2024 INTERNATIONAL TOPICAL MEETING ON NUCLEAR APPLICATIONS OF ACCELERATORS

Charge stripper ring for RIBF

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on behalf of Accelerator Group at Nishina Center, RIKEN

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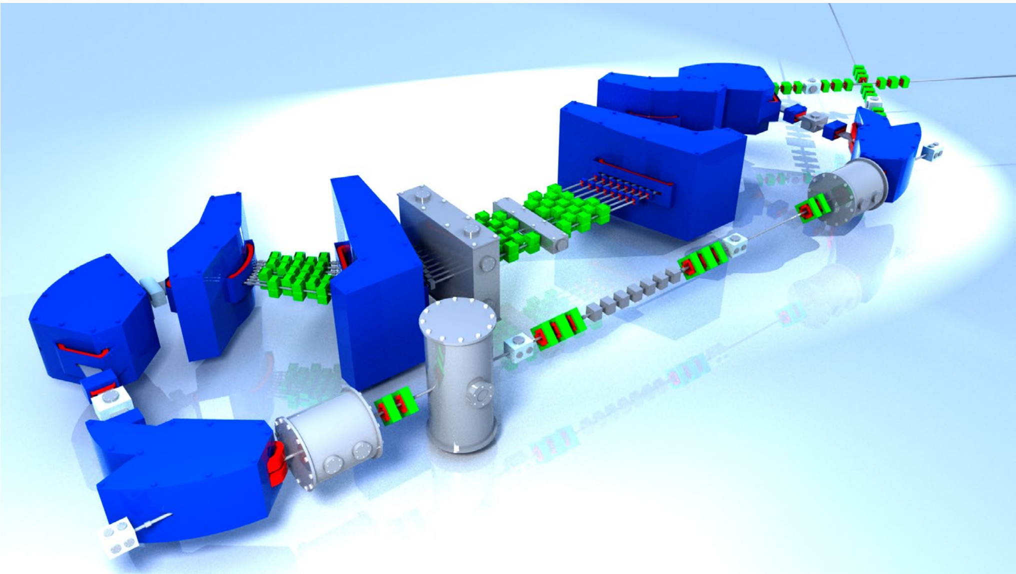
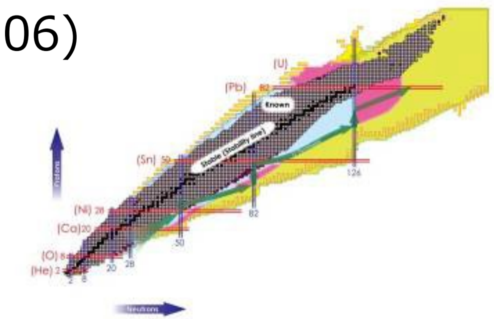
Table of contents



RIKEN RI beam factory (RIBF)

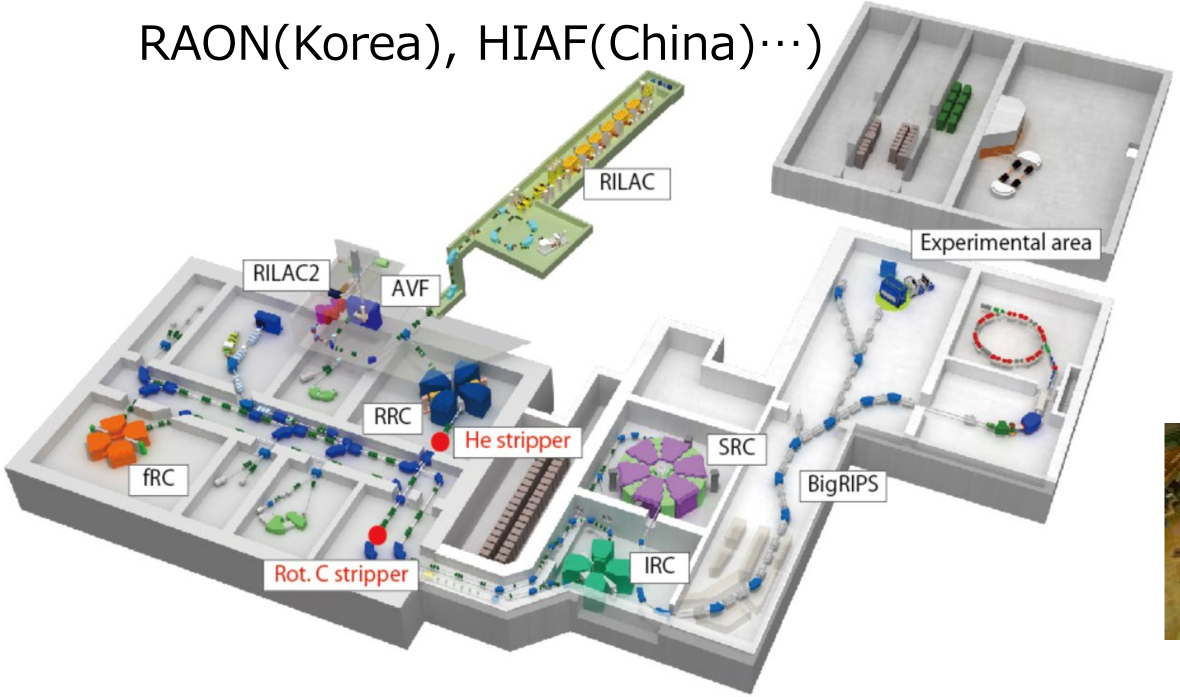
RIBF

- 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

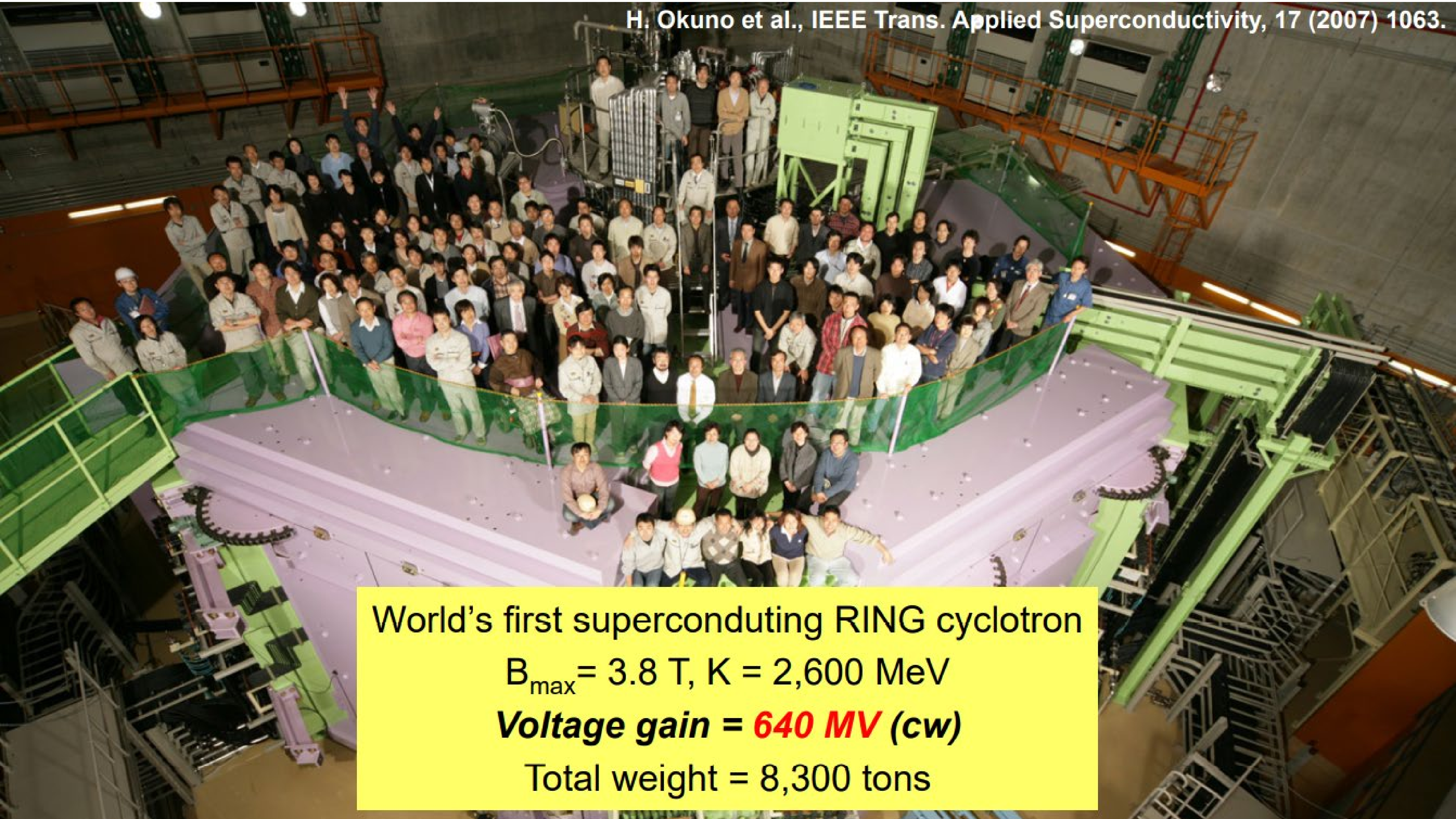
- Generation of in-flight fission RI beams (A~100) for elucidation of elemental synthesis
- Only 0.1% of the goal intensity 1 pμA（ion sources, strippers, space charge effects)
- Construction of next-generation facilities worldwide (FRIB(USA), FAIR(Germany), RAON(Korea), HIAF(China)…)



	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



H. Okuno et al., IEEE Trans. Applied Superconductivity, 17 (2007) 1063.



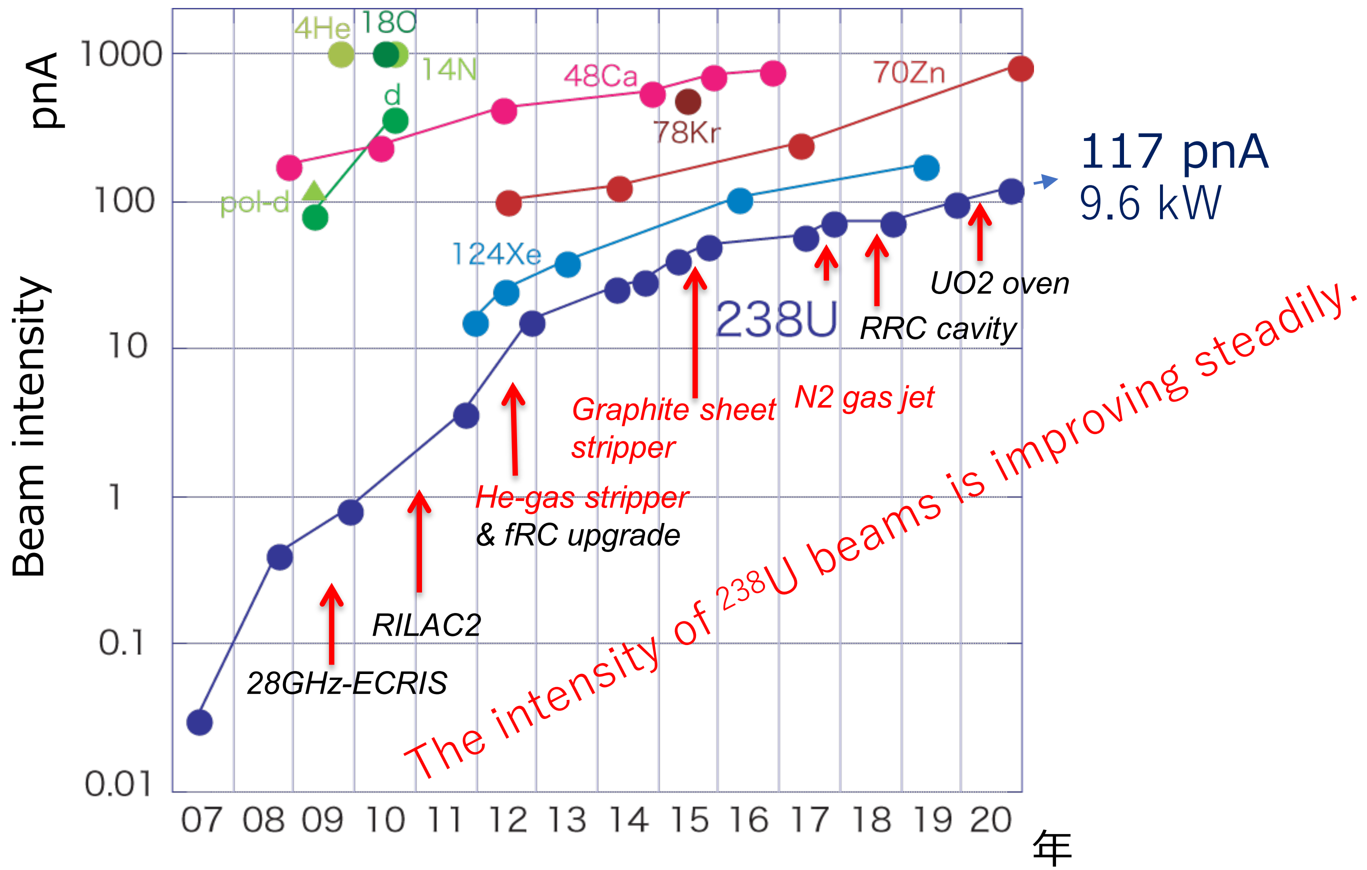
World's first superconduting RING cyclotron

B_{max}= 3.8 T, K = 2,600 MeV

Voltage gain = 640 MV (cw)

Total weight = 8,300 tons

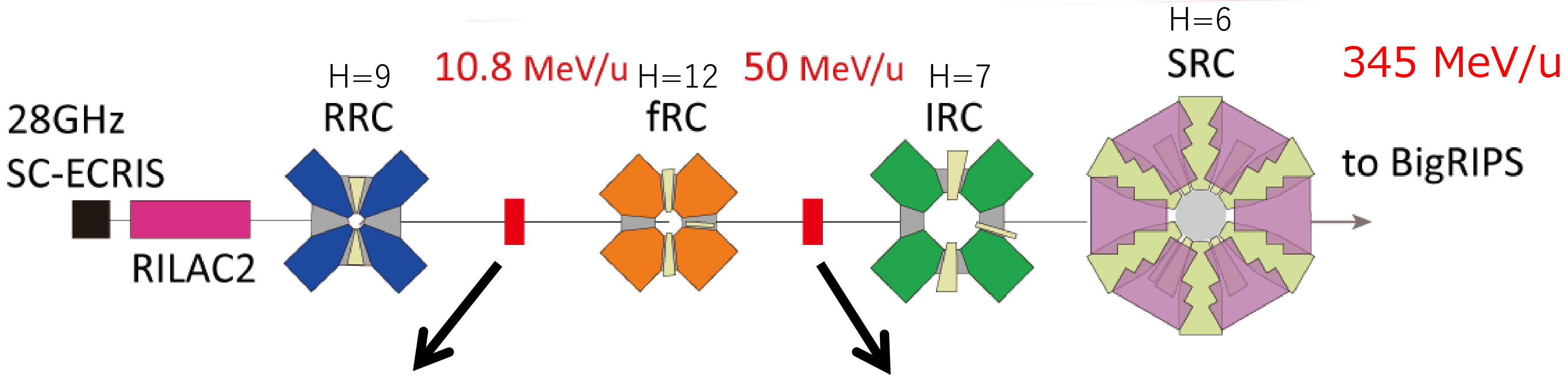
Intensity upgrade of ^{238}U



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

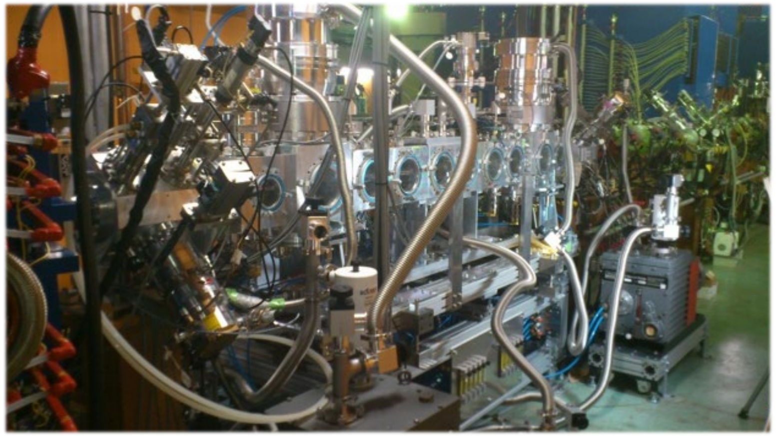
- Improvements of 28GHz-ECRIS and injector (RILAC2)
- **He gas stripper** and graphite disk stripper (lifetime problem)
- Refinement of accelerator operation techniques
- RF cavities upgrade for RRC (space charge problem)

Acceleration scheme of ^{238}U at RIBF



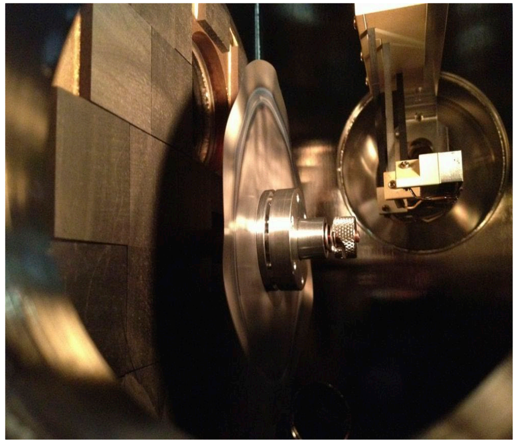
1． He gas stripper
(since 2012)

35+⇒64+ (20%)



2． Rotating disk stripper
(since 2012)

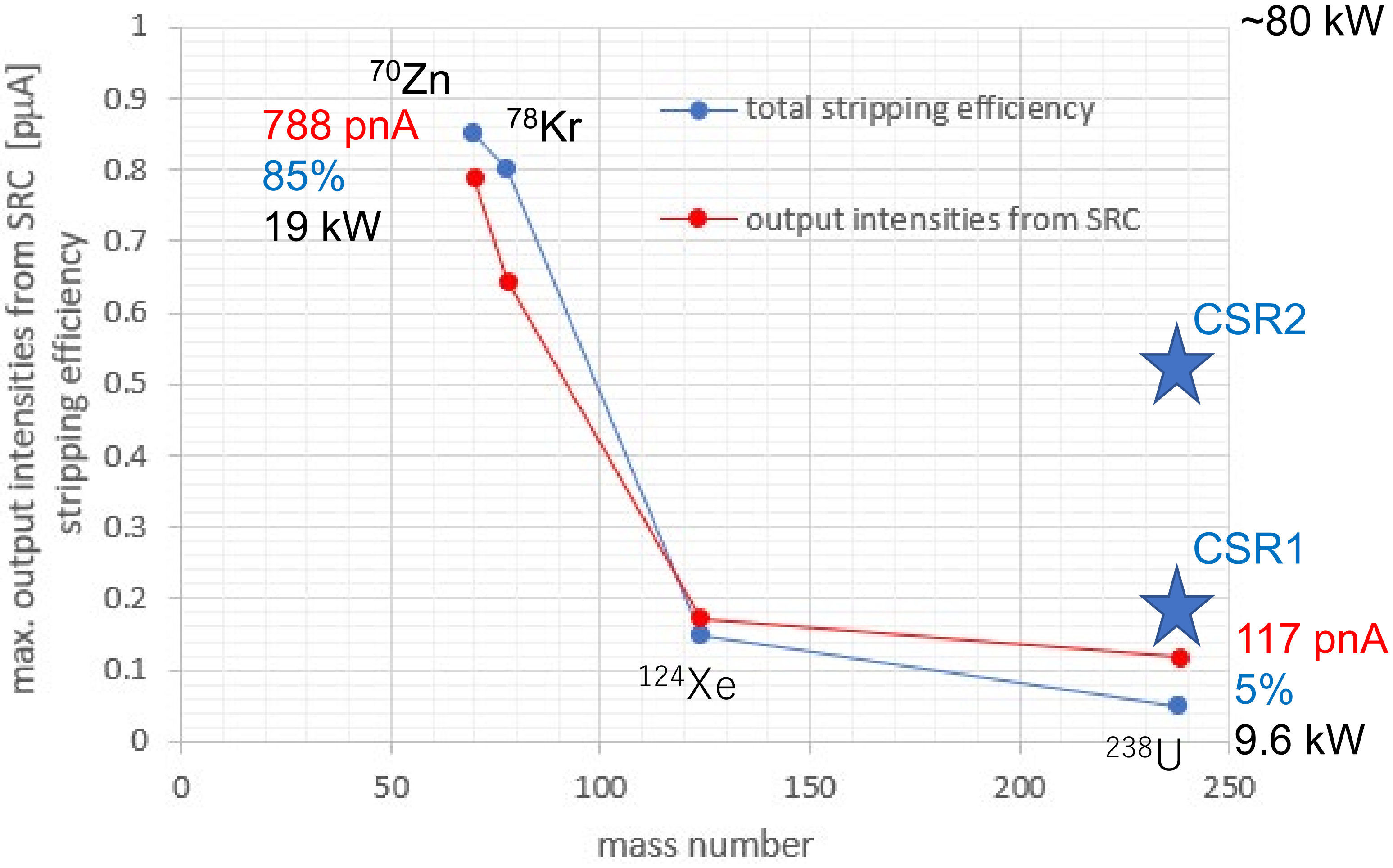
64+⇒86+ (25%)



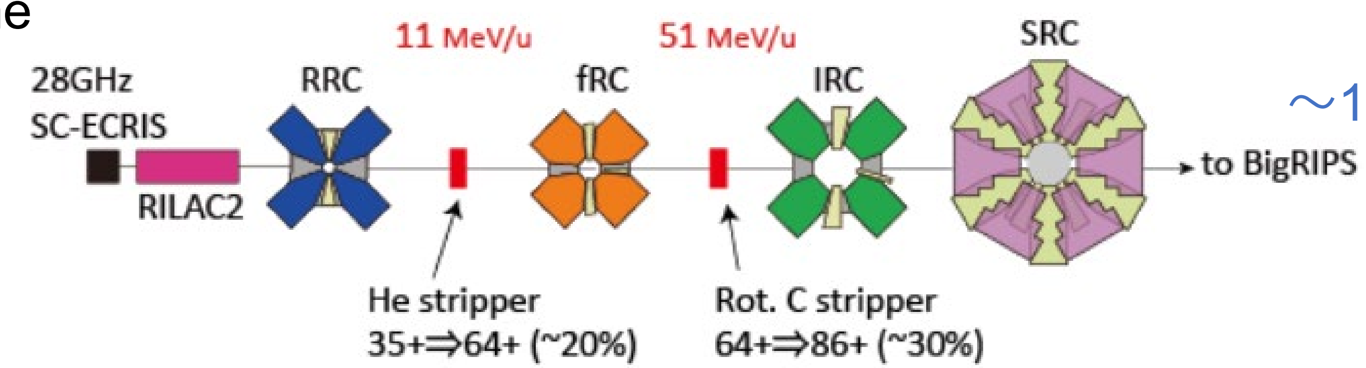
Conventional carbon foil strippers cannot be applied for U acceleration

Dependence of total charge stripping efficiency on mass

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



Present scheme



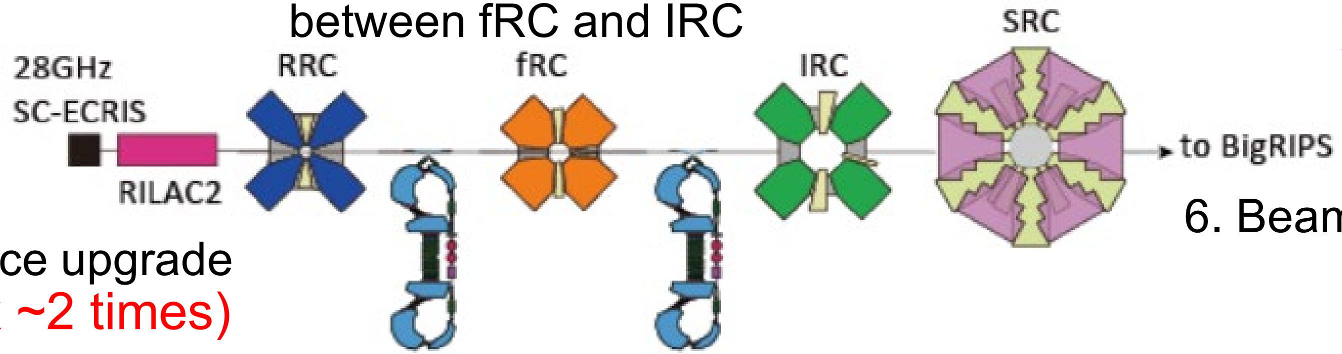
～100 pnA

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 (x ~2 times)

4. CSR1

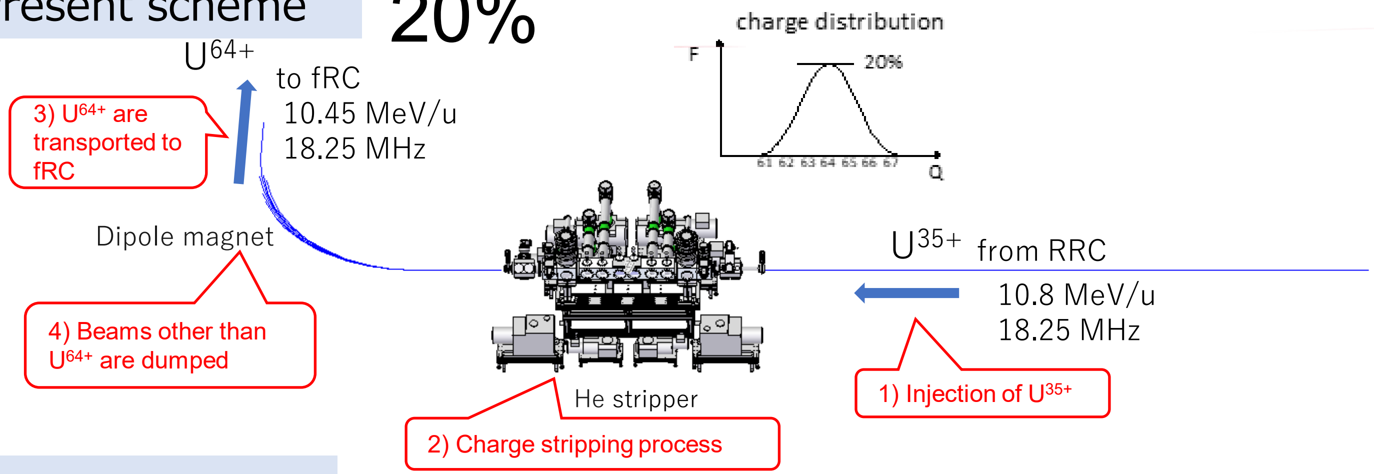
5. CSR2

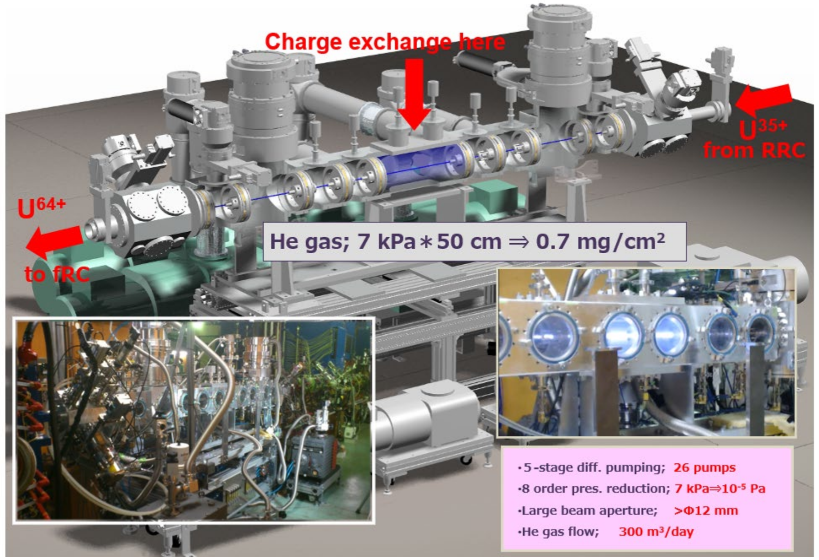
total ~50%

(x 10 times)

Present scheme

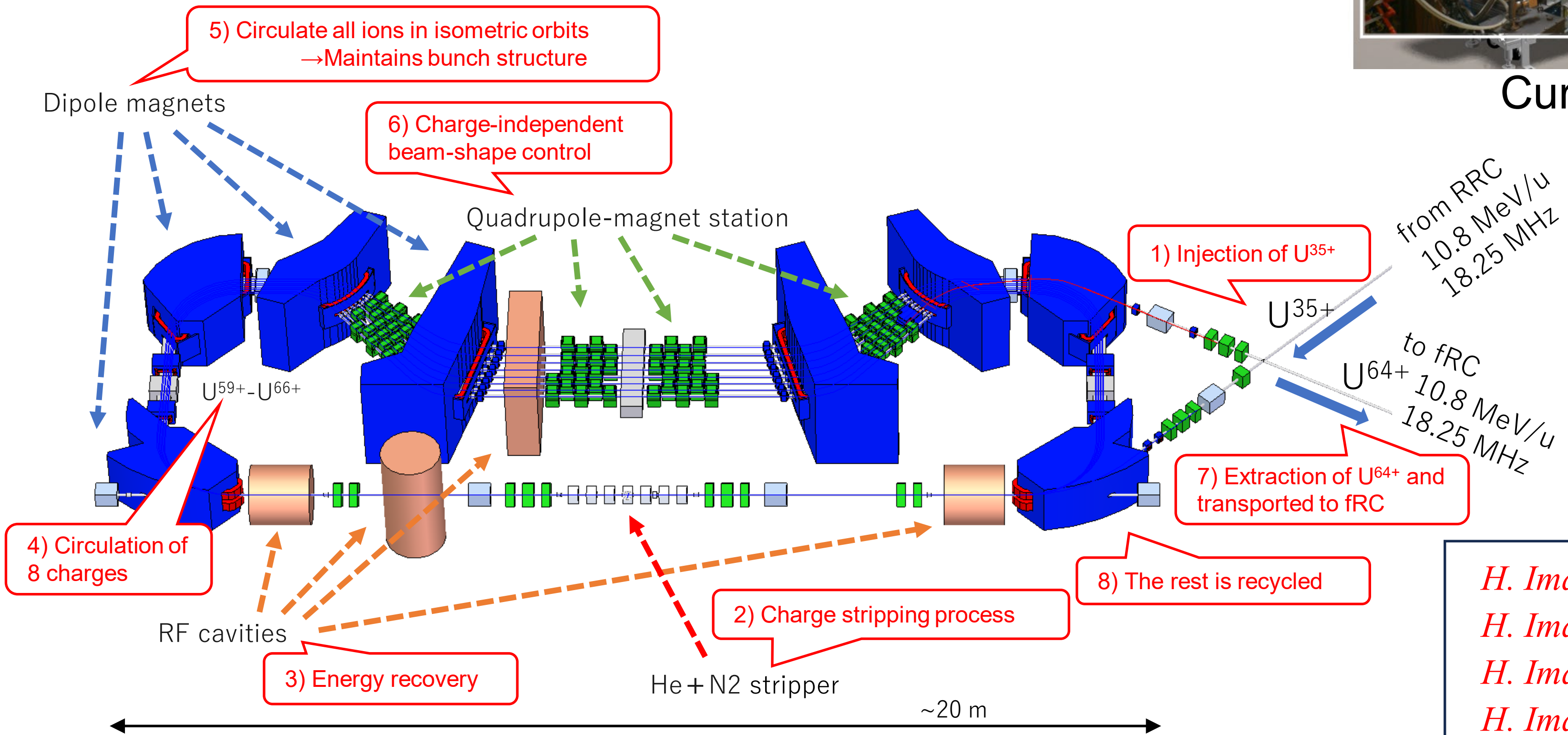
20%





Current He gas stripper

CSR1 scheme



Charge Strippers + recirculation Ring (59-66+)
= Charge Stripper Ring 1 (CSR1)

\>70% $\varepsilon_r \varepsilon_q/(1-\varepsilon_r+\varepsilon_r \varepsilon_q)$

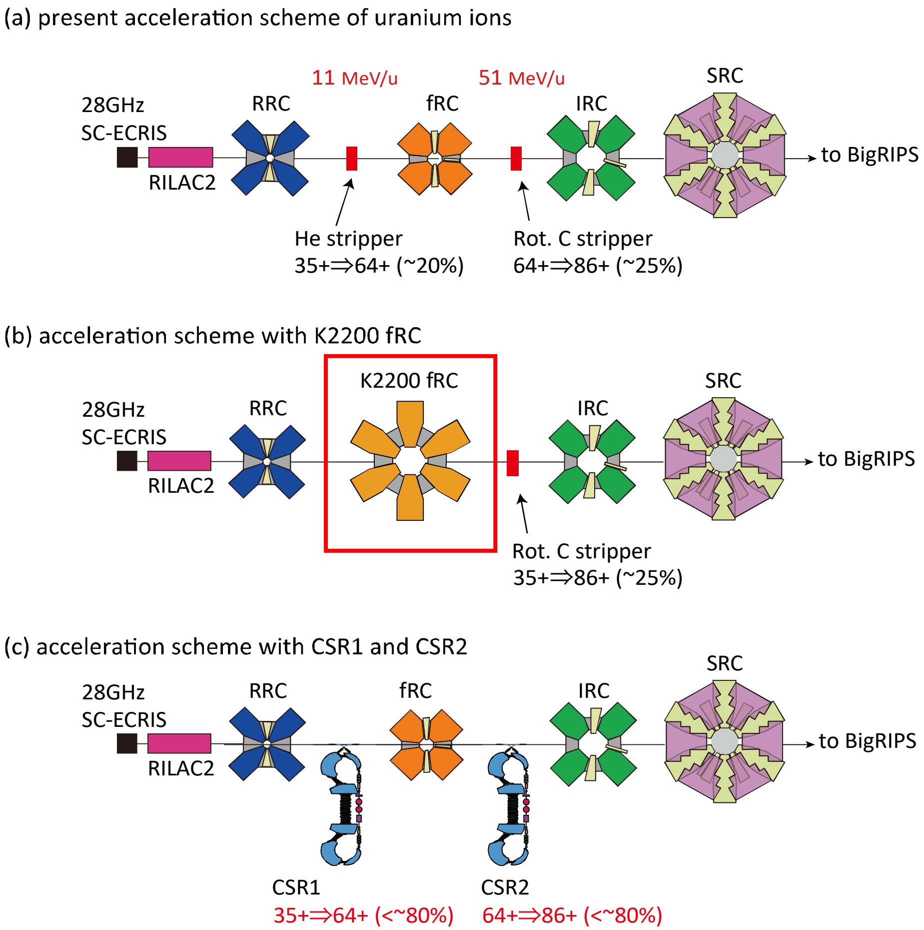
ε_r: survival prob. / turn

ε_q: efficiency for 64+

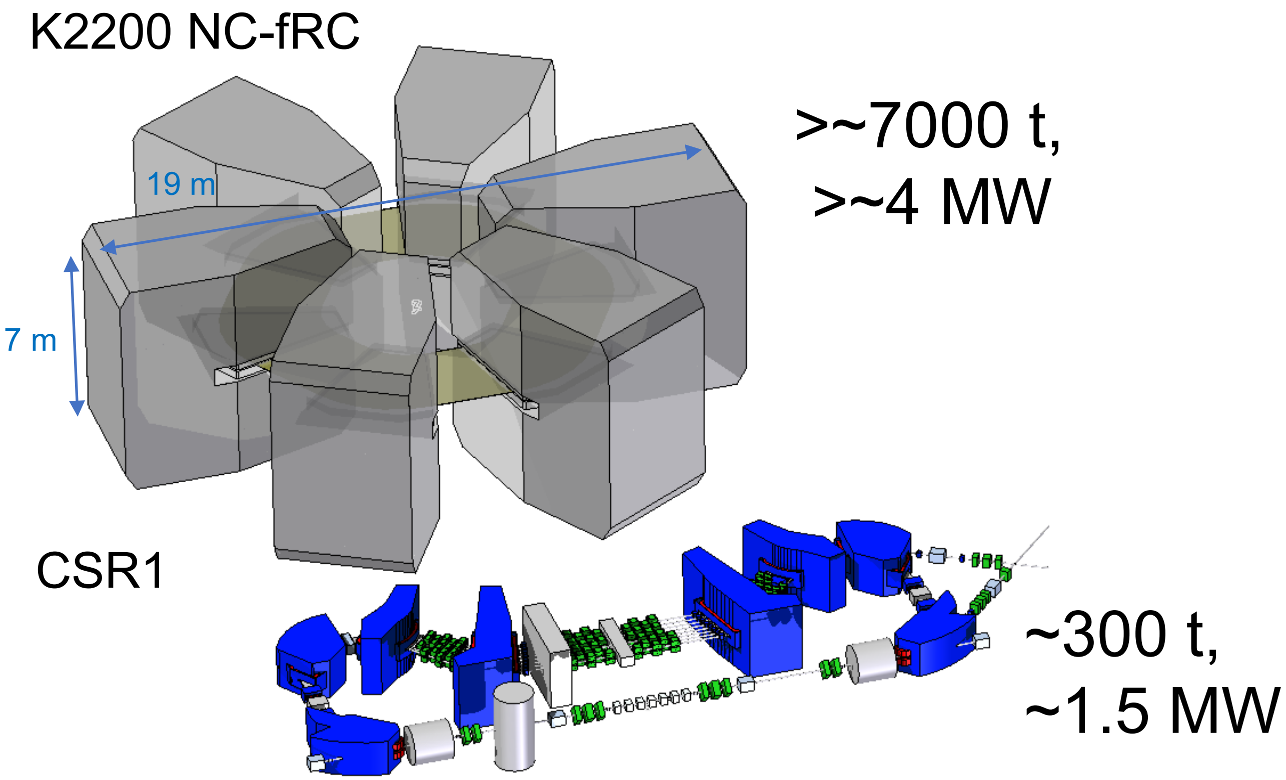
H. Imao et al., CYC2016, pp. 155-159.
H. Imao, J. Inst. (2020) 15 P12036.
H. Imao, IPAC2022, pp. 796-801.
H. Imao, J. Inst. (2023) 18 P03028.

Advantages of CSR

Various acceleration scheme for ^{238}U

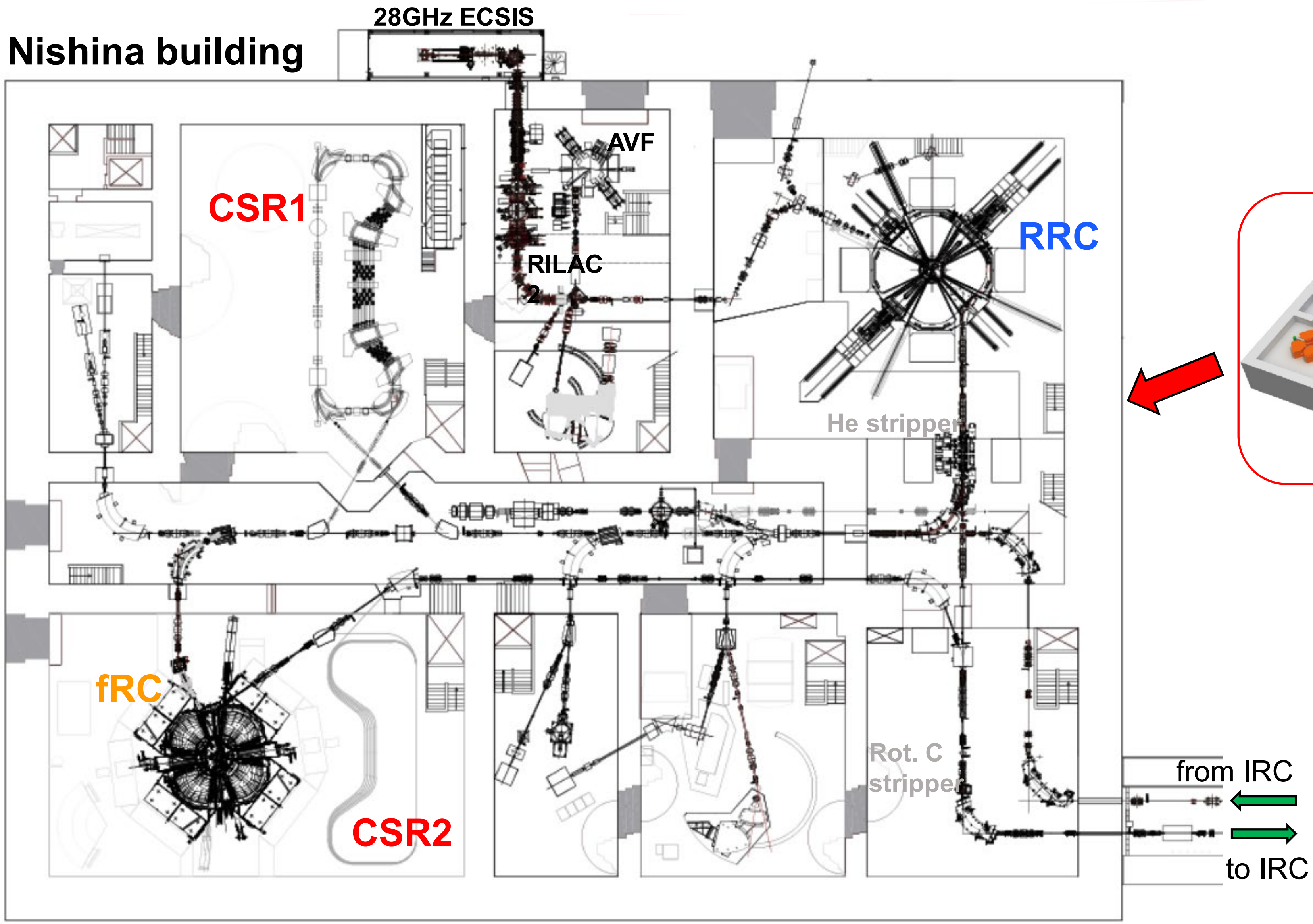


A usual way to increase efficiency is to remove the He stripper and renew the fRC to accelerate U^{35+} without strippers.

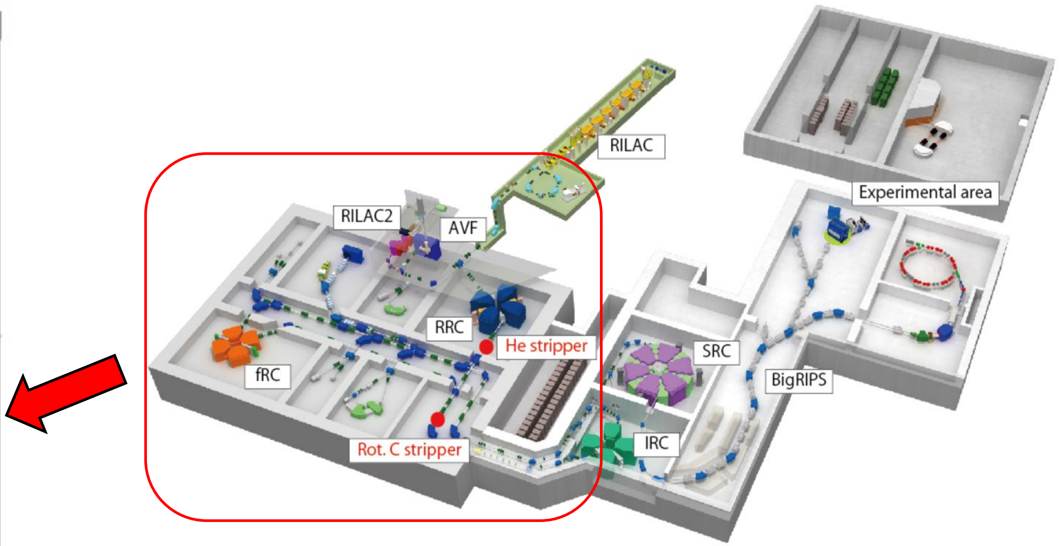


- Compact (**no building expansion**), low construction cost, low running cost

Layout

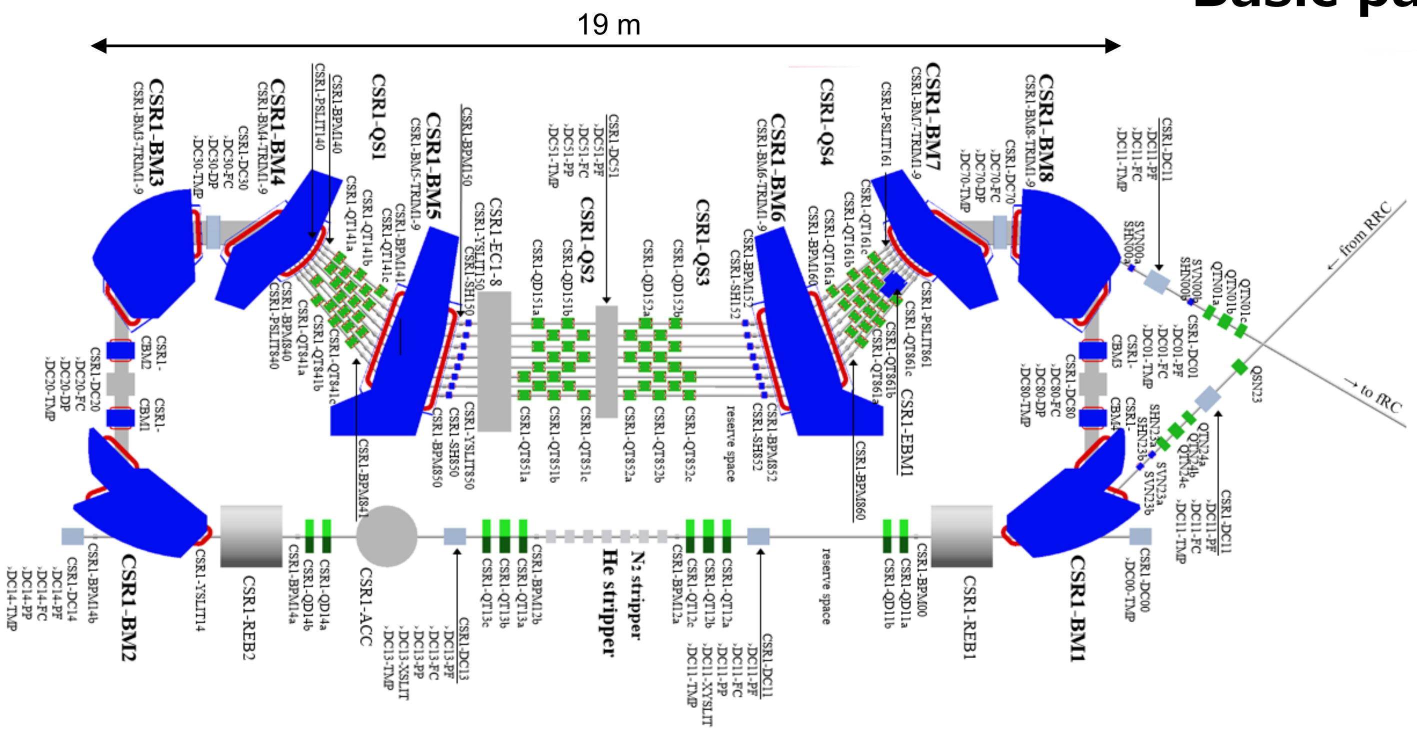


Nishina building
28GHz ECSIS
AVF
CSR1
RILAC 2
RRC
He stripper
fRC
CSR2
Rot. C stripper
from IRC
to IRC



RILAC
Experimental area
RILAC2
AVF
RRC
He stripper
fRC
SRC
BigRIPS
IRC
Rot. C stripper

Basic parameters and components of CSR1



CSR1 basic parameter	
circumference [m]	44.639
circulation energy [MeV/u]	10.80
velocity β	0.151
number of bunches	18
revolution time [ns]	986.30
revolution charge state	59+-66+
injection charge state	35+
extraction charge state	64+

Main components

Bending magnet（BM1-8）	BM1-2 1.27 T, BM3-8 1.43 T
Acceleration cavity（ACC1）	73 MHz 0.8 MV
Rebuncher（REB1-2）	109.5 MHz 1.3 MV
Energy correction (EC1)	73 MHz 200 kV
Q-mag station（QS1-4）	QS 73 units＋EDM1
He stripper（He）	0.3 mg/cm^2
N2 stripper (N2)	0.1 mg/cm^2

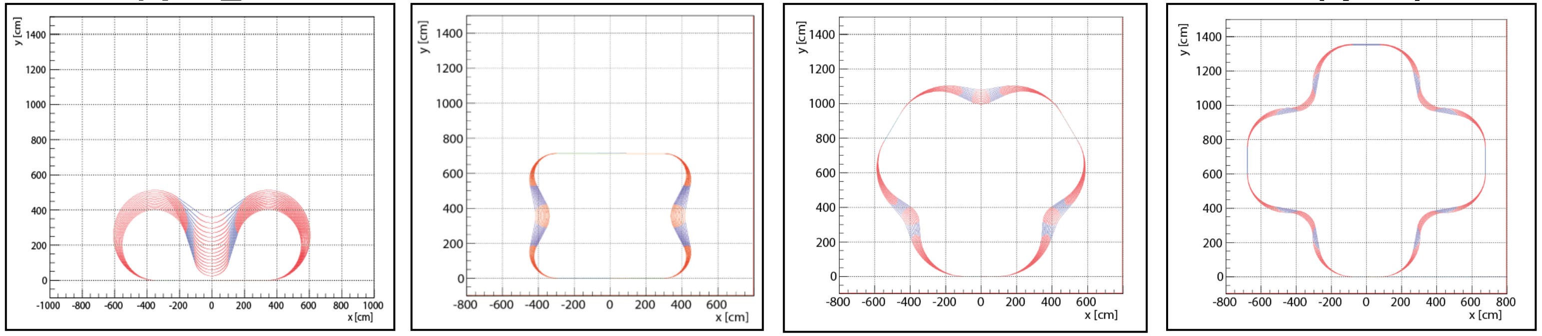
Key features of CSR

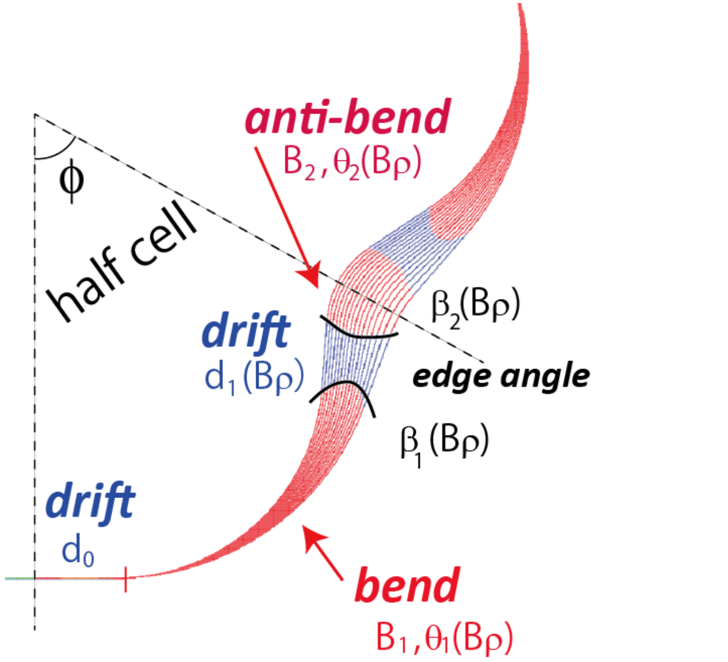
- **Isometric orbits**
- **Principle of β function matching**
- **Quadrupole-magnet stations**
- **Two-stage stripper scheme**
- **Role of effective beam slit**

Isometric orbits to hold bunch structure

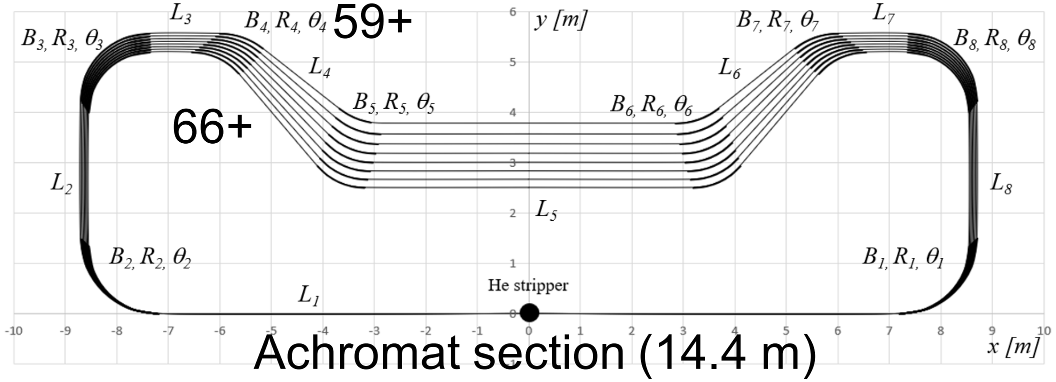
Isometric rings of various symmetries

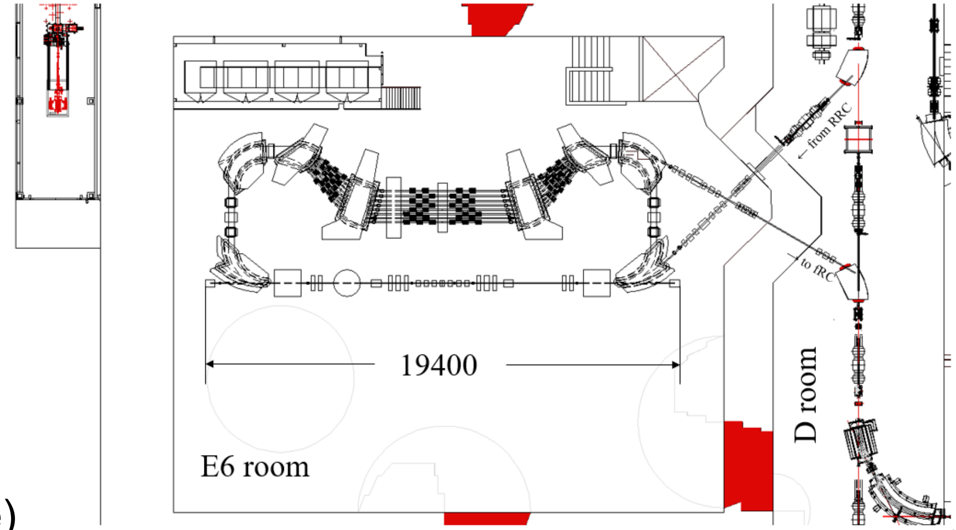
N=1 N=2 N=3 N=4





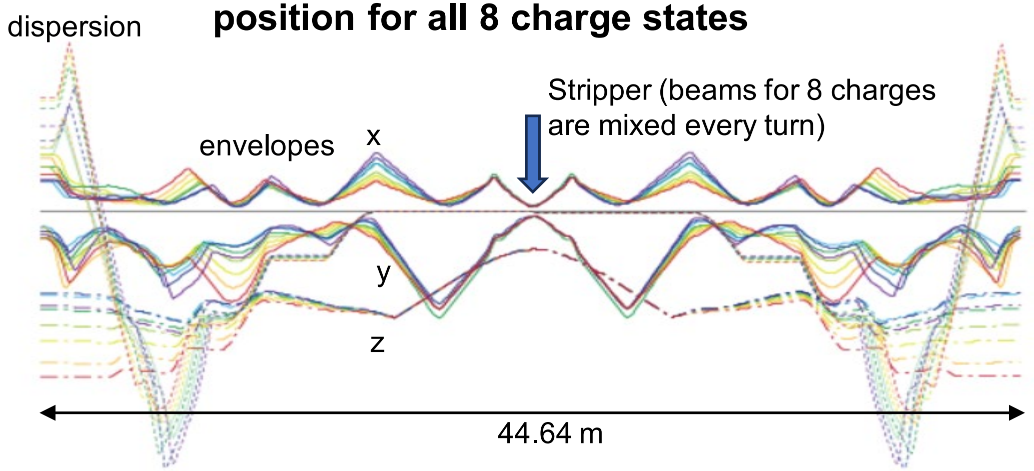
Isometric orbits of CSR1 for U^{59+}-U^{66+}



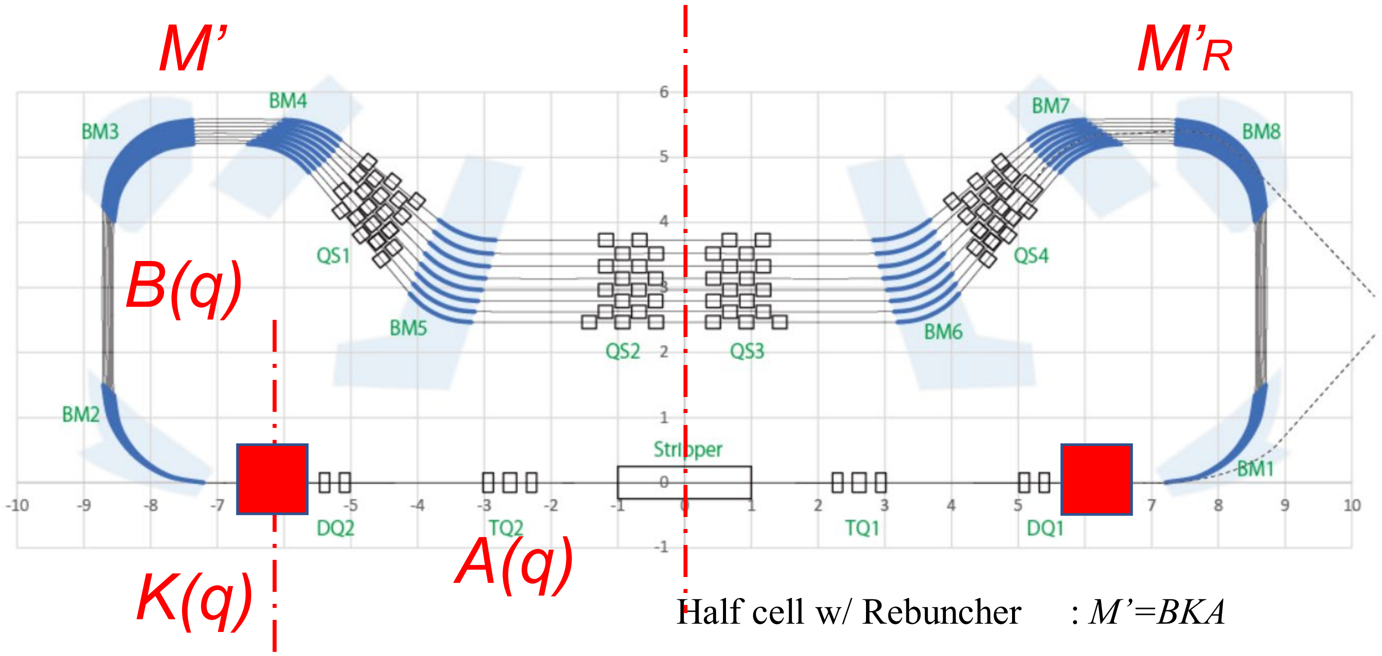


- Sufficient dispersion for **Q-mag. station (~10 cm)**
- Sufficient drift distance to place necessary equipment
- The system should be fitted in E6 room (construction site)

Matchings of beam shapes at the stripper position for all 8 charge states



- **Beta function matching**
- **Dispersion matching (*η*=*η'*=0)**



Half cell w/ Rebuncher : *M'=BKA*

Full cell w/ Rebunchers : *R'=MR'M'*

Mirror-symmetric focusing lattice

6x6 linear transfer matrix for one period R'

$$= \begin{pmatrix} 2M_{11}M_{22}-1 & 2M_{12}M_{22} & 0 & 0 & \frac{2(a+b-2)}{M_{56}}M_{12}M_{26} & 2aM_{12}M_{26} \\ 2M_{21}M_{22} & 2M_{11}M_{22}-1 & 0 & 0 & \frac{2(a+b-2)}{M_{56}}M_{11}M_{26} & 2aM_{11}M_{26} \\ 0 & 0 & 2M_{33}M_{44}-1 & 2M_{34}M_{44} & 0 & 0 \\ 0 & 0 & 2M_{43}M_{33} & 2M_{33}M_{44}-1 & 0 & 0 \\ -2aM_{11}M_{26} & -2aM_{12}M_{26} & 0 & 0 & 2ab-1 & 2\left\{\frac{a(ab-1)}{a+b-2}M_{56}-a^2M_{16}M_{26}\right\} \\ \frac{-2(a+b-2)}{M_{56}}M_{11}M_{26} & \frac{-2(a+b-2)}{M_{56}}M_{12}M_{26} & 0 & 0 & \frac{2b(a+b-2)}{M_{56}} & 2ab-1-\frac{2a(a+b-2)}{M_{56}}M_{16}M_{26} \end{pmatrix}$$

Here, $a=(KA)_{66}=1-kA_{56}$ (magnification of dispersion) $b=1-kB_{56}$ *looks a little complicated…*

Impose the condition ***M*₂₆=0 (angular dispersion of half cell)**,

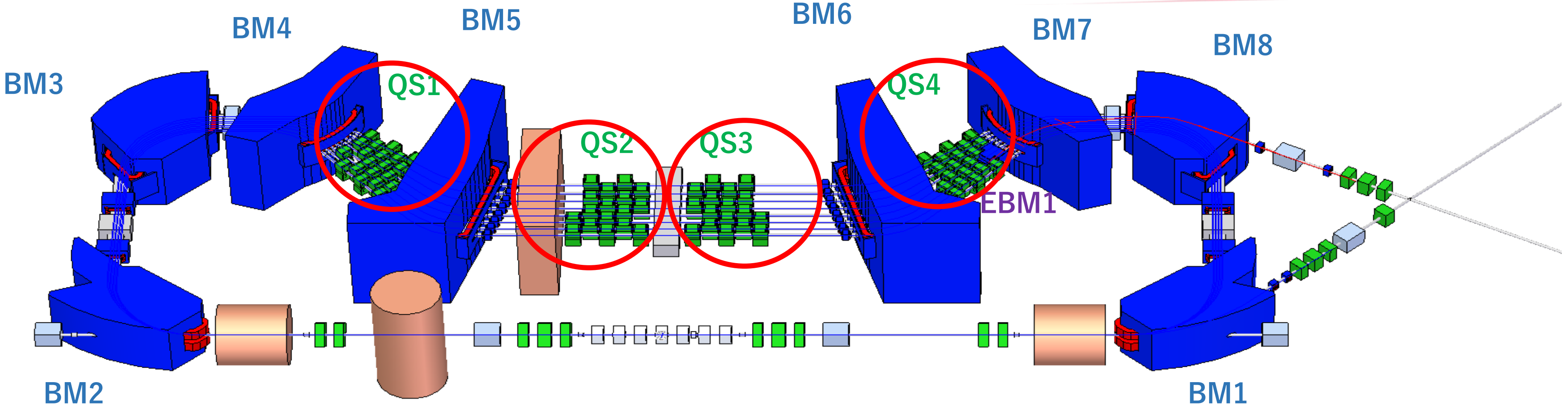
$$R' = \begin{pmatrix} 2M_{11}M_{22}-1 & 2M_{12}M_{22} & 0 & 0 & 0 & 0 \\ 2M_{21}M_{22} & 2M_{11}M_{22}-1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2M_{33}M_{44}-1 & 2M_{34}M_{44} & 0 & 0 \\ 0 & 0 & 2M_{43}M_{33} & 2M_{33}M_{44}-1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2ab-1 & \frac{2a(ab-1)}{a+b-2}M_{56} \\ 0 & 0 & 0 & 0 & \frac{2b(a+b-2)}{M_{56}} & 2ab-1 \end{pmatrix}$$

- Betatron oscillation has no coupling in 3 directions
- Achromatic system ($R'_{16}=R'_{26}=0$)
- Orbit length is independent of angle and position ($R'_{51}=R'_{52}=0$, symplectic condition)
- Beam ellipse at stripper is upright (fine transmission of stripper)

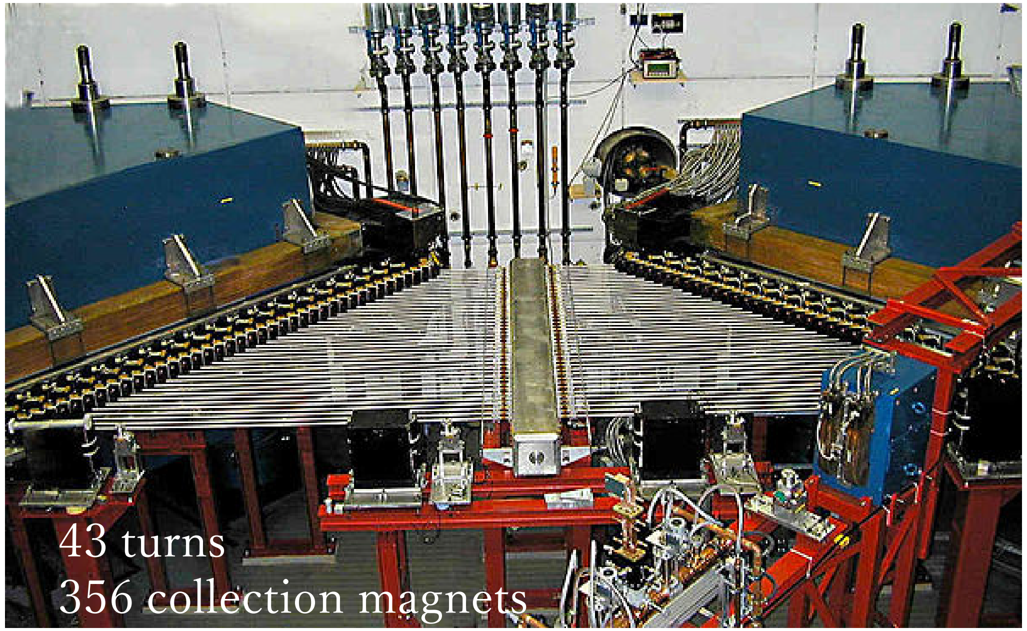
$M_{26}=0$ and beta function matching (β_x, β_y, β_z) should be required.

→ **Require at least 4 charge independent focusing elements** for each charge

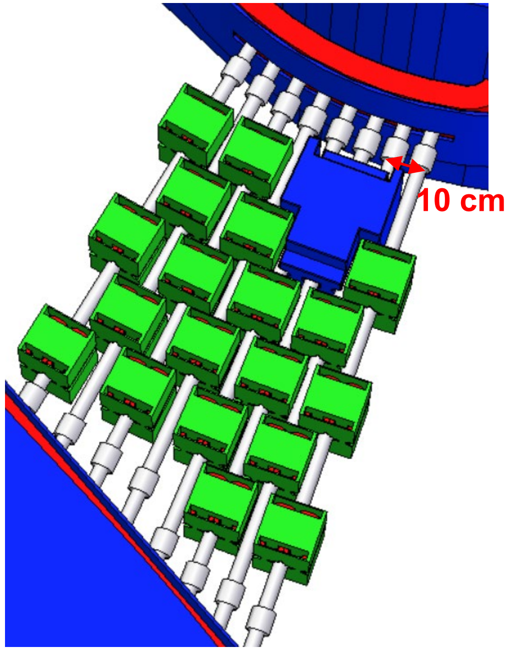
Q-magnet station (QS1-4) for charge independent focusing



MAMI C (Microtron HDSM at Mainz univ.)



Close-up view of QS4



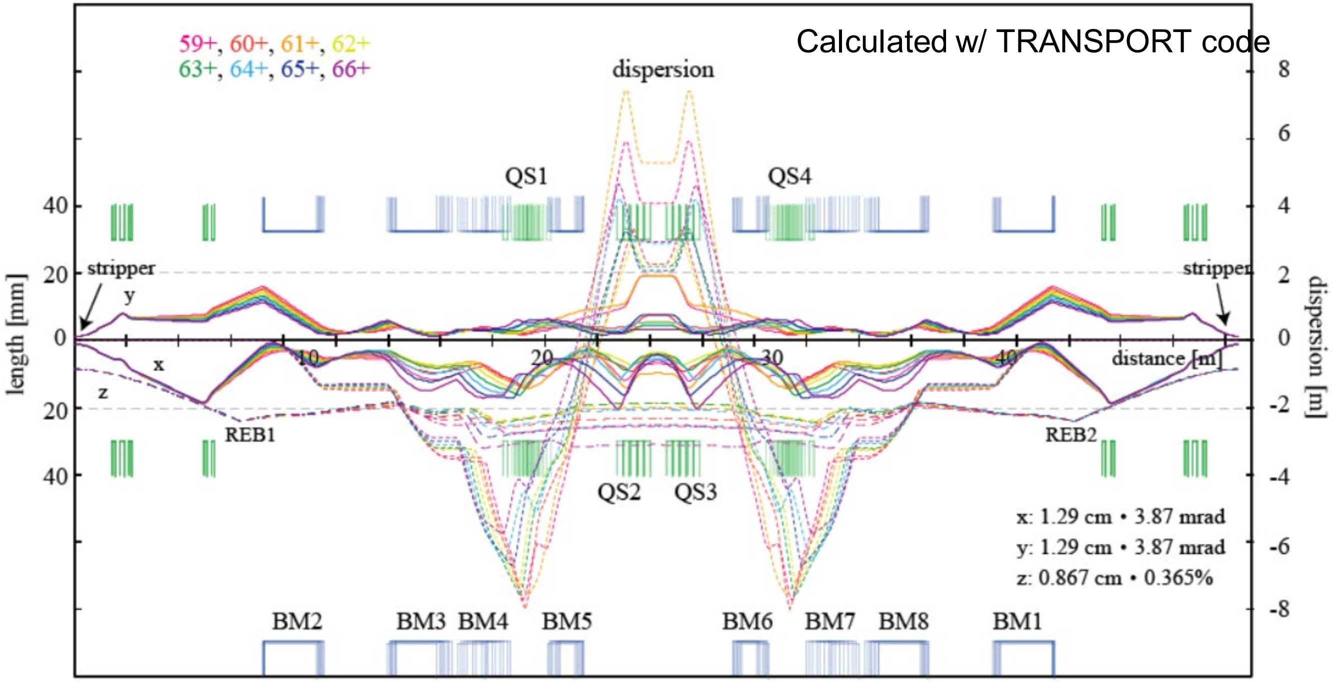
Crowded quadrupoles in parallel beamlines within a limited space, which is unprecedented.

The situation may be similar to the microtron.

Design works will be discussed later.

Orbits satisfying matching conditions

Beam envelopes, bunch lengths and dispersion functions for 8 charge states



Optimized with 37 + 5 quadrupoles

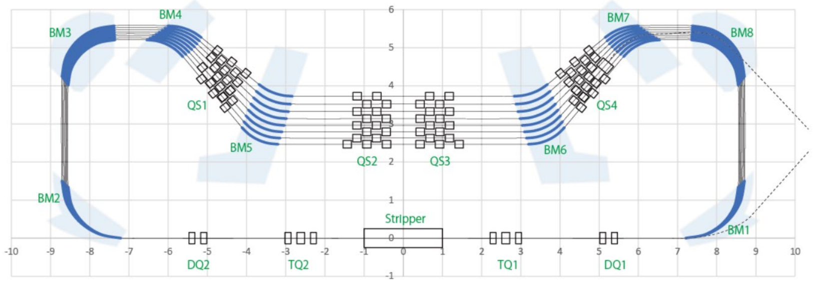
- β_x, β_y, β_z matchings
- M_{26}=0

- Q magnets can be placed
- Magnetic field gradient < ~20 T/m
- Beam envelopes < ~20 mm
- Momentum dispersion < ~8 m

Calculated integrated magnetic field gradient for quadrupole magnets in QS1-2

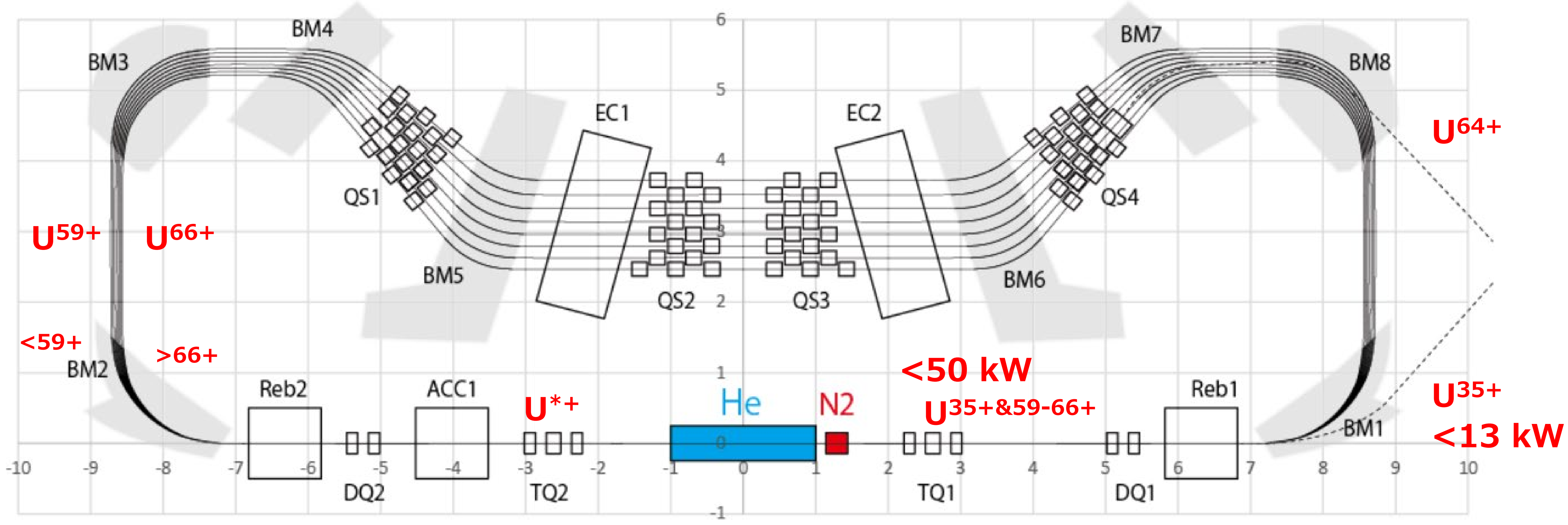
q	Name	Integrated gradient [T]	q	Name	Integrated gradient [T]	q	Name	Integrated gradient [T]	q	Name	Integrated gradient [T]
59+	QT141a	1.8272	61+	QT341a	0.2516	63+	QD541a	1.6847	65+	QD741a	1.5762
	QT141b	-1.4516		QT341b	0.6901		QD541b	-1.1859		QD741b	-1.2722
	QT141c	1.3049		QT341c	0.6728		QD551a	2.8736		QD751a	2.6816
	QD151a	2.8128		QD351a	2.4064		QD551b	-1.8808		QD751b	-2.0000
	QD151b	-1.8128		QD351b	-1.5848						
60+	QD241a	2.1035	62+	QD441a	1.9468	64+	QT641a	1.2235	66+	QT841a	1.2962
	QD241b	-1.5355		QD441b	-1.6114		QT641b	-2.0171		QT841b	-1.9117
	QD251a	2.9288		QD451a	2.9120		QT641c	1.6175		QT841c	1.3721
	QD251b	-1.7864		QD451b	-1.9280		QD651a	2.6784		QT851a	2.3880
							QD651b	-1.6720		QT851b	-1.6192
										QT851c	-0.1696

All within feasible limits (<18 [T/m])



The fact that ideal orbits was found within so many constraints is an important milestone.

2-stage stripper scheme



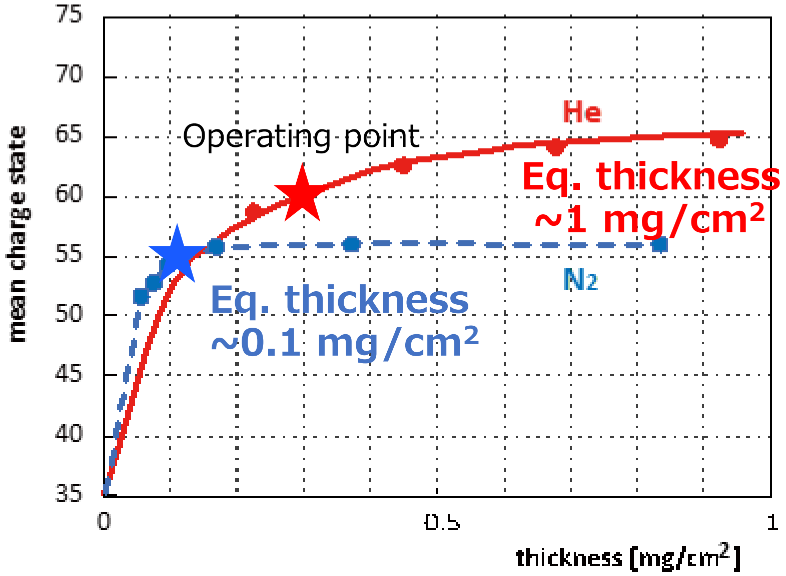
The charge conversion cycle, using a two-stage stripper, is unique and important.

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

Gas stripper is required for high-power beams.

He gas is required to obtain high charge state (e.g., the current first He stripper)

Mean charge evolution as a function of thickness



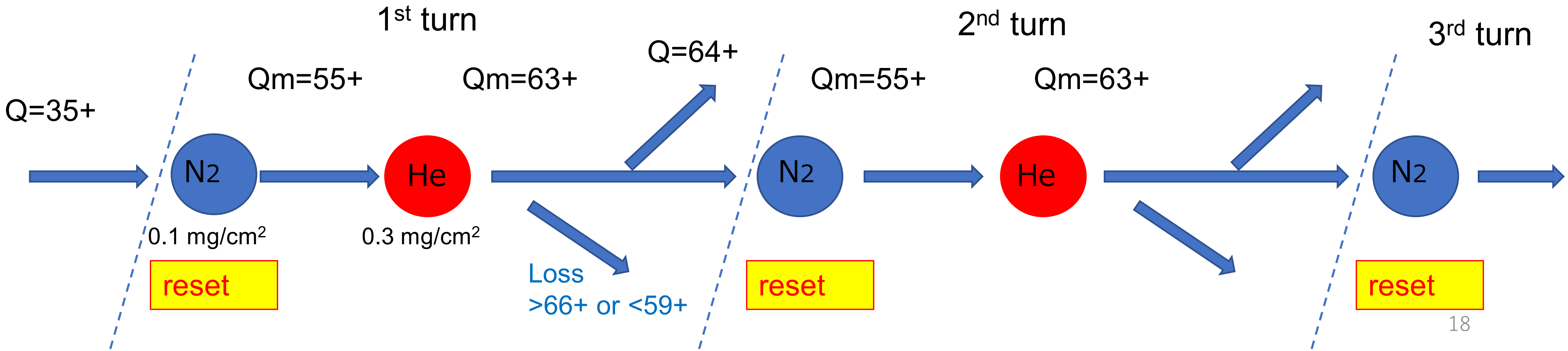
Thin stripper to reduce emittance growth

The charge state is reset with N_2 stripper every circulation, e.g., Q_m=55+

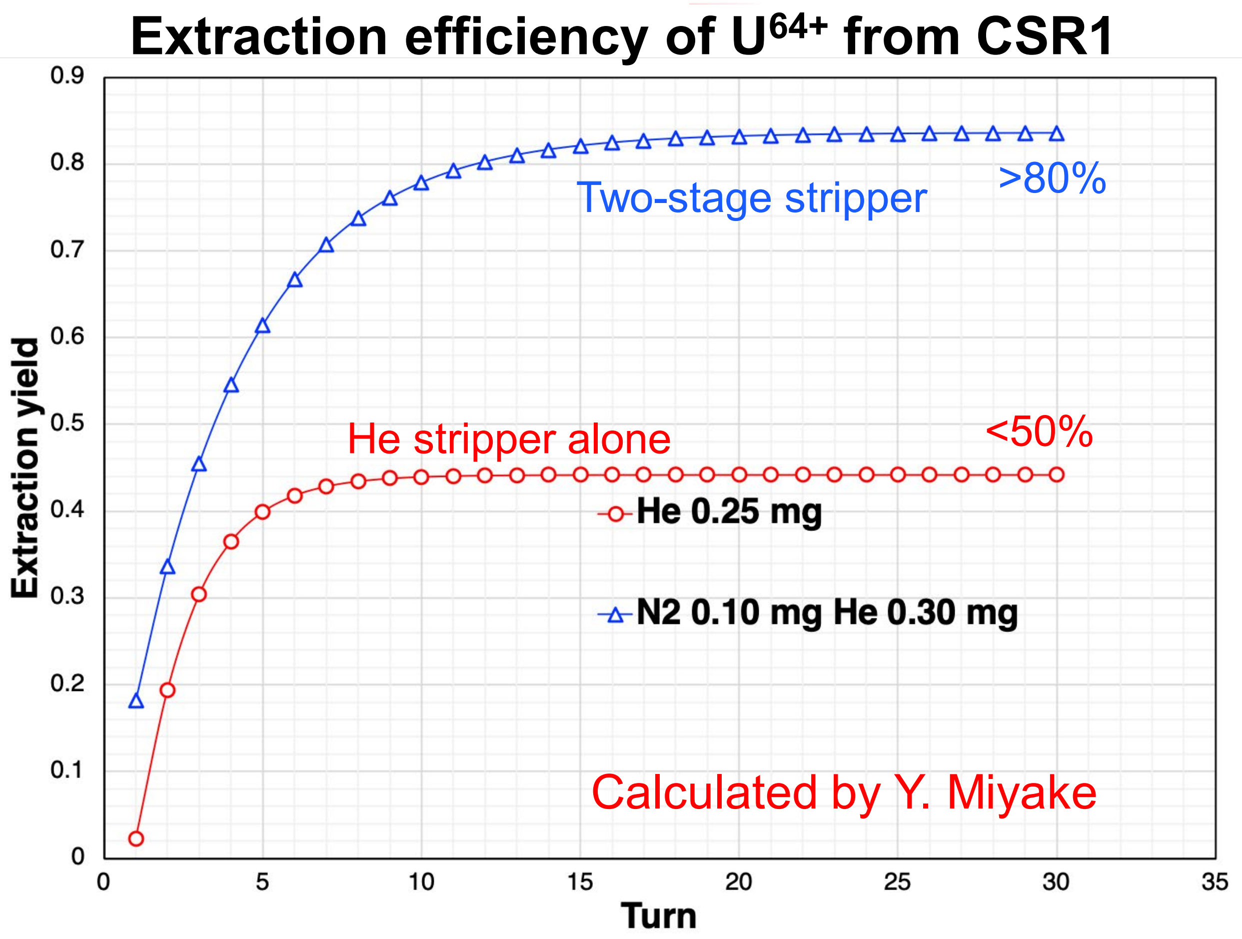
Average charge states during circulation are fixed, e.g., Q_m=63+

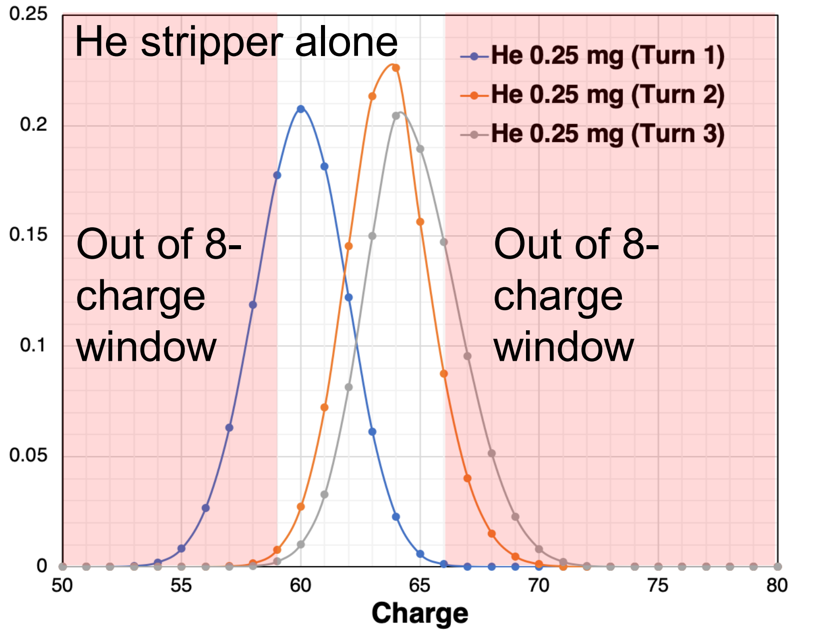
Beam loss due to going outside the 8-charge window

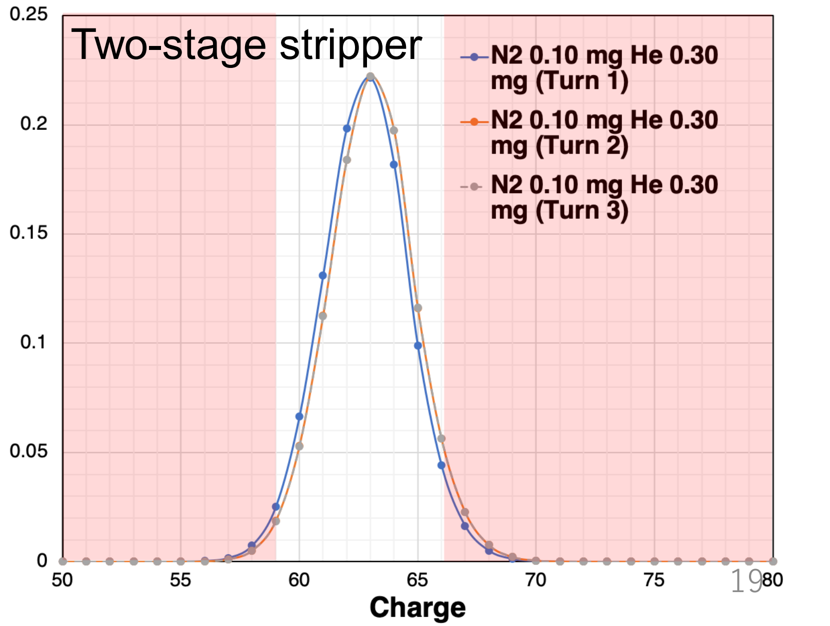
Charge conversion cycle



Calculation results of stripping cycle







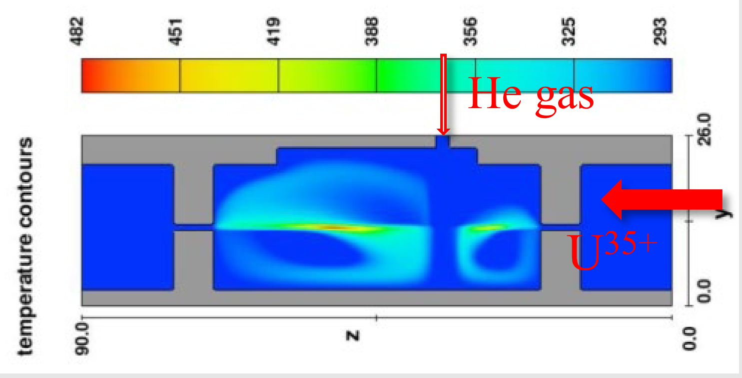
The use of a two-stage stripper is one of the key ideas for an efficient CSR.

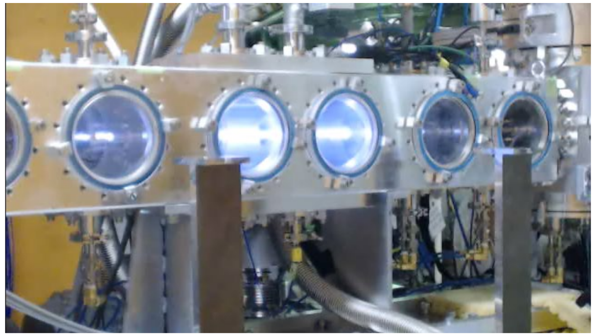
Comparison of the specifications

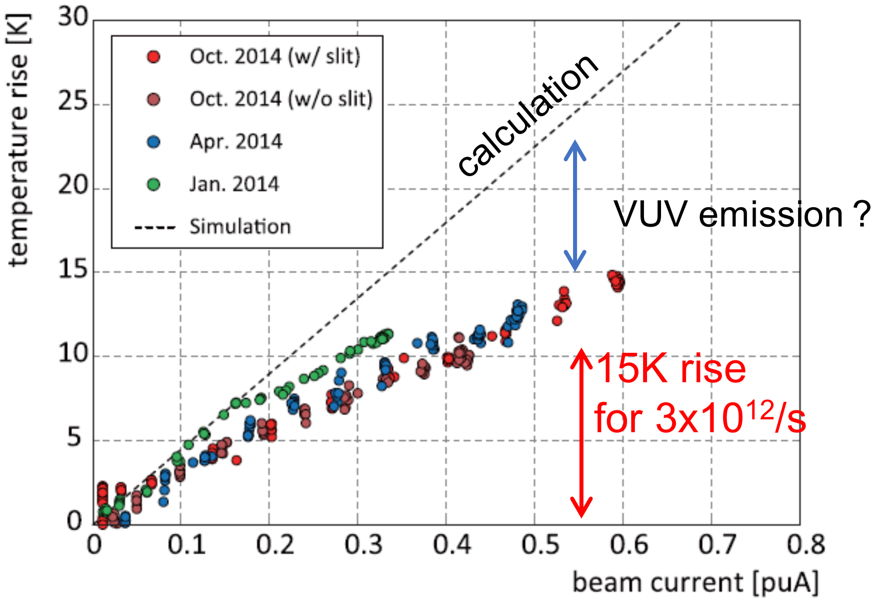
		Stripper for CSR1	Present He stripper
Total length of system	[m]	2.7	2.7
Thickness of He stripper	**[mg/cm^2]**	**0.3**	0.6
Thickness of N_2 stripper	[mg/cm^2]	0.1	0.001
Target length of He	[cm]	30	50
Minimum orifice diameter	**[mm]**	**20**	12
Number of differential pumping stages	#	5	5
Maximum heat load	**[W]**	**800**	200
Gas circulation flow rate	**[SLM]**	**1060**	380

Three techniques of the He stripper

1) He recirculation with MBP array
2) Gas diffusers
3) N_2 gas-jet curtain





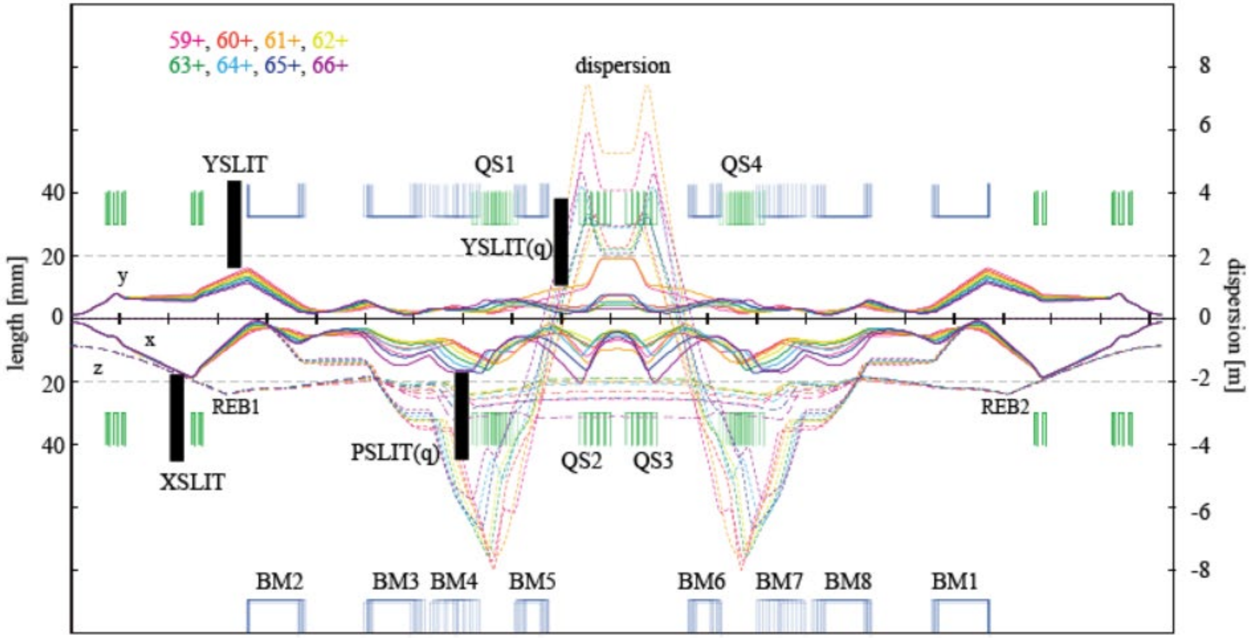


Powerful beams make a hole even in the gas (ρ=PM/RT$\propto$1/T)
Even at the present beam intensities, the heat load causes the target thinning by about 10%

Derived from the TOF of U beams after stripper as a function of beam current

Beam loss control with slits

Planned beam slits insertion position



Beam slits currently used for the He stripper

Water-cooled baffle type current detector
500 W max. for each side

Water-cooled electric slit
1 kW max. for each side

Emittance growth by the stripper is unavoidable in CSR1.

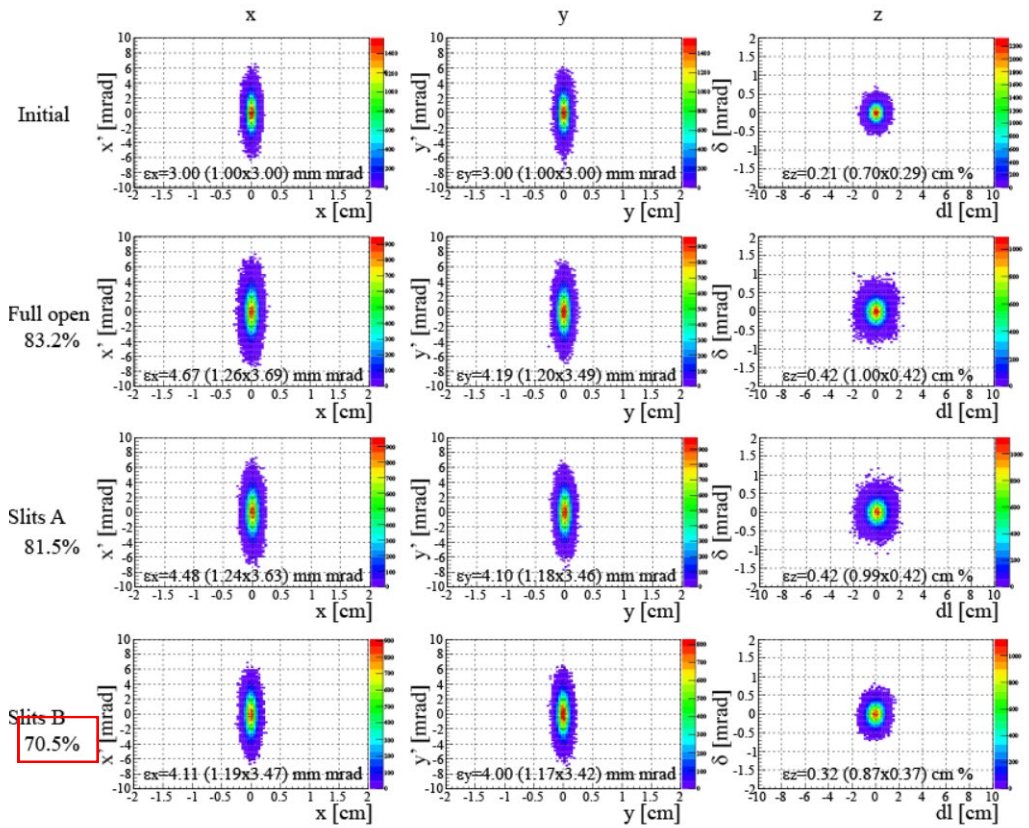
The losses at the physical aperture are controlled and localized by using appropriate slits.

CSR1 can serve as an “**effective slitting system**” to make high-quality beams.

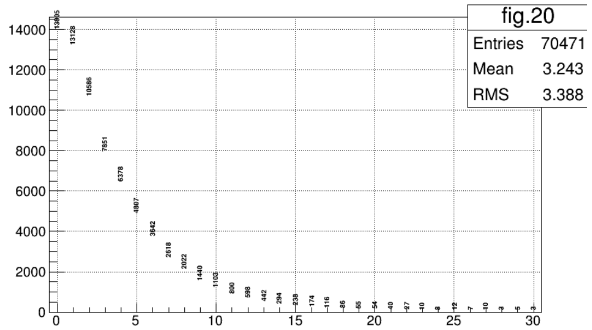
Sources of emittance growth

		expected errors (half width)
x	total	0.40
COD	[mm]	0.20
high-order effects	[mm]	0.20
dispersion missmatching	[mm]	0.20
eigenelipse missmatching	[mm]	0.20
x'	total	0.87
angular straggling at stripper	[mrad]	0.80
high-order effects	[mrad]	0.20
angular dispersion missmatching	[mrad]	0.20
Eigenelipse missmatching	[mrad]	0.20
y	total	0.35
COD	[mm]	0.20
high-order effects	[mm]	0.20
eigenelipse missmatching	[mm]	0.20
y'	total	0.85
angular straggling at stripper	[mrad]	0.80
high-order effects	[mrad]	0.20
Eigenelipse missmatching	[mrad]	0.20
θ	total	0.07
path length error	[ns]	0.05
Eigenelipse missmatching	[ns]	0.03
power supply fluctuation	[ns]	0.03
δ	total	0.11
energy straggling at stripper	[%]	0.10
ununiformity of stripper	[%]	0.03
Eigenelipse missmatching	[%]	0.03

Beam emittance and efficiency

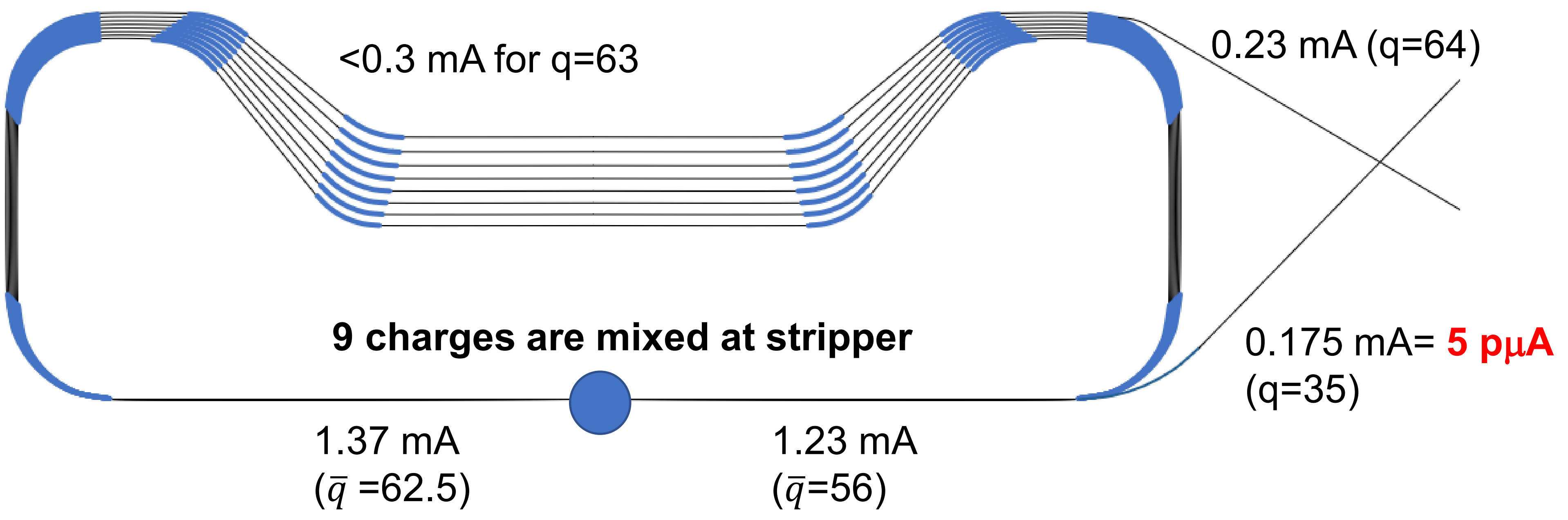


The beam emittance in the *x*, *y*, and *z* directions for the initial injection and the 64+ beam emittance for the three cases, Full open, Slit A and Slit B conditions



The average number of turns is about 3 to 4

Space charge effect in CSR1

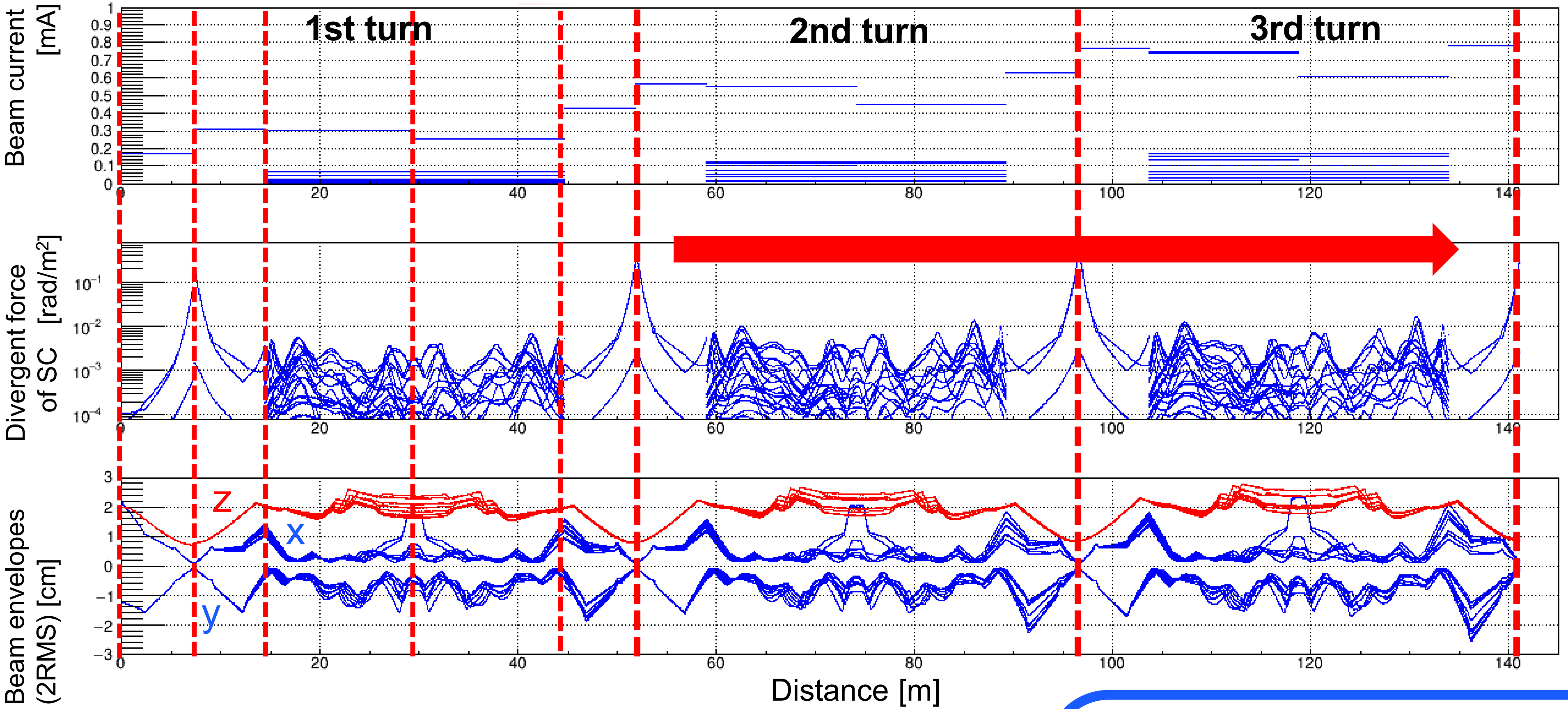


- Beam circulation with varying charge and intensity
- **Complex causality** due to beam mixing at the stripper

➡Envelope simulation with linear divergent force of SC

- Causality in the space-charge corrections
- Optimum focusing parameters at various beam intensities
- Strategy to realize optimum parameters

Envelope simulation

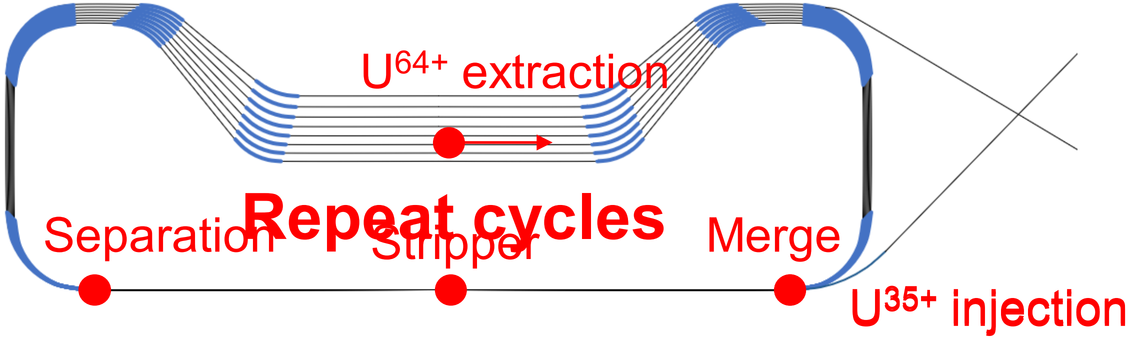


Sequentially calculated

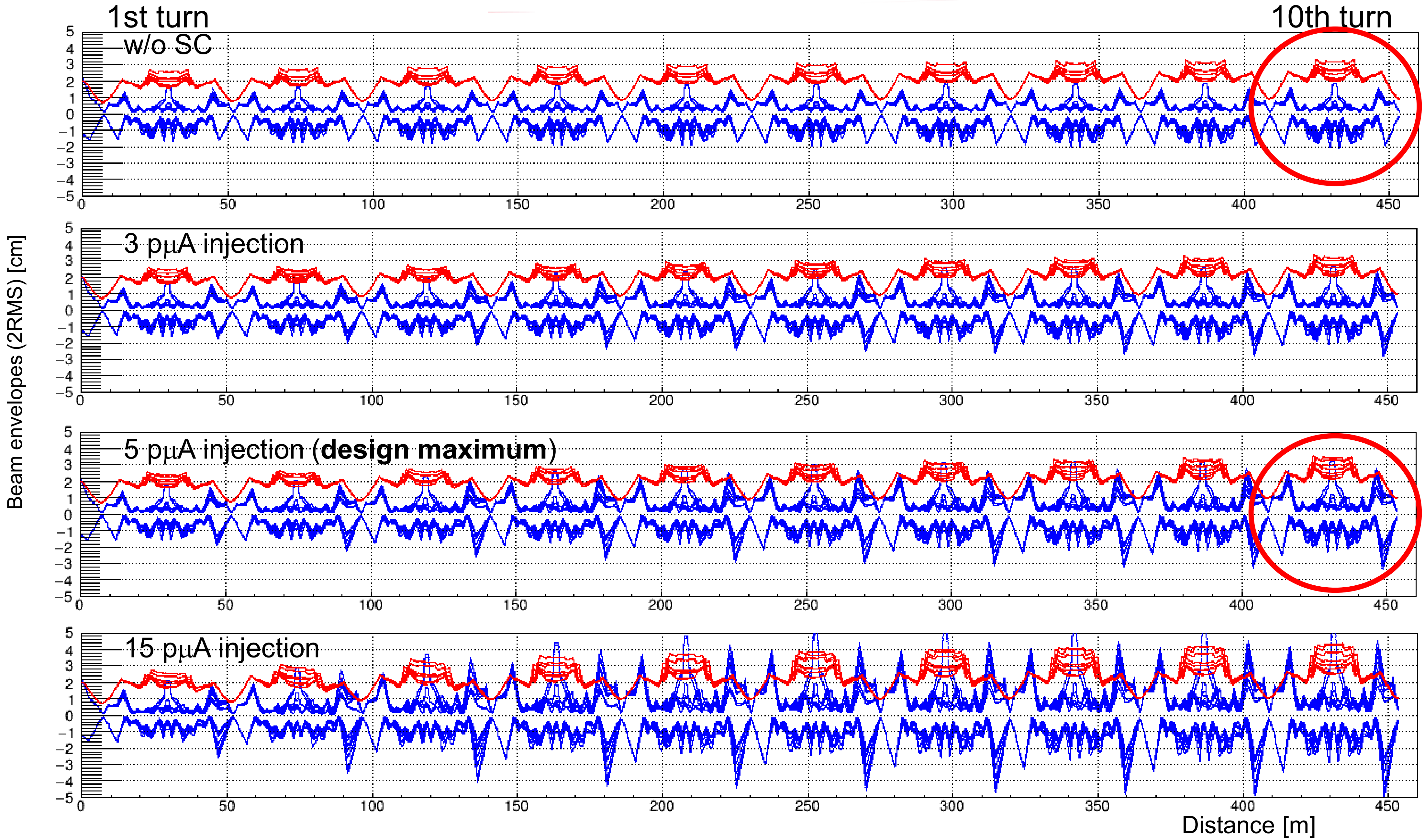
Linear divergent force (approximation that the mixed beam has elliptical symmetry)

$$\begin{cases} k_{sc,x}(q) = \dfrac{qN_t}{4\pi\varepsilon_0}\dfrac{\bar{q}}{\gamma^3\beta^2 mc^2}\left(\dfrac{1}{5\overline{x_{\bar{q}}^2}}\right)^{\frac{3}{2}} R_D\left(\dfrac{\overline{y_{\bar{q}}^2}}{\overline{x_{\bar{q}}^2}},\dfrac{\overline{z_{\bar{q}}^2}}{\overline{x_{\bar{q}}^2}},1\right), \\ k_{sc,y}(q) = \dfrac{qN_t}{4\pi\varepsilon_0}\dfrac{\bar{q}}{\gamma^3\beta^2 mc^2}\left(\dfrac{1}{5\overline{y_{\bar{q}}^2}}\right)^{\frac{3}{2}} R_D\left(\dfrac{\overline{z_{\bar{q}}^2}}{\overline{y_{\bar{q}}^2}},\dfrac{\overline{x_{\bar{q}}^2}}{\overline{y_{\bar{q}}^2}},1\right), \\ k_{sc,z}(q) = \dfrac{qN_t}{4\pi\varepsilon_0}\dfrac{\bar{q}}{\gamma^3\beta^2 mc^2}\left(\dfrac{1}{5\overline{z_{\bar{q}}^2}}\right)^{\frac{3}{2}} R_D\left(\dfrac{\overline{x_{\bar{q}}^2}}{\overline{z_{\bar{q}}^2}},\dfrac{\overline{y_{\bar{q}}^2}}{\overline{z_{\bar{q}}^2}},1\right), \end{cases}$$

R_D: Carlson elliptic integral of the second kind.

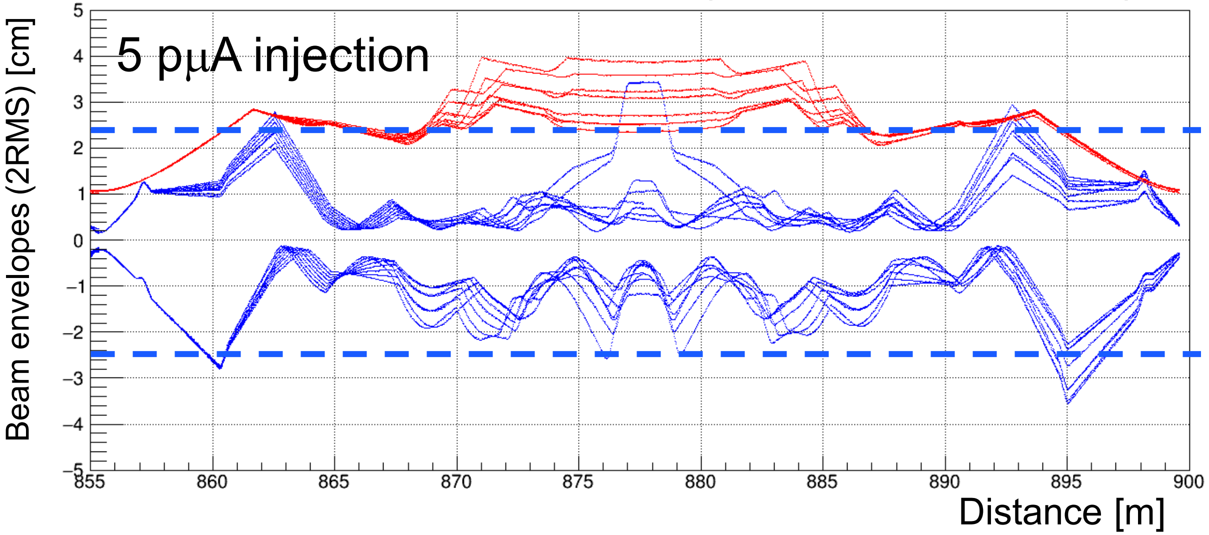


Blow-up of the beam envelopes due to space charge forces

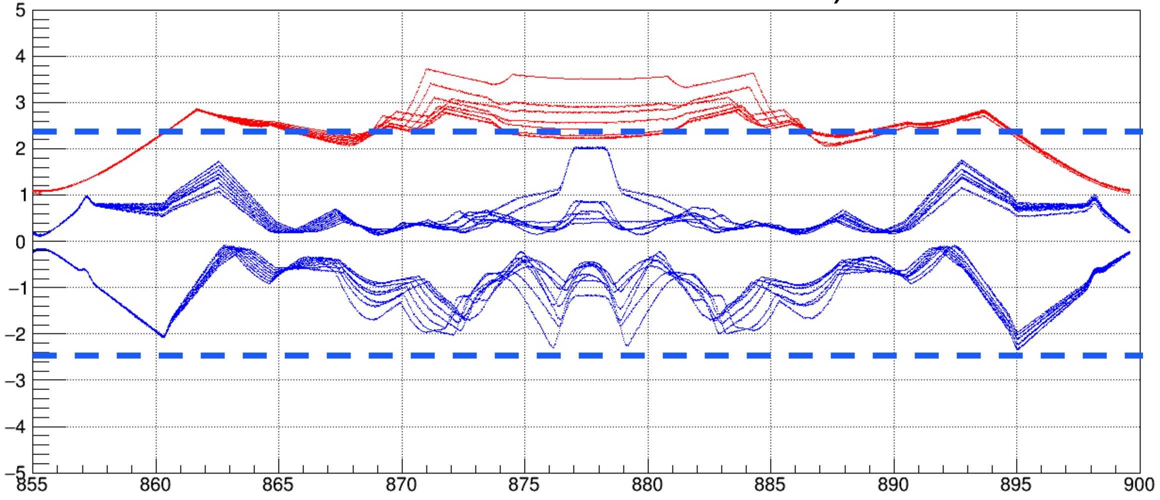


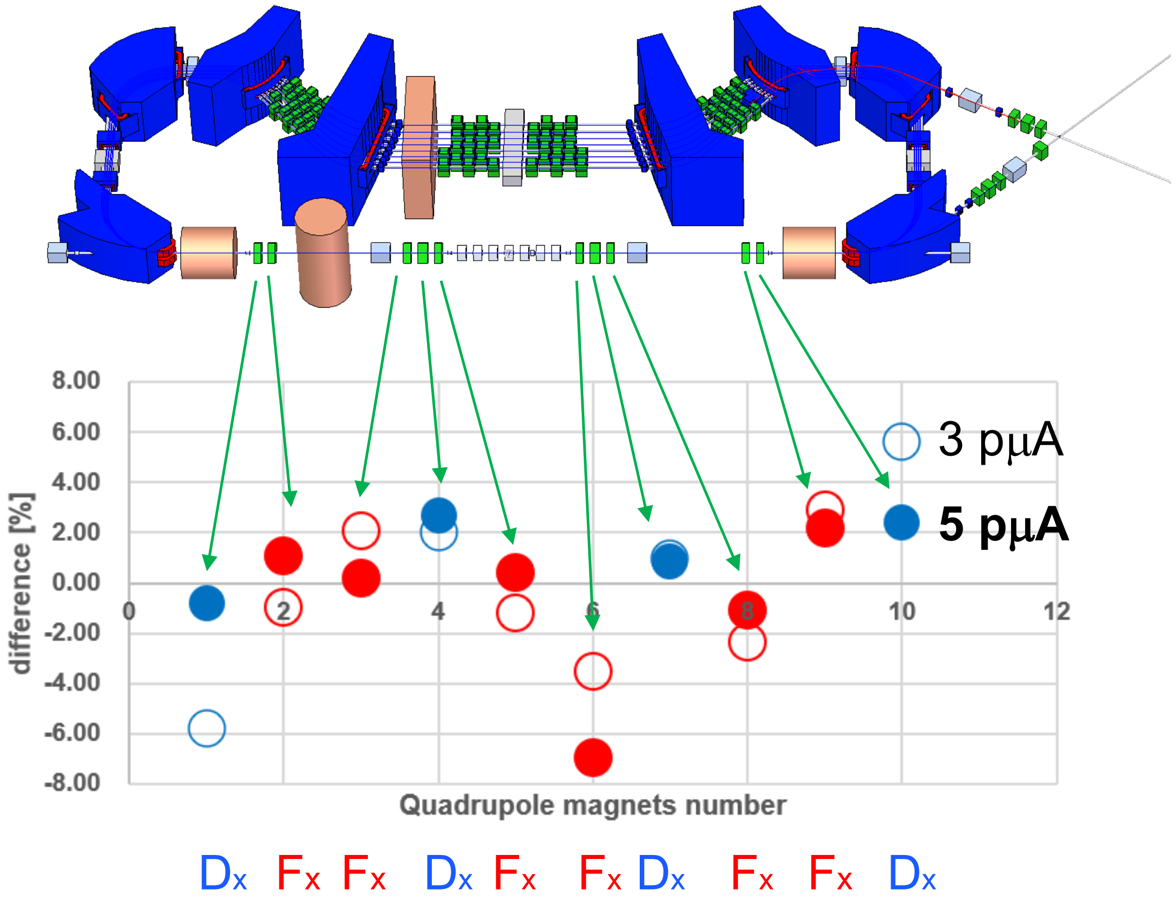
Correction of space charge effect

Beam envelope of 20th turn (~ equilibrium beam)



Corrected only by quadrupole magnets at achromat section (CERN's MINUIT was used for the minimization routine.)





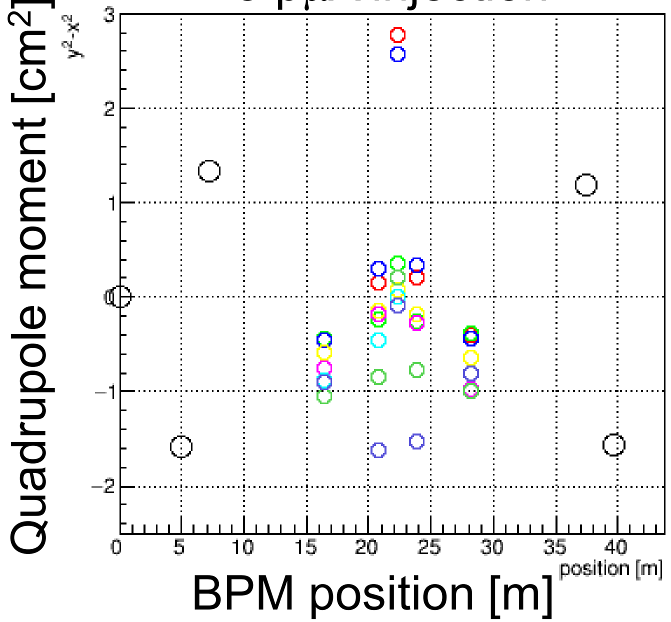
The correction of the quadrupole magnet's focusing force was less than 7%.

We can calculate optimal parameters for various intensities

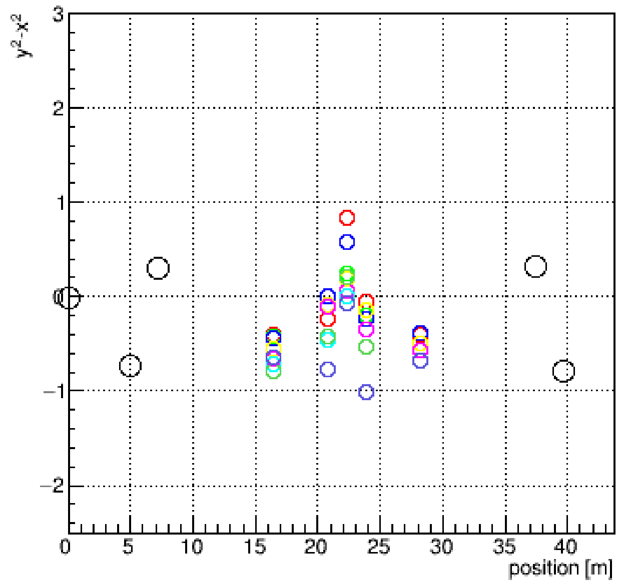
Demonstration of beam tuning with BPM

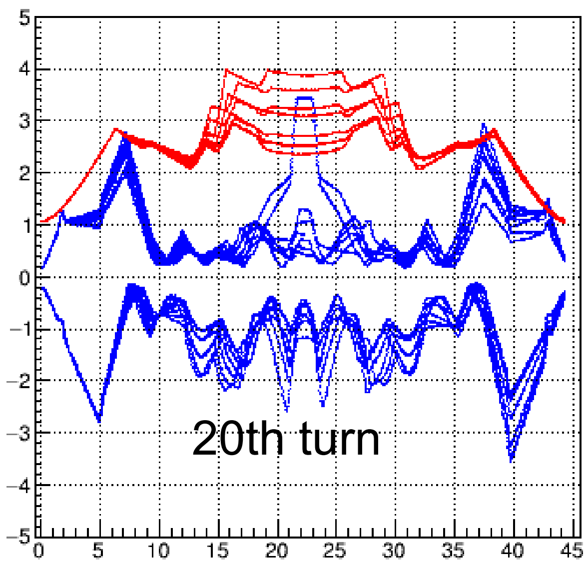
Before correction

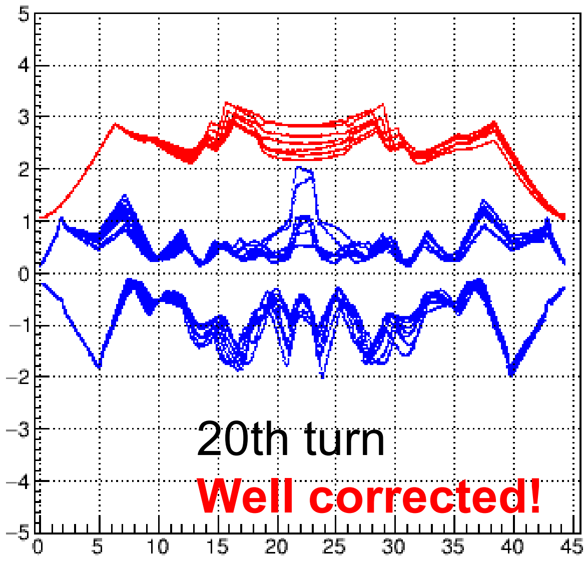
5 pμA injection



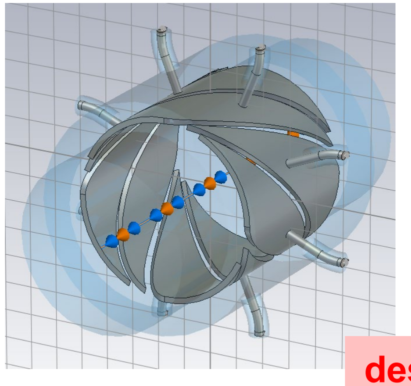
After correction







The actual tuning of the high-intensity beam is carried out using BPM

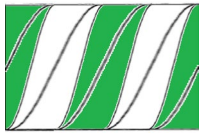


8-segmented BPM (non-destructive monitor for high-intensity beams)

designed by T. Adachi

- Timing
- Intensity
- Position (x, y)
- **Quadrupole moment (x^2-y^2)**

$$\frac{\sum_i V_i \cos 2\theta}{\sum_i V_i}$$

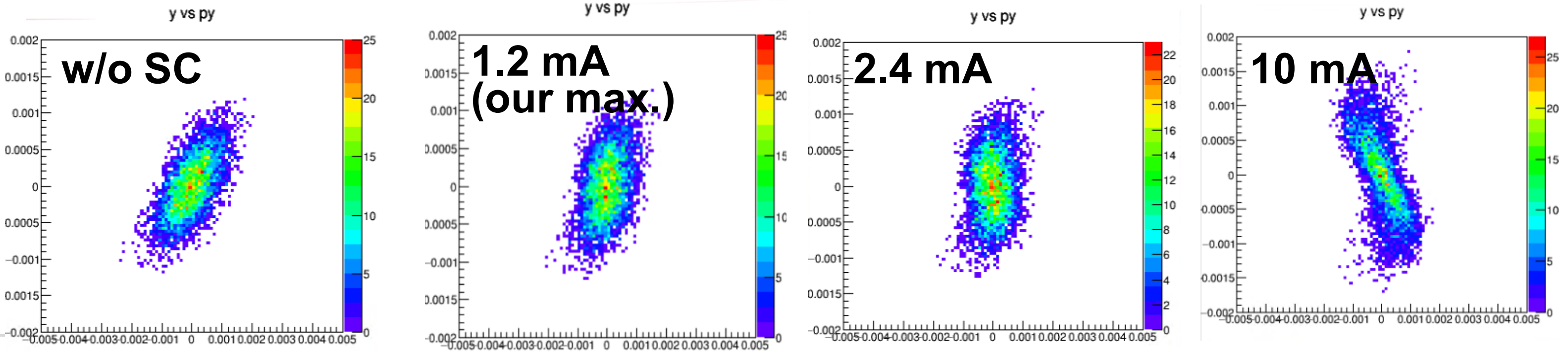


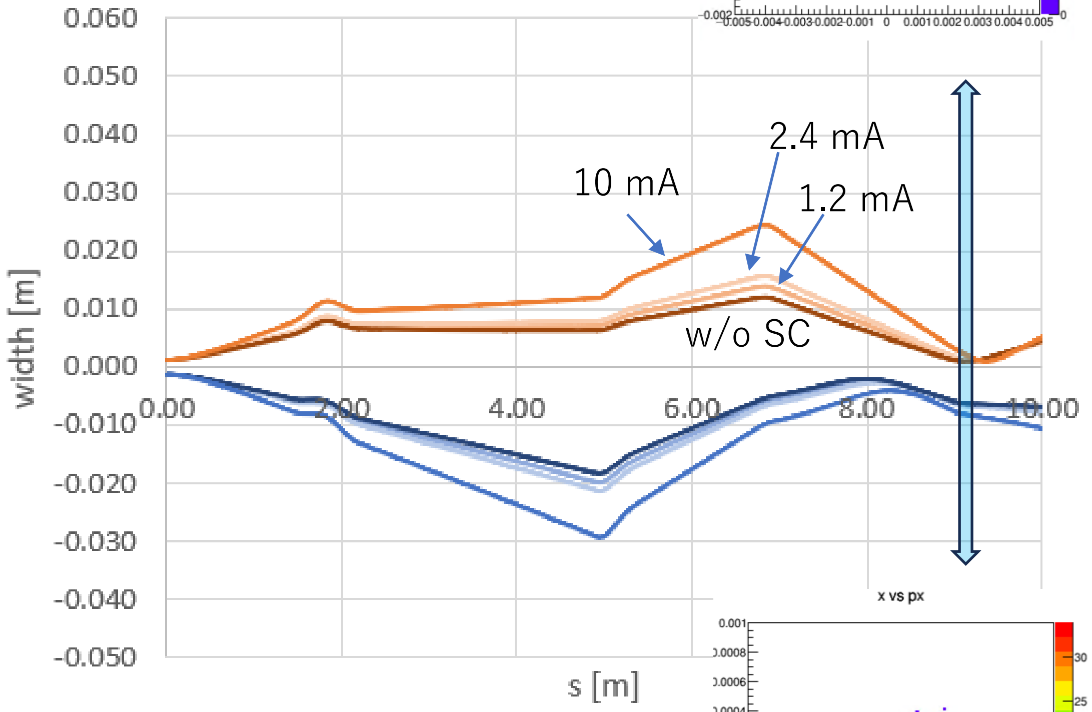
Correction of space charge effects using BPMs was demonstrated.
The simulator is being further upgraded.

Non-linear effect of SC with OPAL code

Phase ellipses calculated by OPAL

y-y’





PAUL SCHERRER INSTITUT PSI

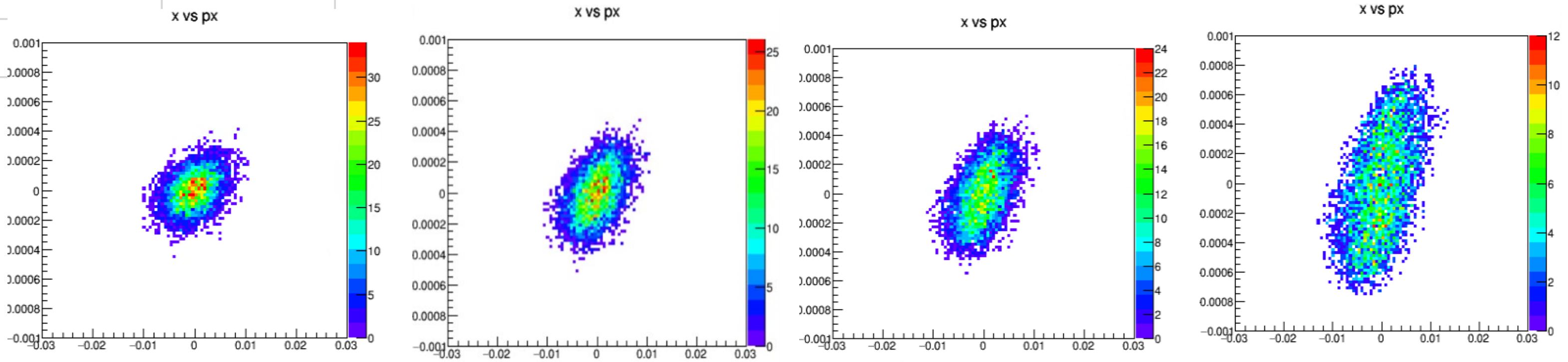
Open Source Development

The *OPAL* Framework: Version 2.5

Andreas Adelmann (PSI) · Pedro Calvo (CIEMAT) · Matthias Frey (PSI) · Achim Gsell (PSI) · Uldis Locans (PSI) · Christof Metzger-Kraus · Nicole Neveu (SLAC) · Chris Rogers (RAL) · Steve Russell (LANL) · Suzanne Sheehy (Oxford) · Jochem Snuverink (PSI) · Daniel Winklehner (MIT) – 2021-07-02

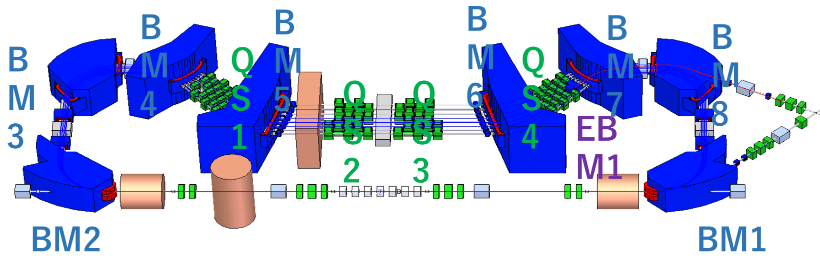
Nonlinear effects are not so significant at our operating intensities.

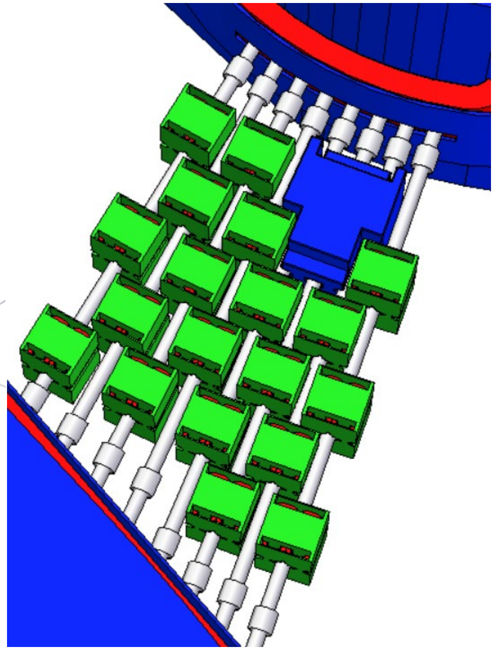
x-x’



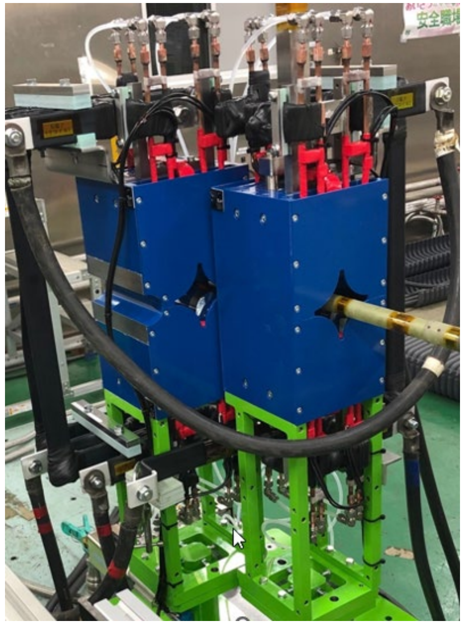
R&D for Q-mag station

3D Design of quadrupole magnets station

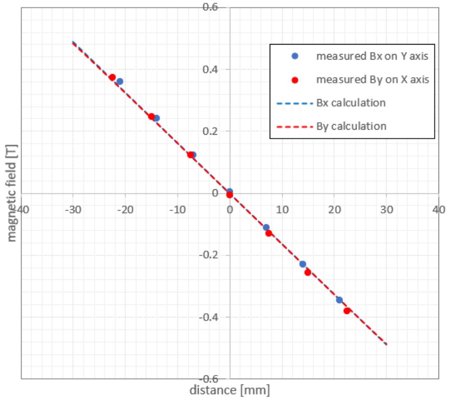




Prototype of QMs and field measurements

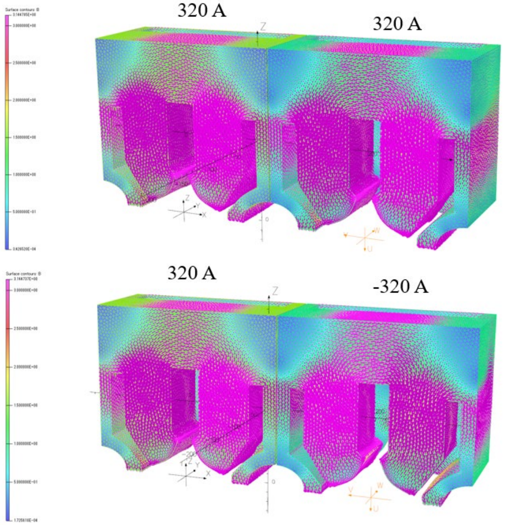


(Patented, JPN 2020-056540)

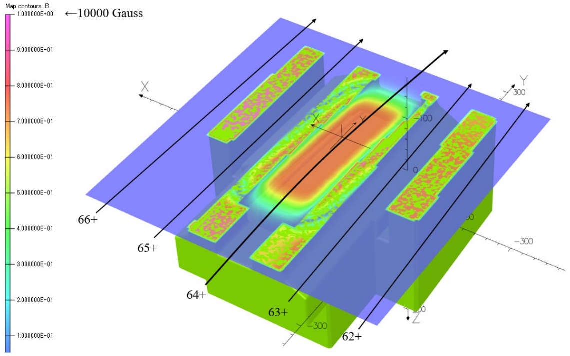


Required magnetic field gradient was confirmed

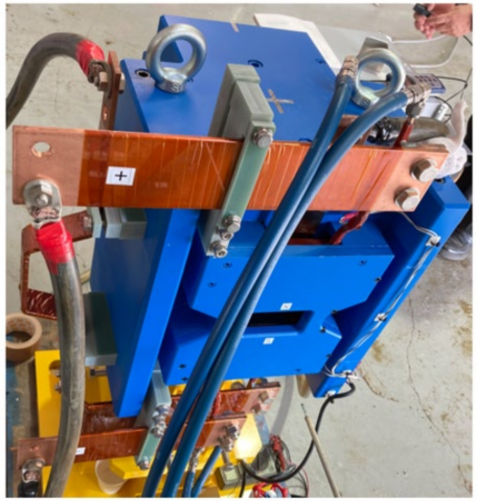
Coupling calculation between QMs

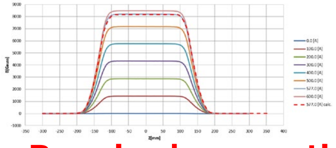


Calculated magnetic field of EBM1



Prototype of EBM1 and field measurements

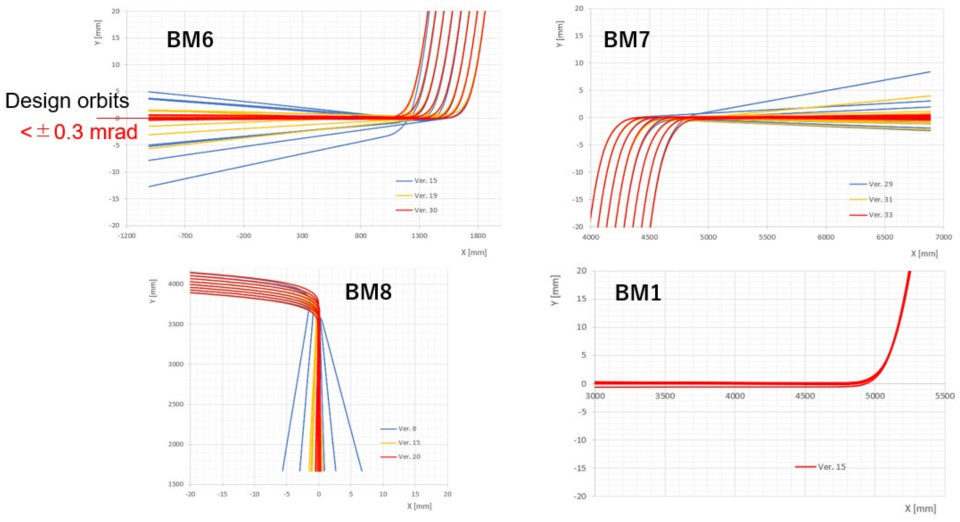




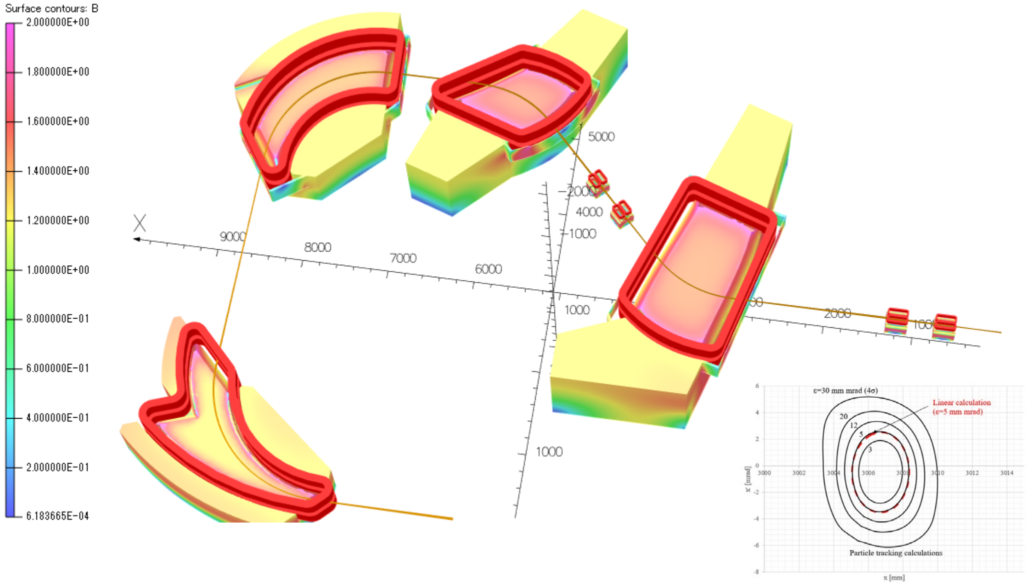
Required magnetic field was confirmed

3D calculation for BMs

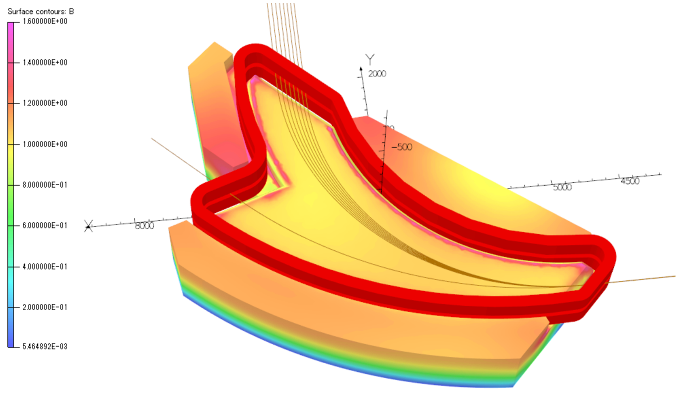
Optimization of orbits for each magnets



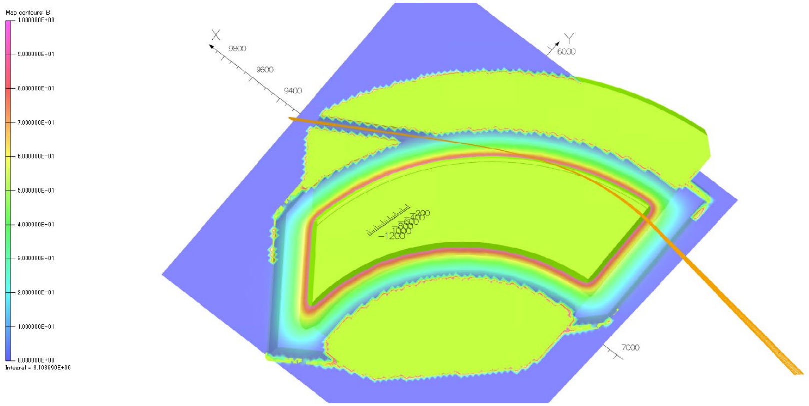
Half-cell orbit calculation



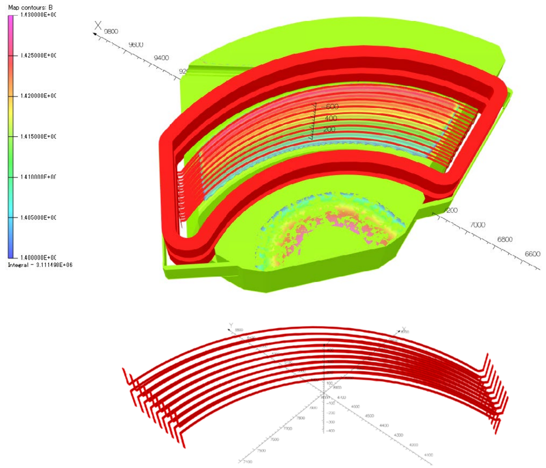
Beam injection



Beam extraction



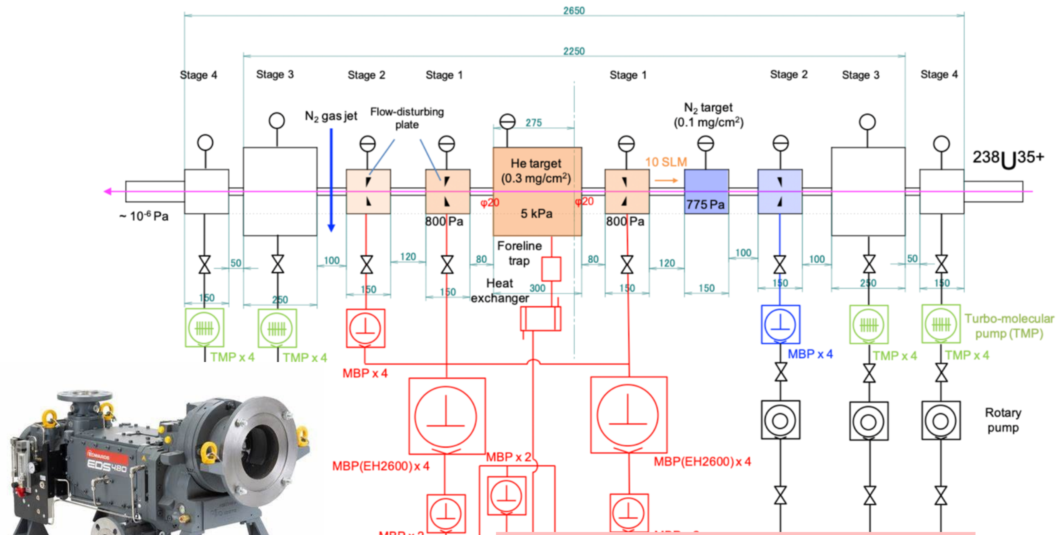
Calculation for trim coils



Conceptual design has been completed and mechanical design is being performed.

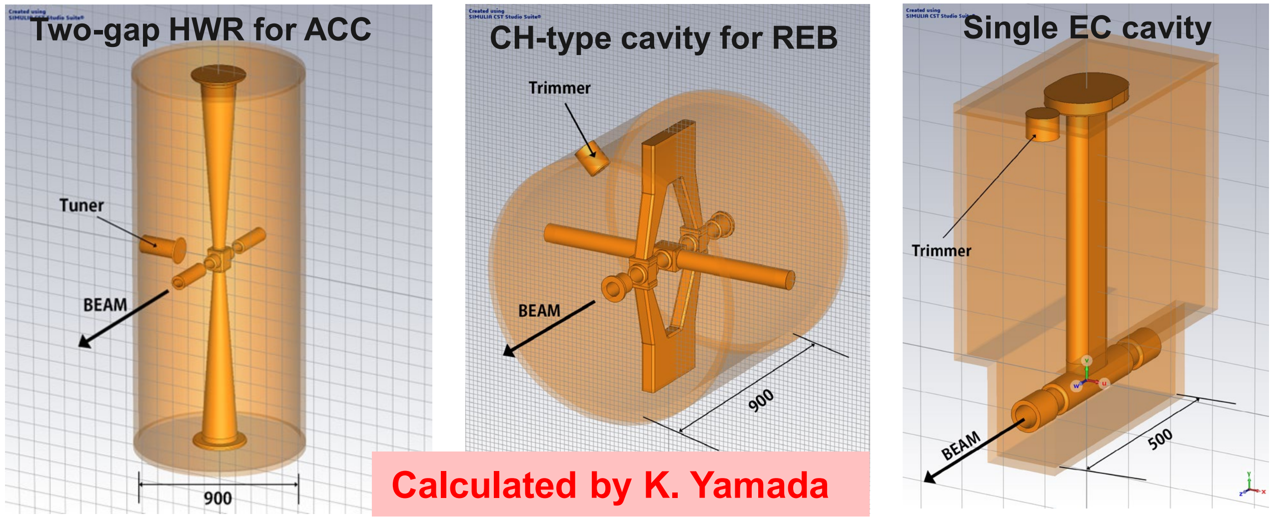
Design works for others

Two-stage stripper design



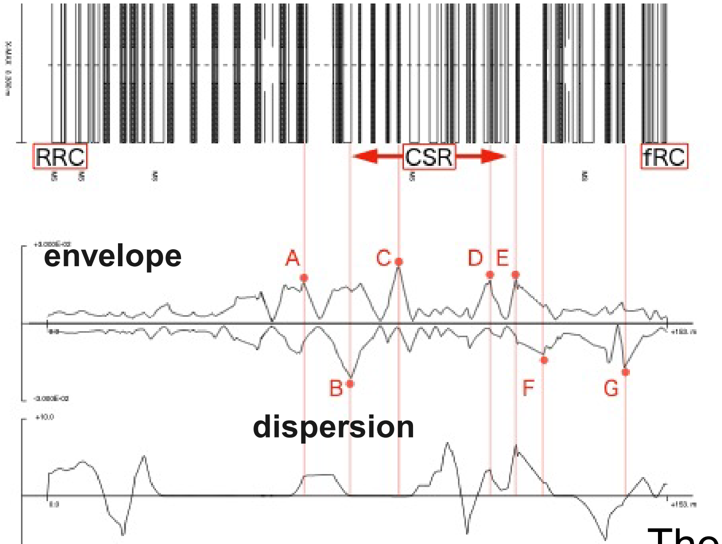
Calculated by Y. Miyake

3D models of RF cavities for CSR1 in calculations



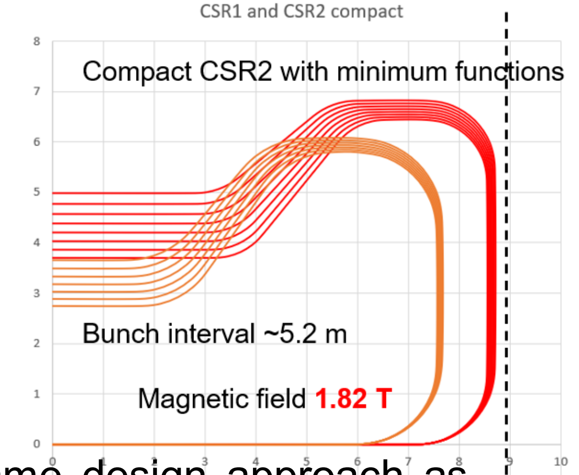
Calculated by K. Yamada

Beam transport calculation from RRC to fRC



Calculated by T. Nishi

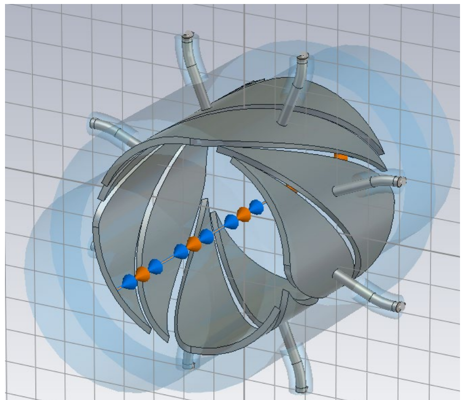
Design for CSR2

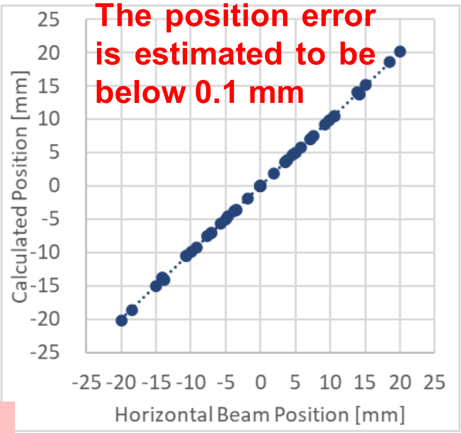


The same design approach as CSR1 can be used for CSR2.

Design of BPM and linearity of beam positions

(Patent Pending, JPN 2023-128268)



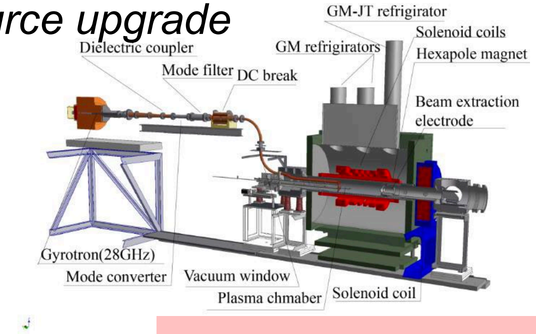


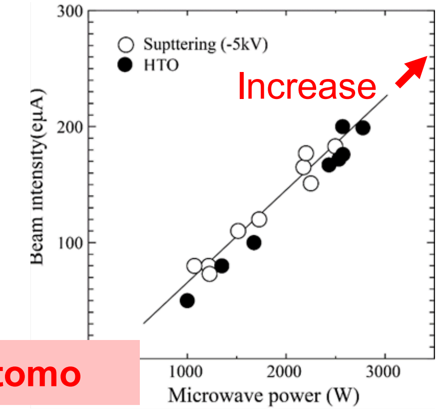
Calculated by T. Adachi

Summary

- Upgrade plan for 20-fold uranium intensity (2000 pnA, 164 kW) is underway.
- CSR is a key device to enhance charge conversion efficiency by recycling beams.
- Design works of CSR1 has progressed well.
- Design works for existing accelerator upgrade is also underway

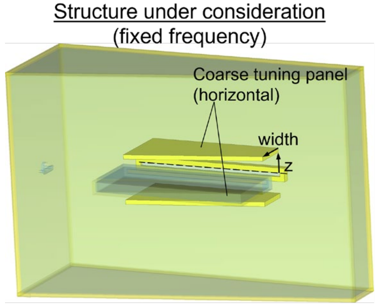
Ion source upgrade

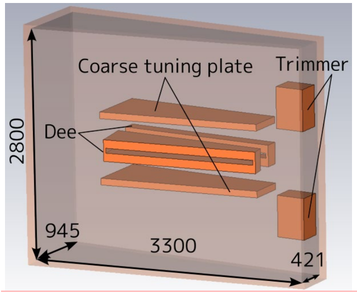




On-going by T. Nagatomo

Design of new RF cavities for SRC and fRC

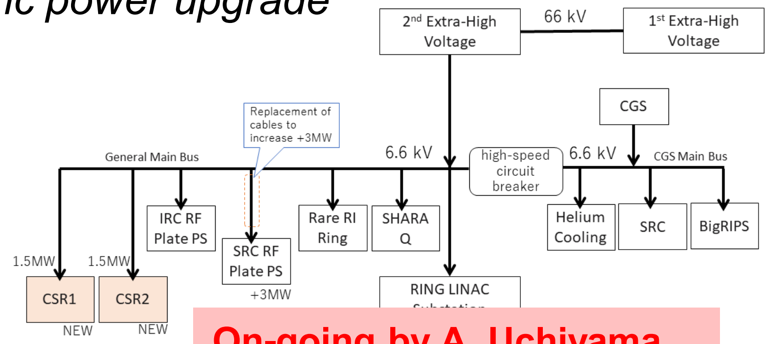




Calculated by K. Ozeki

Calculated by K. Suda

Electric power upgrade



On-going by A. Uchiyama

Acknowledgements

- All members of accelerator group at Nishina center
- Y. Yano（RIKEN）, M. Wakasugi（RIKEN, Kyoto U.）
- Hitachi engineering; T. Hori, M. Abe, T. Chiba、S. Taniyama, T. Imamura, N. Iwaki
- Sumitomo Heavy Industries; S. Kusuoka, J. Kanakura, A. Miura, Y. Matsubara
- SIGMAPHI; M. Sugitani, W. Beeckman
- TOYAMA; N. Kuwahara, D. Kobayashi