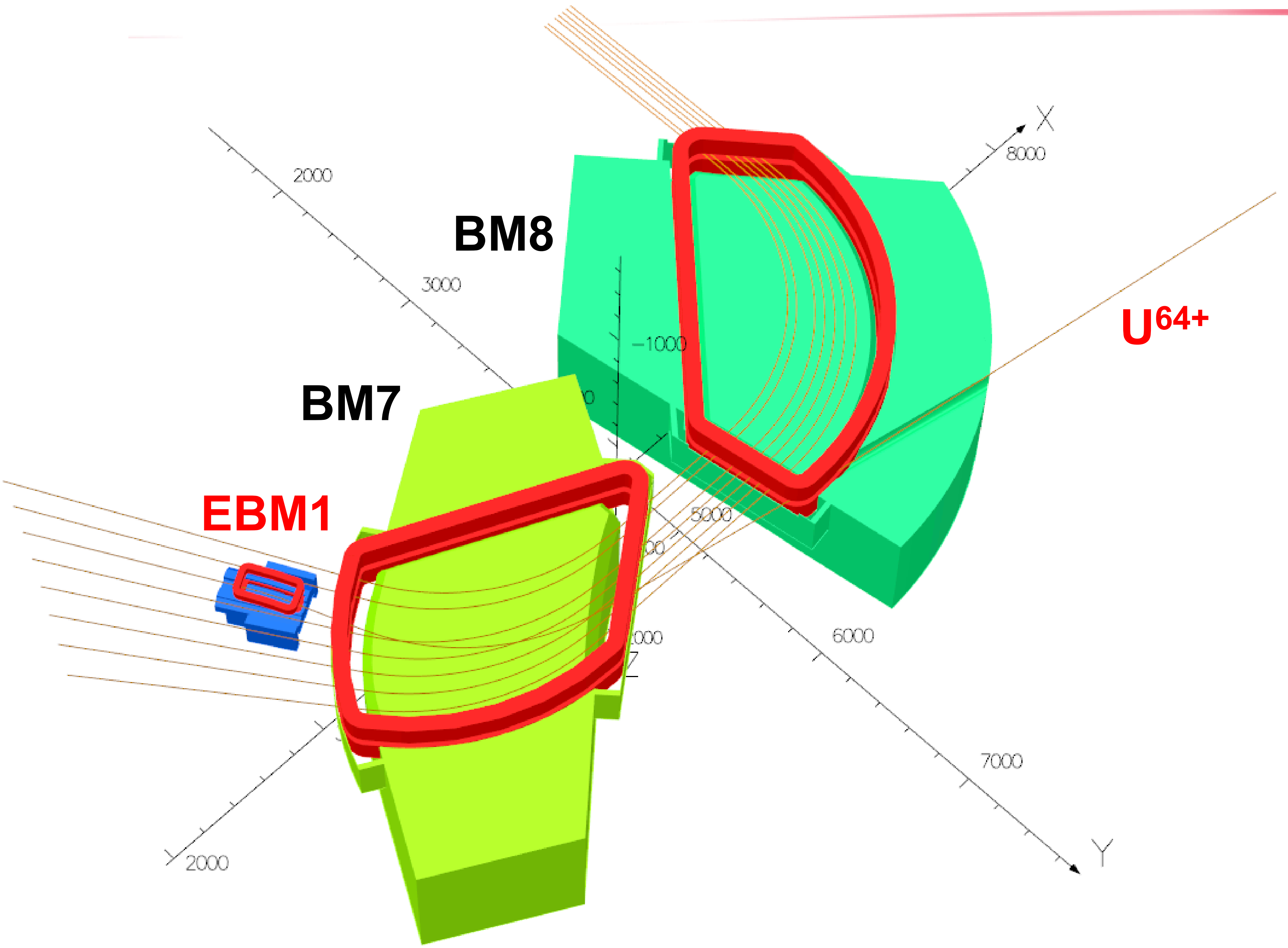




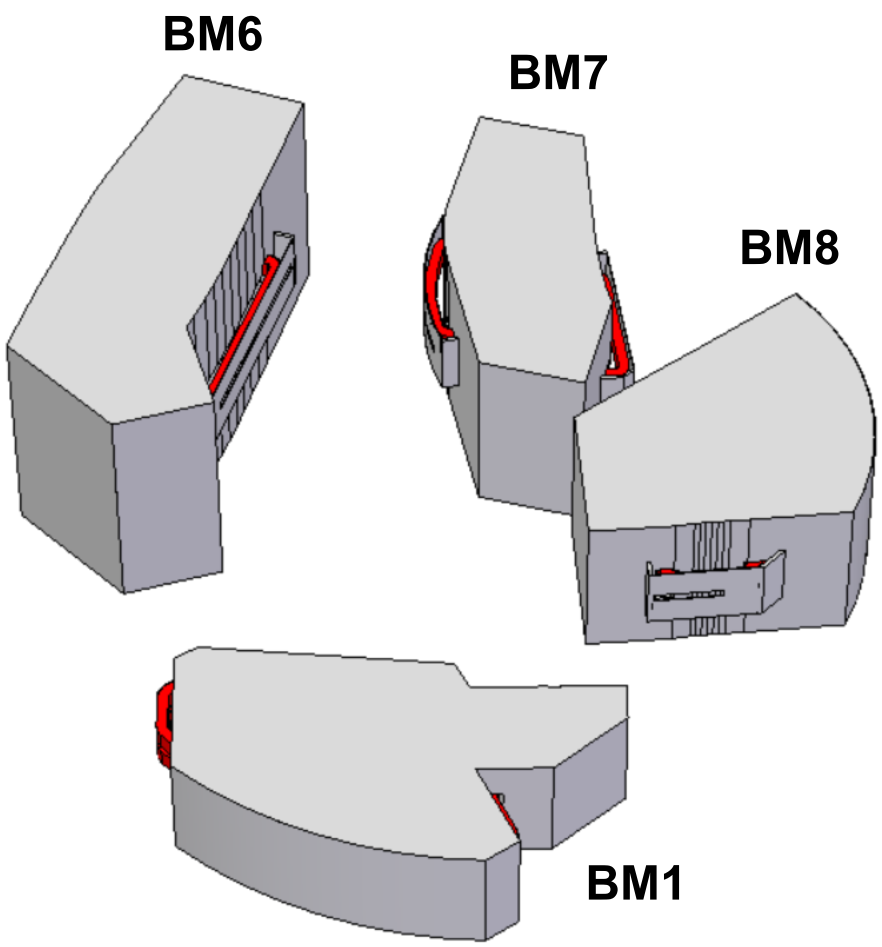
The structure has return yokes in four directions (front, back, left, and right) while keeping the paths of adjacent beams

Specifications
- Mag. field 0.8 T
- Mag. force 30000 AT
- Pole gap 45 mm
- Pole length 260 mm

Calculated trajectories for extraction



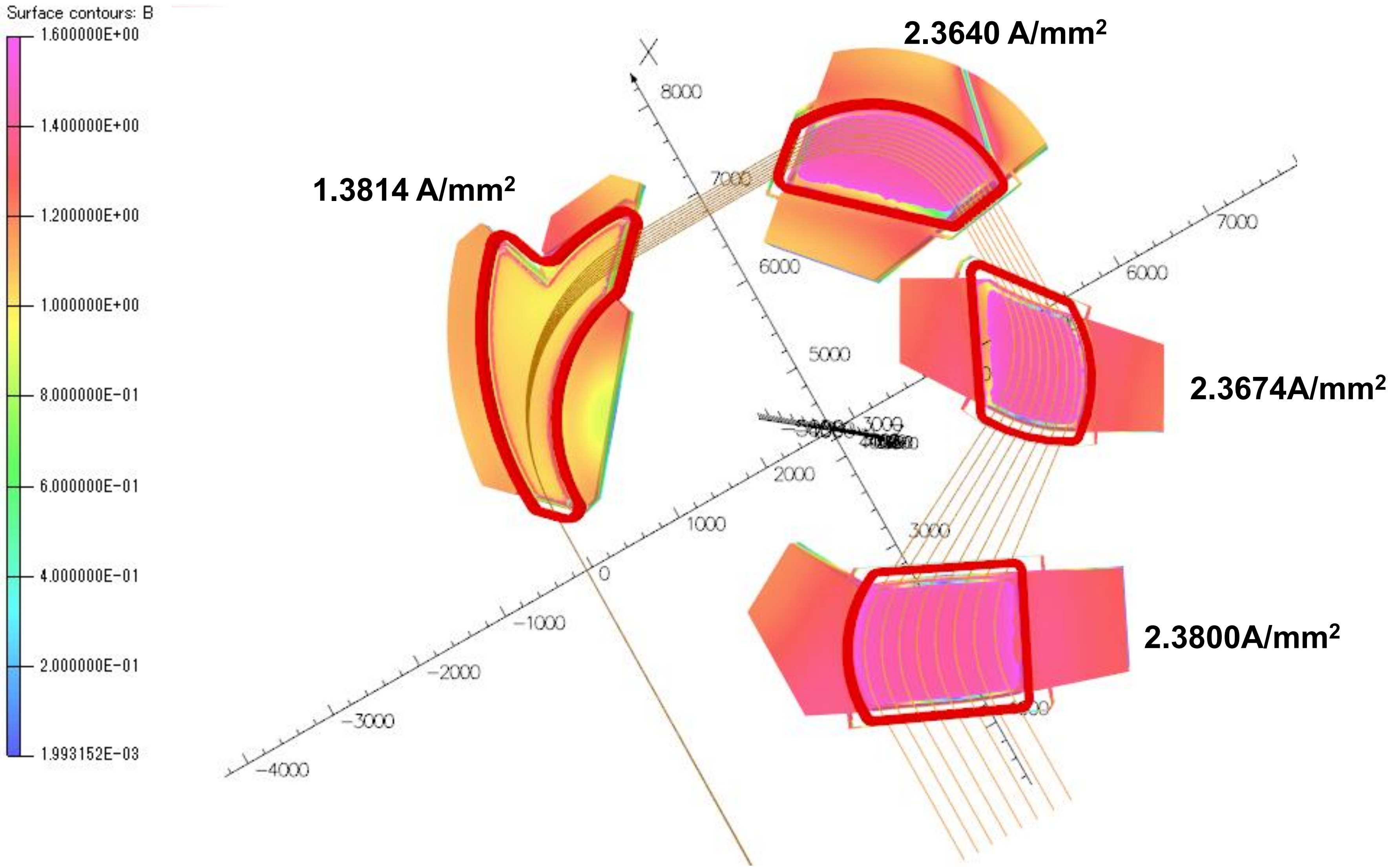
Parameters of bending magnets



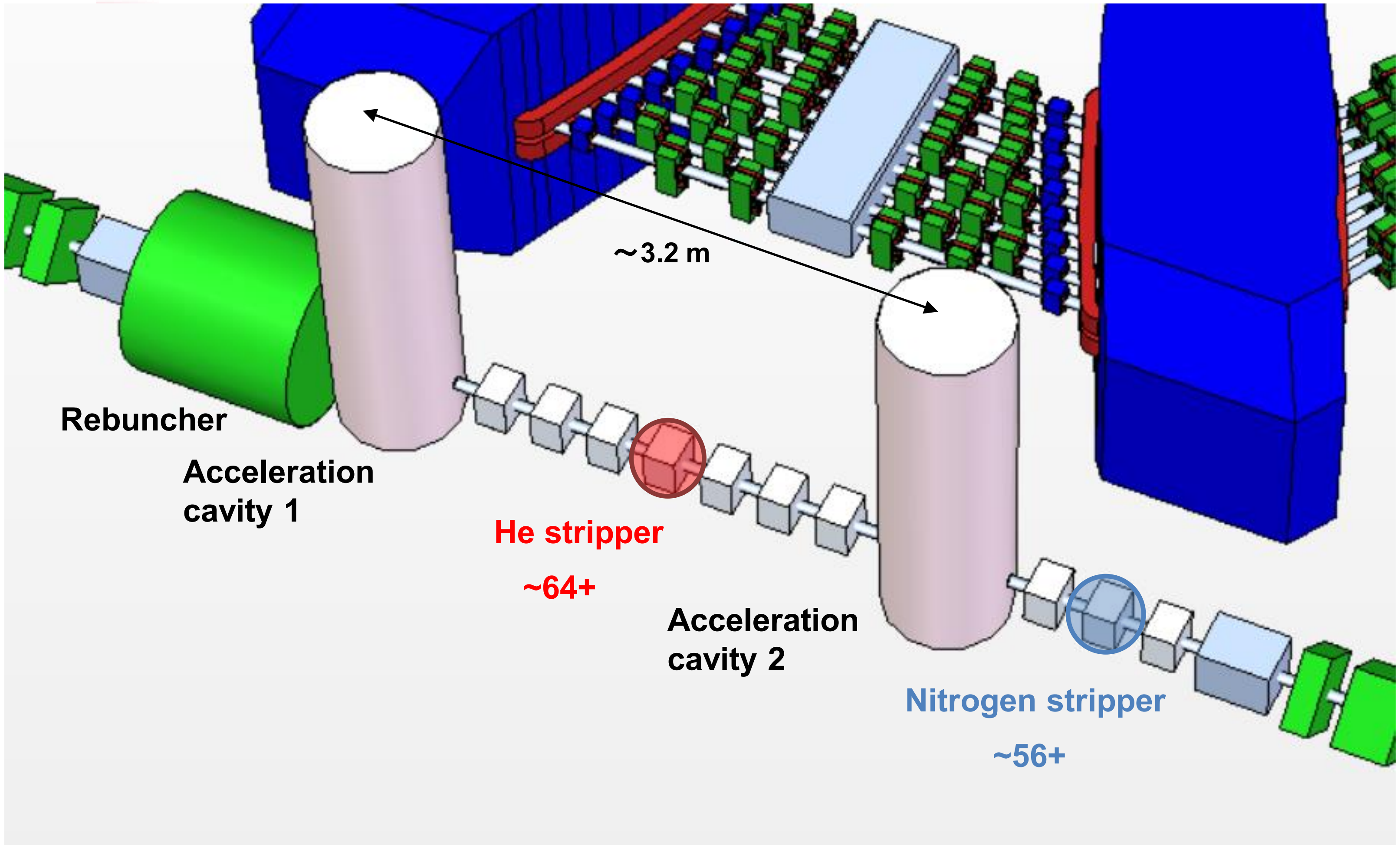
	BM1, 2	BM3, 8	BM4, 7	BM5, 6
magnetic field	1.0067 T	1.4261 T	1.4261 T	1.4261 T
pole gap	50 mm	45 mm	45 mm	45 mm
weight	25.5 t	32.6 t	28.5 t	56.3 t
height	930 mm	1525 mm	1285 mm	1925 mm
magnetomotive force	40200 AT	52300 AT	52300 AT	52300 AT
current	350 A	450 A	450 A	450 A
coil size	T134xH82 mm	T134xH82 mm	T134xH82 mm	T134xH82 mm
number of turns	120 turns	120 turns	120 turns	120 turns
hollow conductor	□12x ϕ 6 mm	□12x ϕ 6 mm	□12x ϕ 6 mm	□12x ϕ 6 mm

- Large pole area to bend 8-charge beams simultaneously
- Similar to sector magnets of ring cyclotrons while the beam separation is large
- Fine tuning of pole edges to adjust BL products to make isometric orbits for all charge states

Calculated orbits



Stripper section



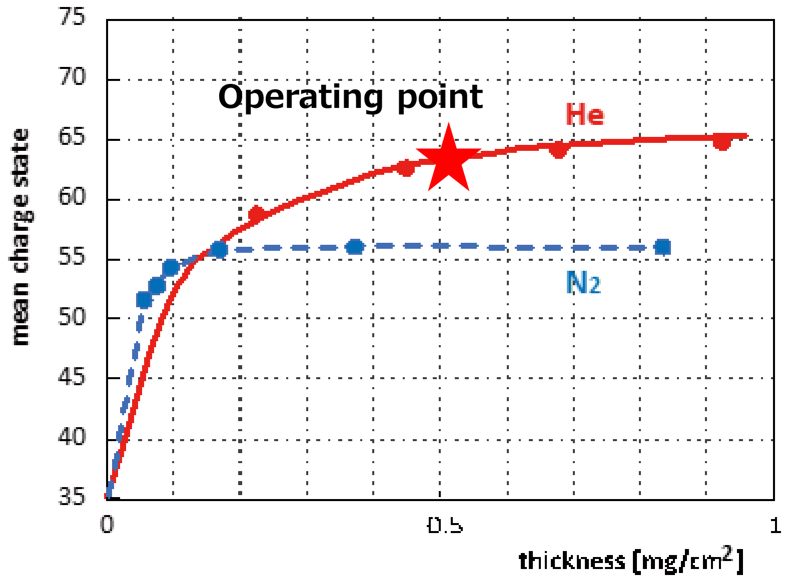
Stripper, acceleration cavities and re-buncher are placed in the stripper section

Gas strippers to withstand the injection of high-power uranium beams of up to ~38 kW

A two-stage stripper with N_2 and He arranged in series will be used.

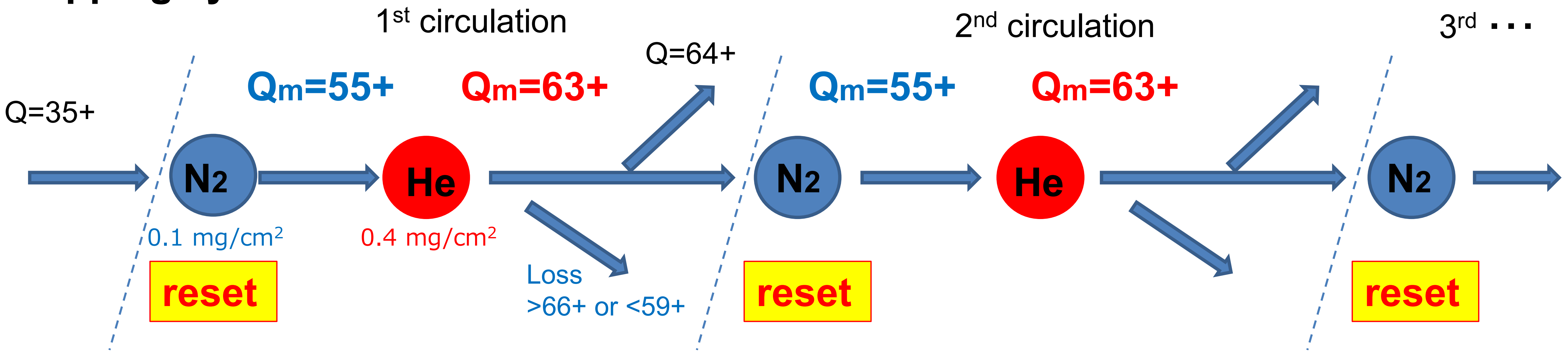
2-stage stripper

N_2 (~0.1 mg/cm^2) +He (~0.4 mg/cm^2)

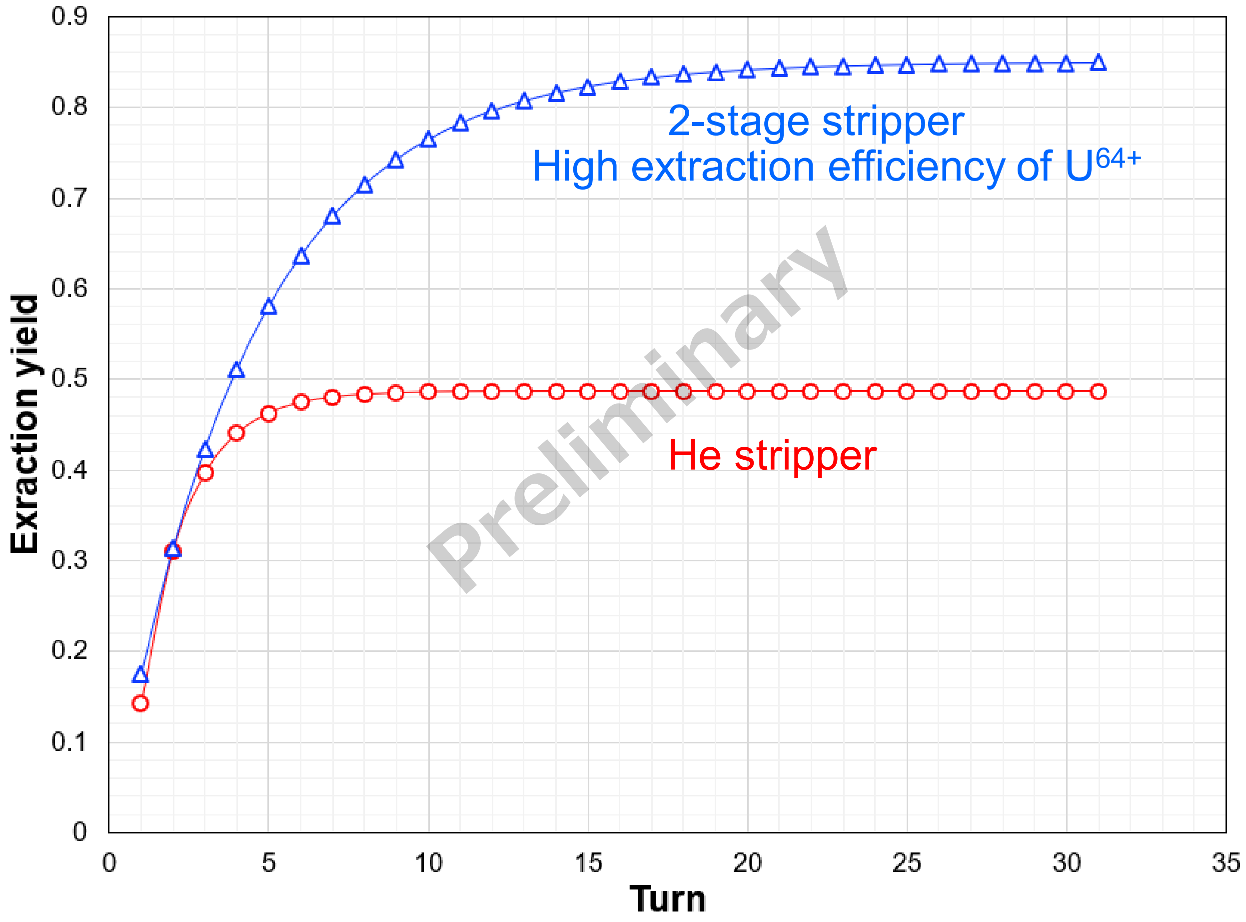


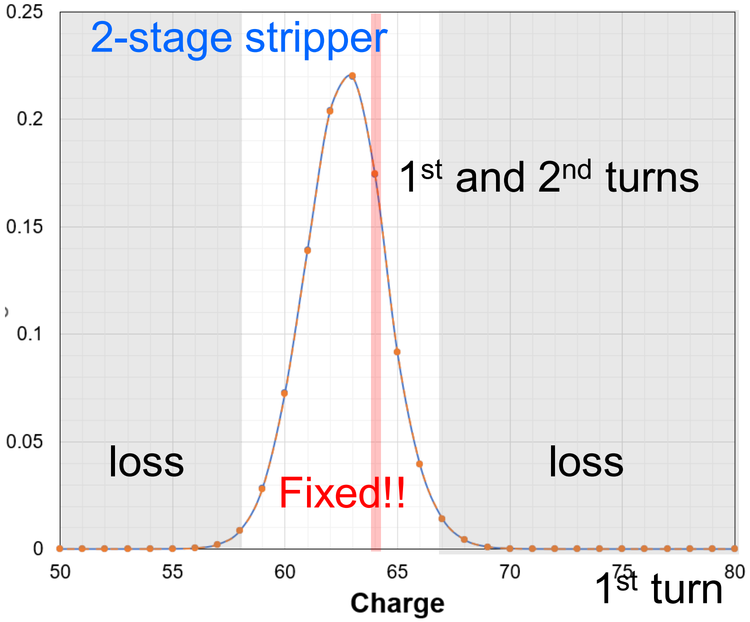
The charge state is reset with N_2 stripper every circulation, e.g., Q_m=55+
Average charge states during circulation are fixed, e.g., Q_m=63+
In the stripping cycle, beam loss due to charge states being out of range is reduced

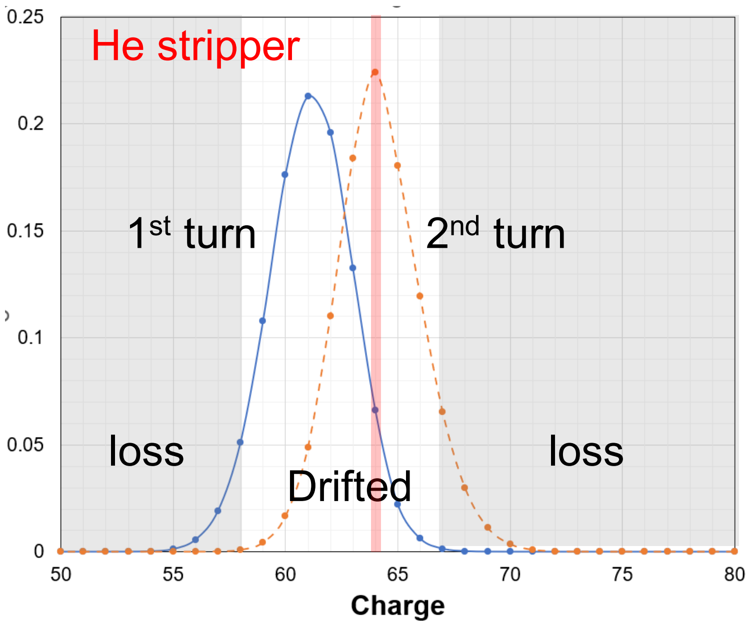
Stripping cycle



Calculation results of stripping cycle

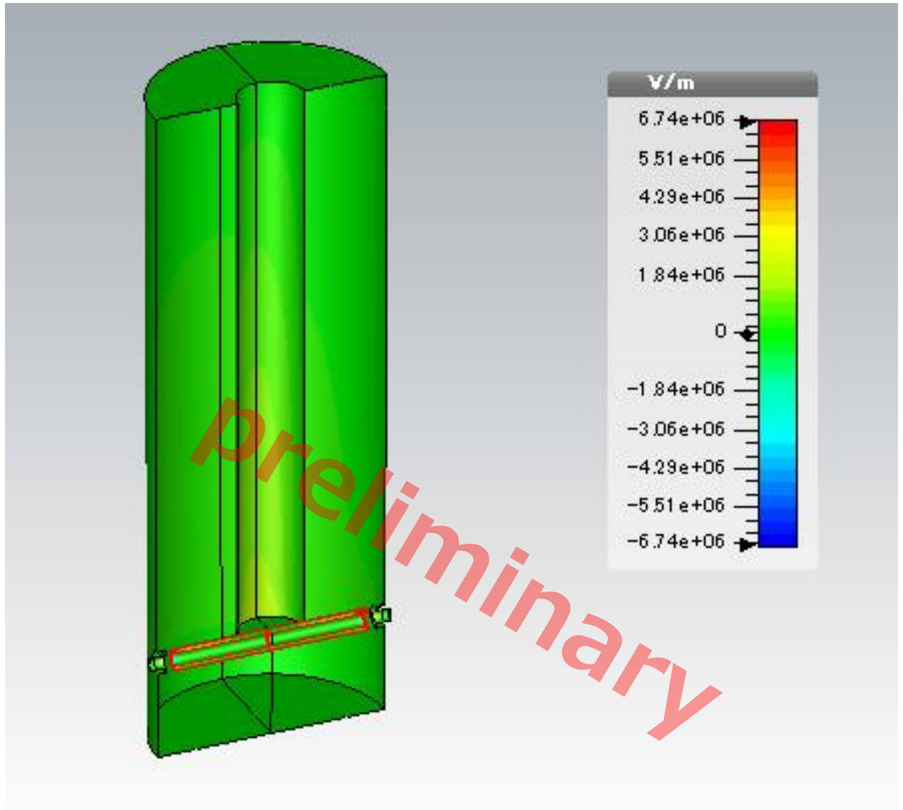






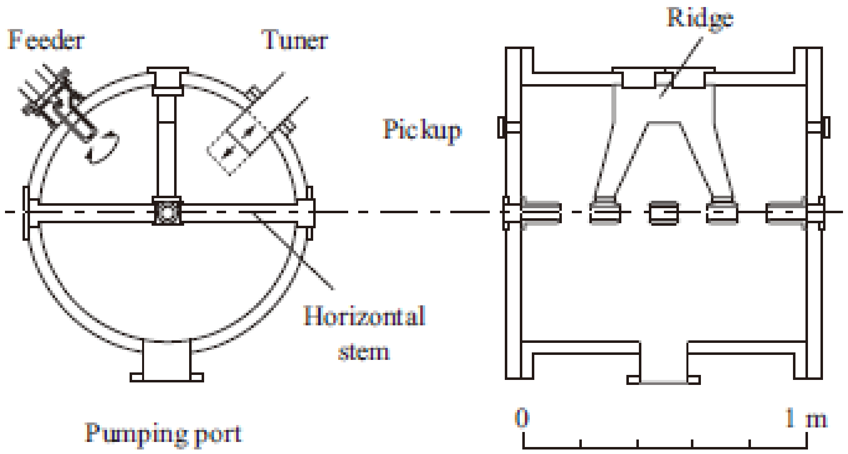
Calculated by Y. Miyake (RIKEN)

Design works of RF cavities



RF cavity for energy recovery

Freq.	36. 5	[MHz]
λ	8.21	[m]
βλ/2	0.62	[m]
λ/4	2.05	[m]
Phase of gap	20°	
Gap	0.0689	[m]
DTL length	0.5510	[m]
Voltage	～1	MV



Design of rebuncher can be based on the present rebuncher (109.5 MHz)

Emittance growth

Sources of emittance growth in CSR1

(The mean number of revolutions is ~3)

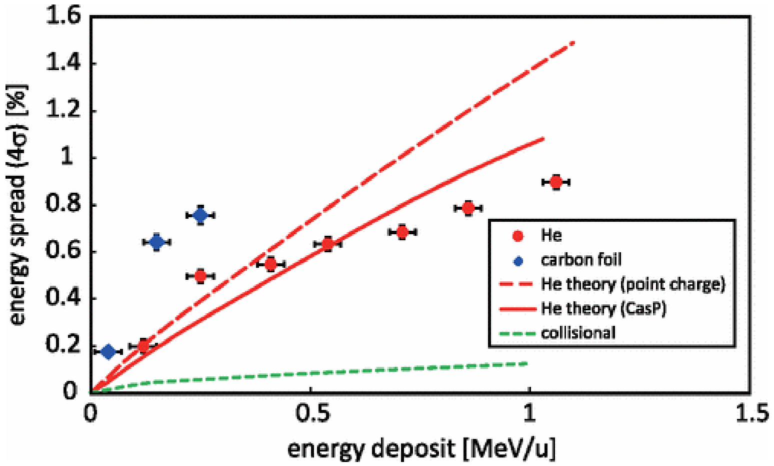
- **Charge-exchange energy struggling**

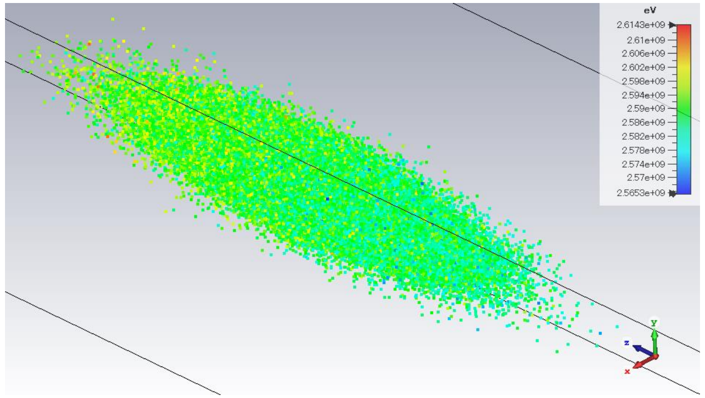
  $\delta p/p < \sim 0.12\%$ (2σ)

- Angular struggling

  $\sigma \sim 0.3$ mrad (N_2), 0.4 mrad (He)

- Energy recovery process
- Space charge effect (negligible)

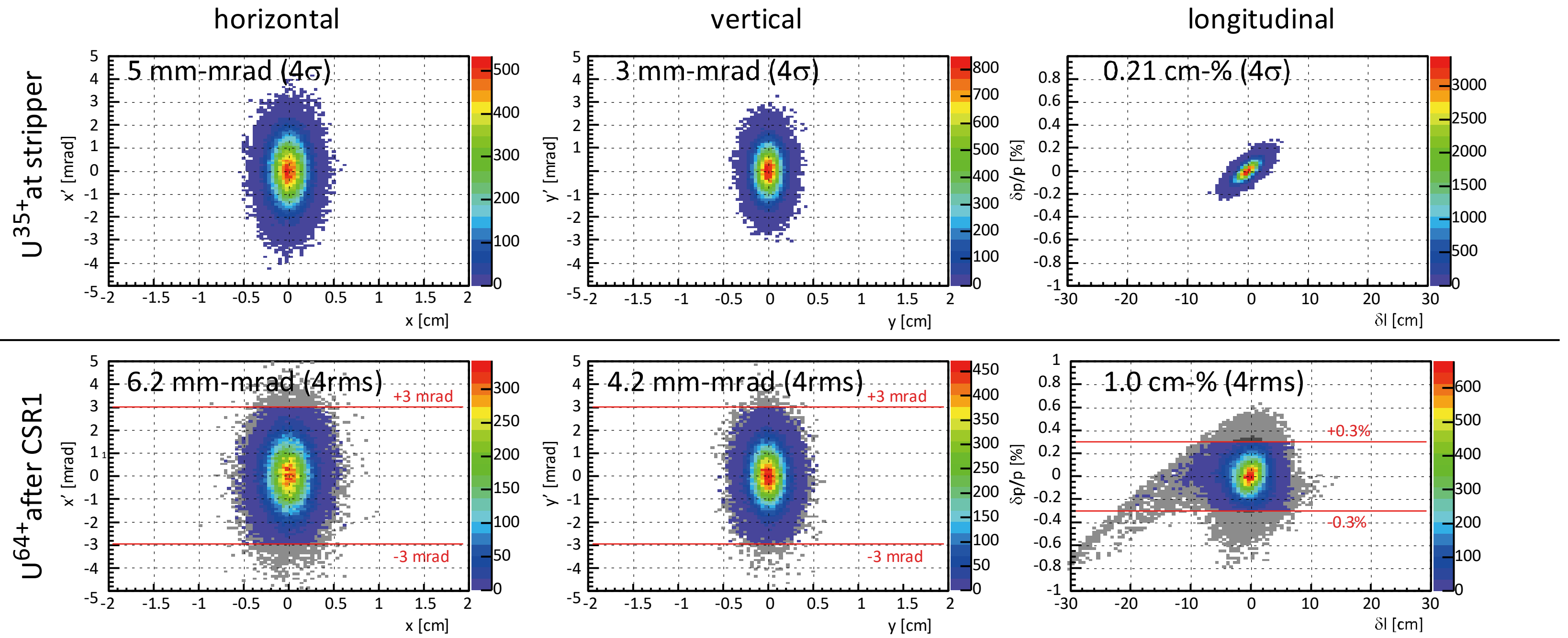




Matrix calculation with 2-stage strippers

Injection beams

Extracted beams

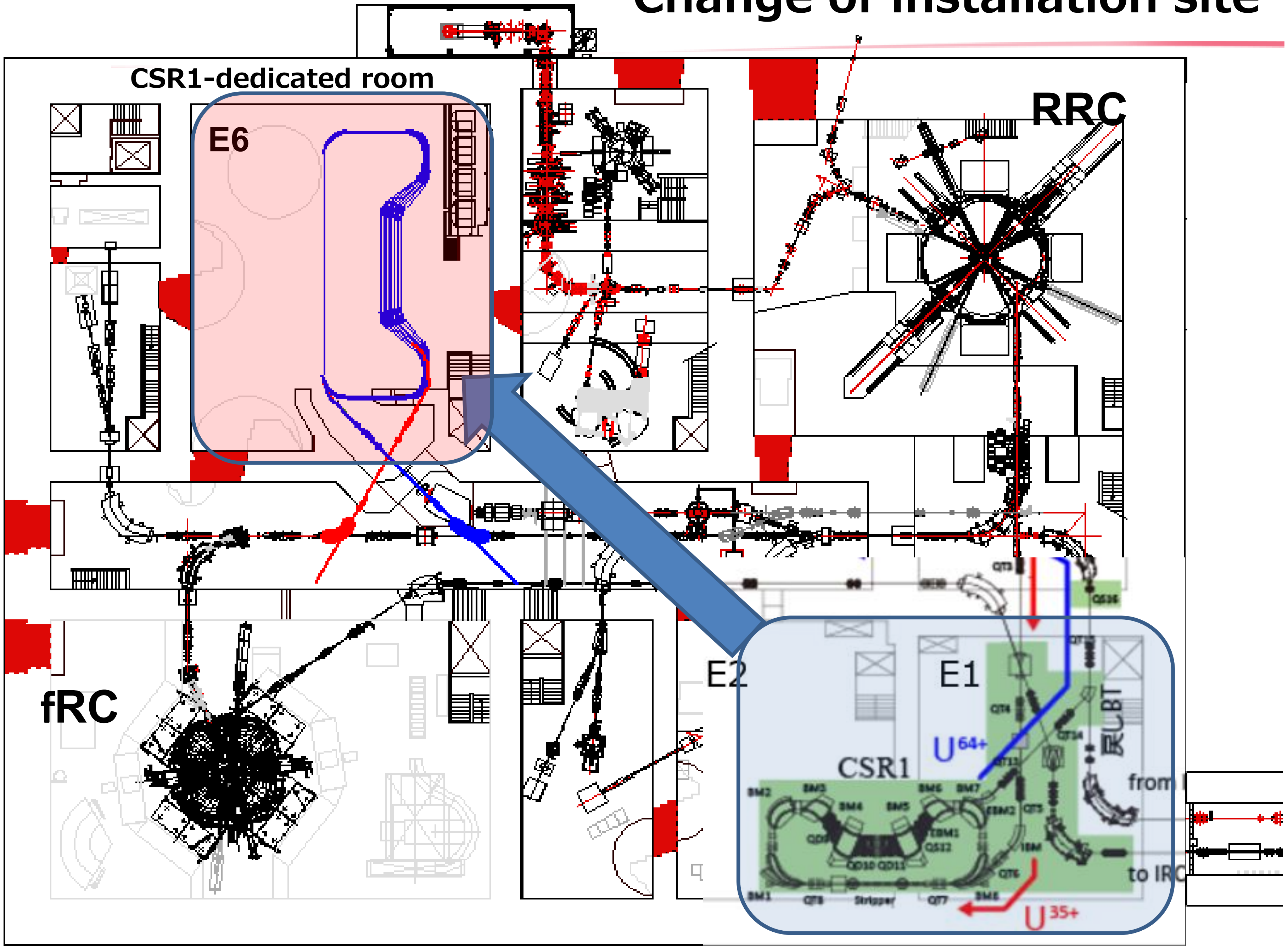


- Emittance growths in transverse are well controlled（eigen ellipse matching)
- Emittance growth due to the charge-exchange struggling is unavoidable in the present longitudinal optics (appropriate slits to cut beams out of acceptance)

Extraction efficiency ~75%

Loss due to energy struggling 14% (cut >±0.3%)
Loss due to charge state being out of range 10% (2-stage stripper)

Change of installation site

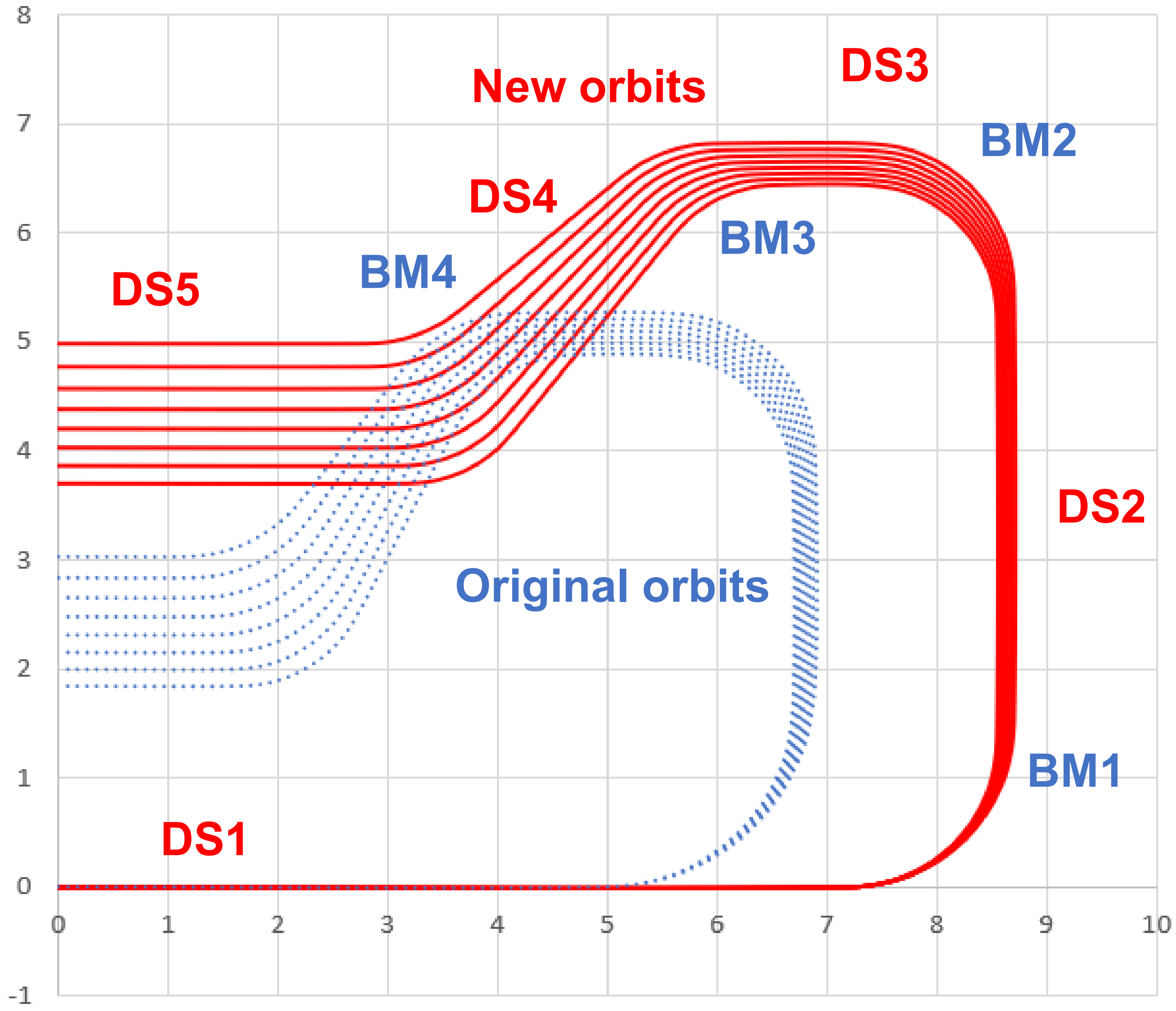


Changing the design of CSR1 for the better

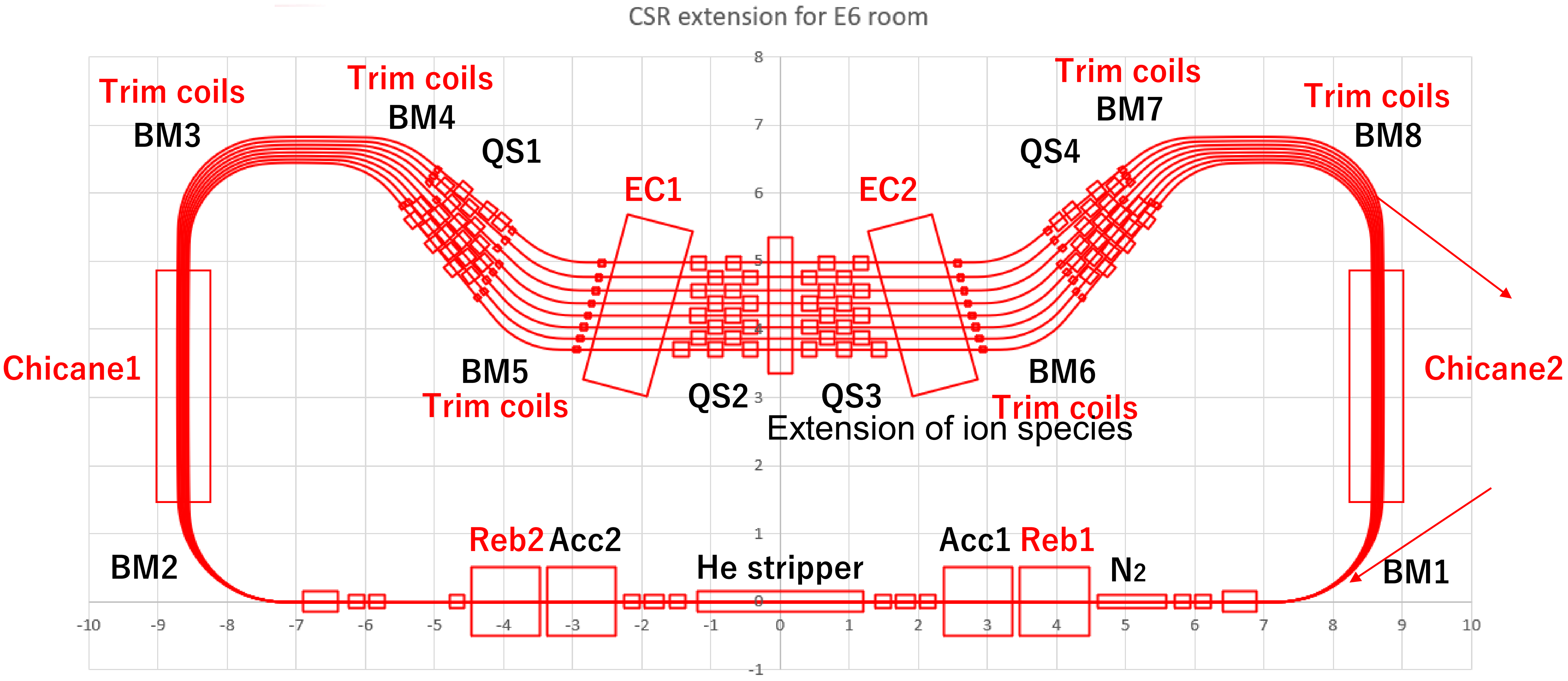
CSR1 extension (CSR1ex)

Expand equilibrium orbits to fit to the large room

Additional functions in CSR1ex being considered



Arrangement diagram of main components in CSR1ex



Additional functions of CSR1ex

①Double rebuncher at DS1（longitudinal optics）

②Strong focusing at DS1（transverse optics）

③Chicane sections for Pb, Pt, W and Xe

④Trim coils for BM3-8

⑤Selective extraction charges (63, 64)

⑥Charge independent energy correctors at DS5

Chicane section for other ions

Chicane sections with 4 dipoles (CBM1-4)

Adjustment of orbit length with bump

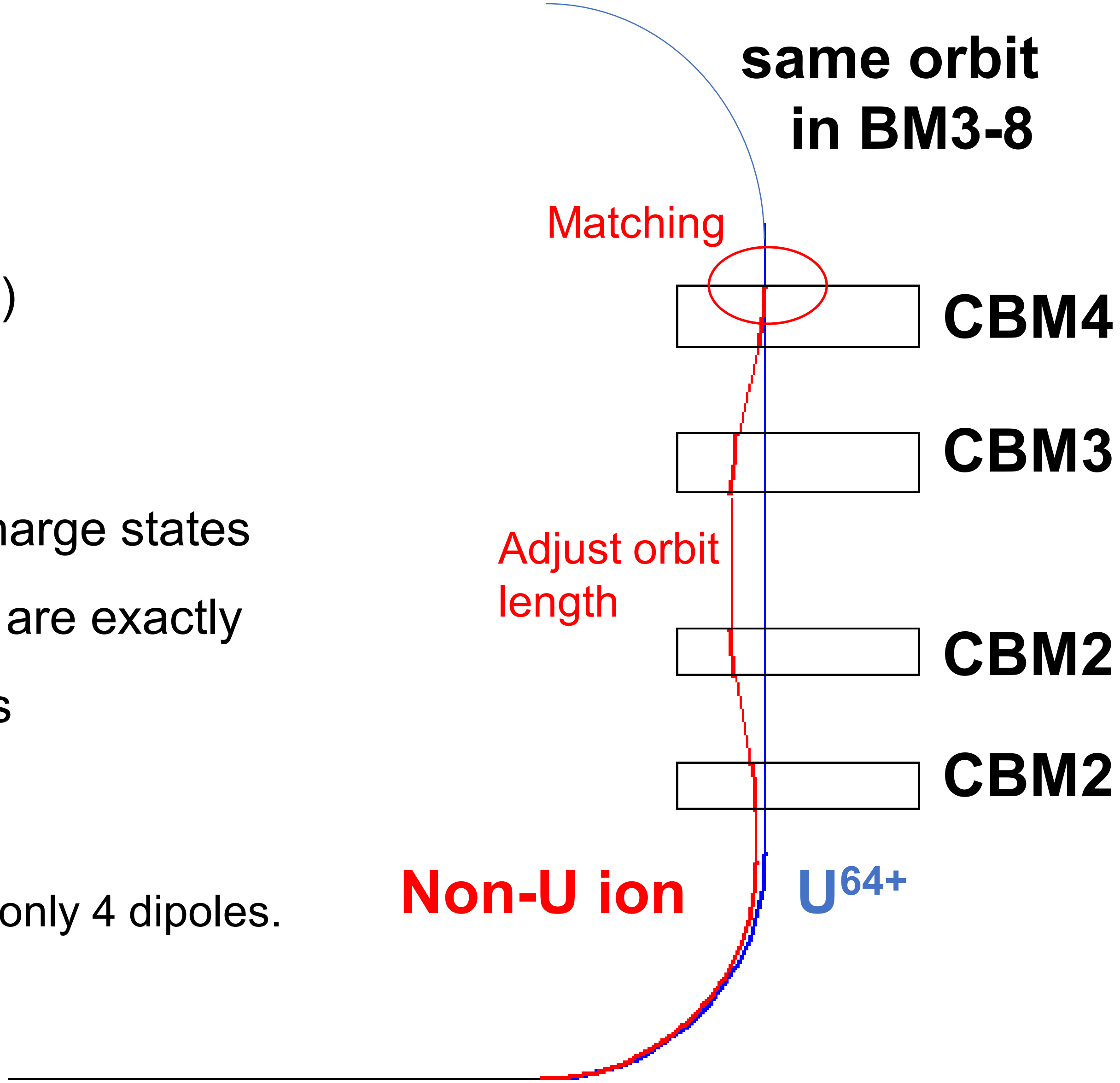
Matching with ^{238}U orbits (dispersion matching)

Trim coils in BM3-8

Trim coils will be installed in BM3-8 for all charge states

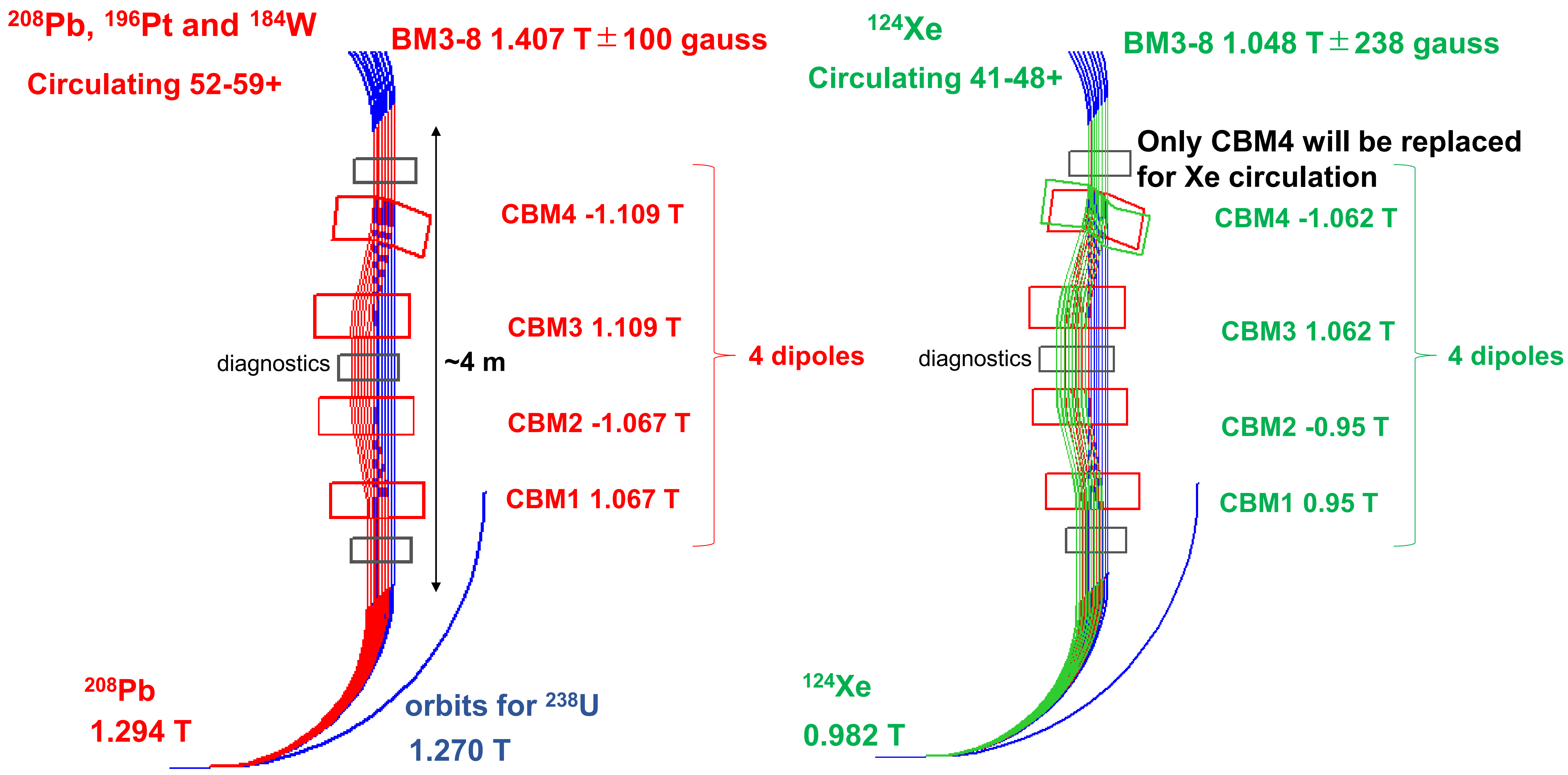
After the chicane section, non-U ion's orbits are exactly

the same as U's orbits by adjusting trim coils



Simultaneous adjustments for all charge states with only 4 dipoles.
The design procedure is similar to that for the CSR.

Design orbits for non-uranium ions



Summary and future prospects

- The performance of the RIBF accelerators is improving steadily.
- Upgrade plan with CSRs is under consideration aiming 20-fold increase of ^{238}U intensities.
- Calculations, design and construction of key devices of CSR1 are undergoing so that it can be built as soon as the budget is approved.
- Installation site for CSR1 is being finalized and the new functions will be added.
- TAC meeting for the upgrade plan with CSR1 are planning to organized in the next year.

Total cost $100 M	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year	8th year	9th year
①CSR1 ($35 M)	design		fabrication		installation				
②SRC RF upgrade ($26 M)	design	fabrication			installation				
③CSR2/fRC-IRC matching ($35 M)			design		fabrication		installation		
④BigRIPS beam dump upgrade ($9 M)		design			fabrication		installation		
beam supply ($40 M/year)						400 pnA			2000 pnA

Acknowledgement

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- SIGMAPHI M. Sugitani, W. Beeckman
- TOYAMA N. Kuwahara, D. Kobayashi