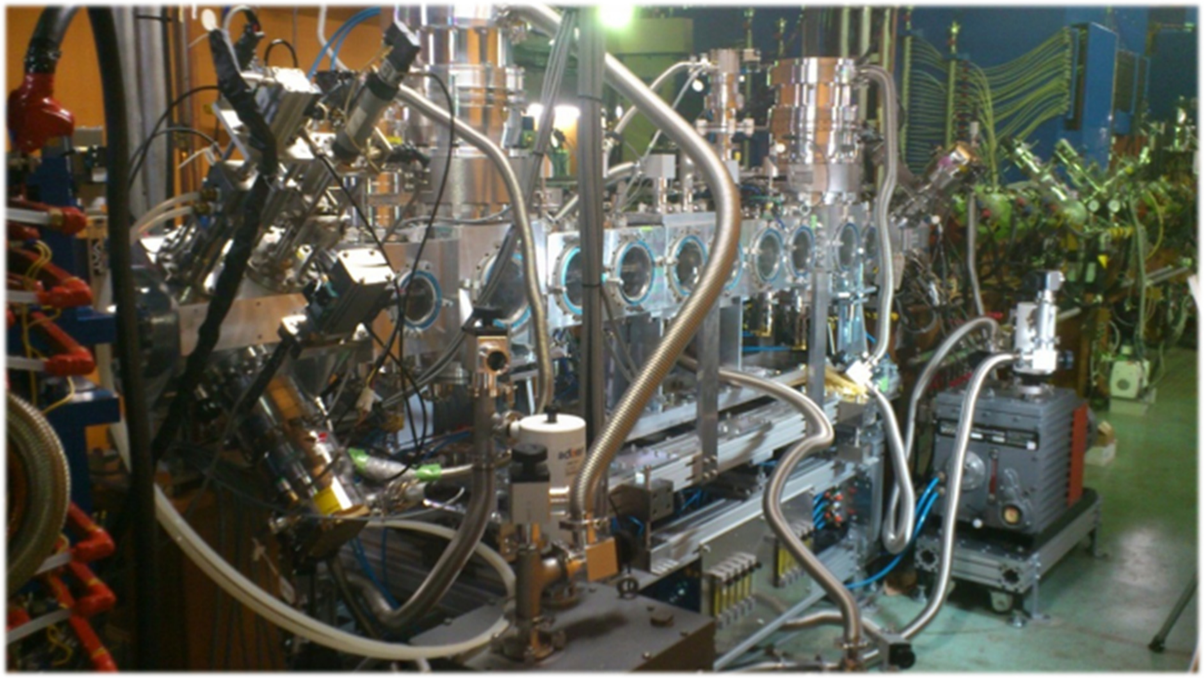
IPAC'18

Development of a Gas Stripper at RIKEN



H. Imao

RIKEN NISHINA CENTER

Outline

1. Introduction

- Situation and requirements for advanced strippers

2. World’s activities

- Acceleration scheme at HIAF, FAIR, FRIB, RAON and RIBF
- FRIB: liquid Li stripper
- FAIR: gas-jet stripper and plasma stripper

3. Strippers at RIBF

- He gas stripper
- Plasma windows
- Rot. GC stripper
- Concept of stripper ring

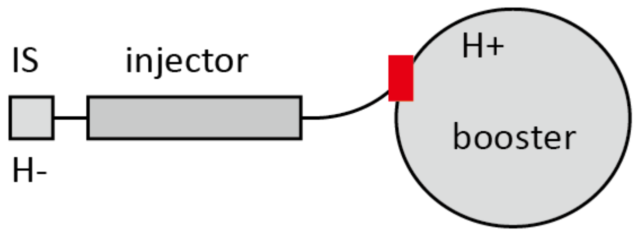
4. Summary and future prospects

1. Introduction

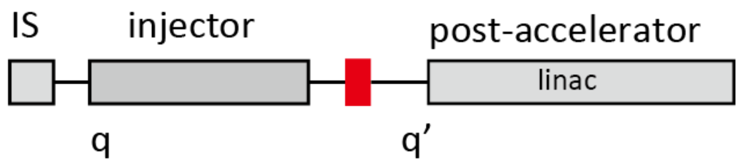
Charge stripper for hadron accelerator

Charge stripper for hadron accelerator complex

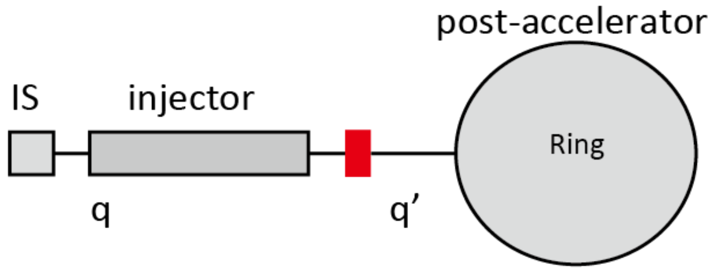
(1) Charge exchange injection for proton accelerators



(2) Charge stripper to increase energy gain for heavy ion accelerators



$E \propto q'$



$E \propto q'^2$

Fixed carbon-foil strippers (thin foil, high temperature)

High-intensity proton accelerators: J-Parc(HBC, I. Sugai), SNS(NDC, R.W. Shaw)…

Relativistic heavy-ion colliders:

BNL-RHIC(AL-GC, P. Thieberger), CERN-LHC, JLab-MEIC…

Scope of today

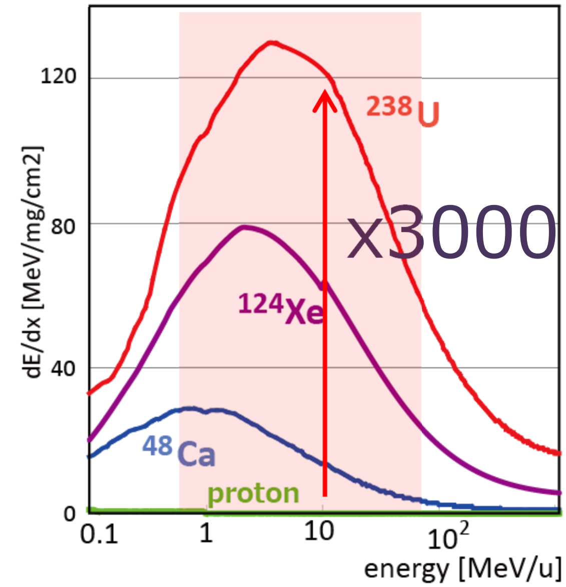
Fixed solid strippers difficult to use in in-flight RI beam facilities

Application limit of fixed C foil

Huge dE/dx of heavy ions on C foils

Heat load: sublimation

Radiation damage : lattice modification

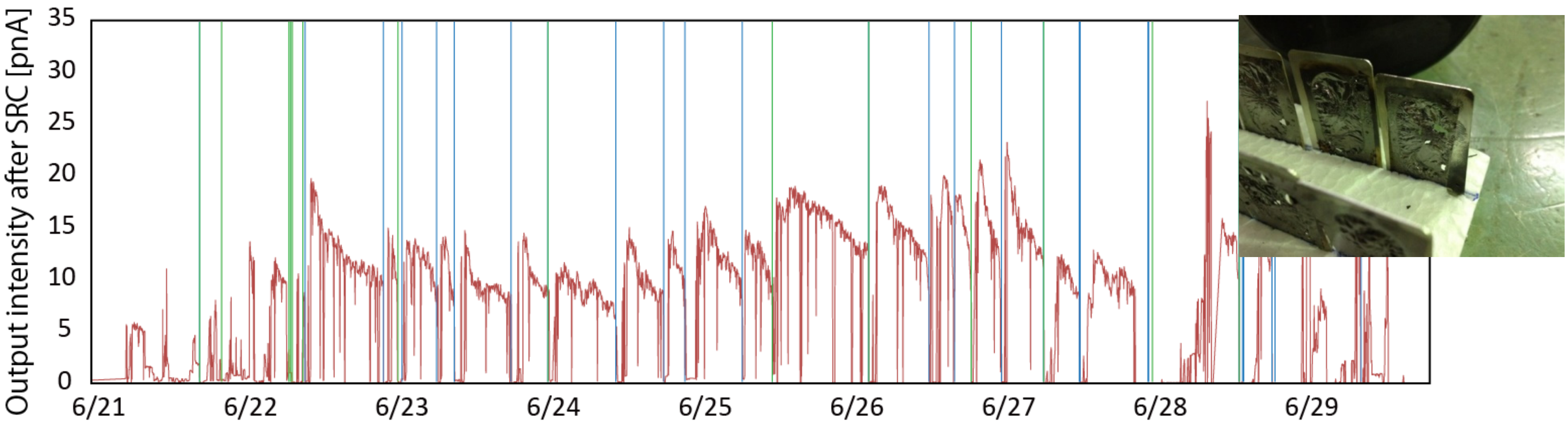


Application limit (rough estimation)

~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)

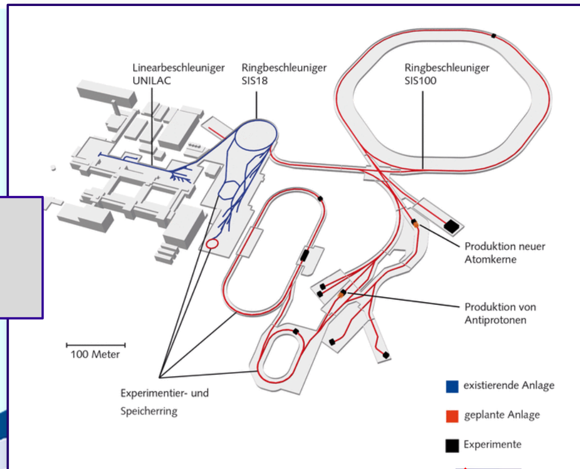
Upcoming in-flight RI beam facilities share the same difficulties

1. Introduction

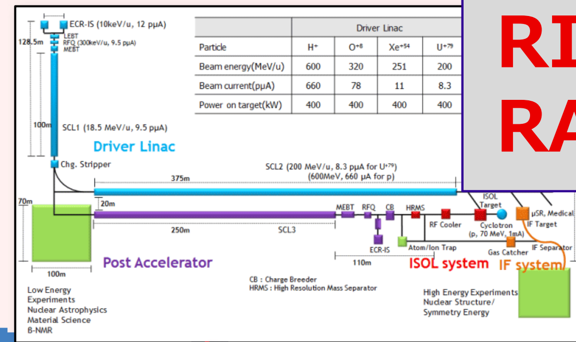
In-flight RI beam facilities

Europe

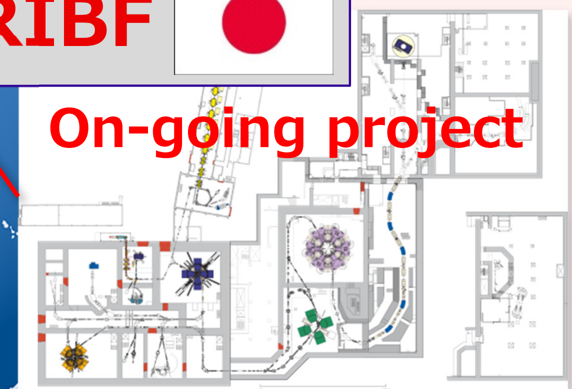
GSI FAIR



RISP RAON



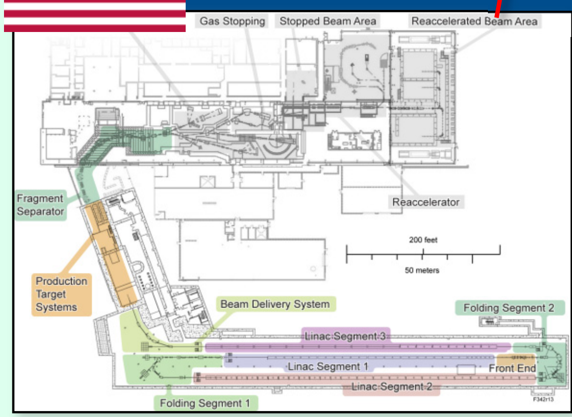
RIKEN RIBF

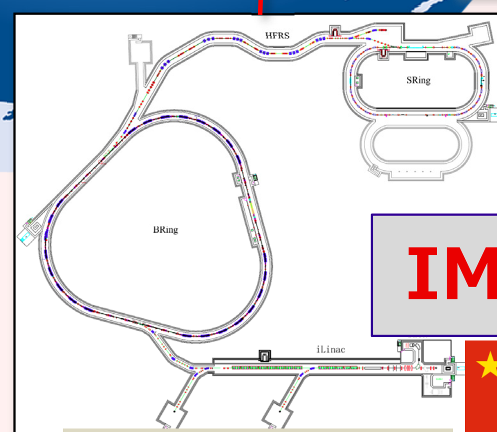


On-going project

$\geq 10^{12}$/s for ^{238}U

MSU FRIB





IMP HIAF

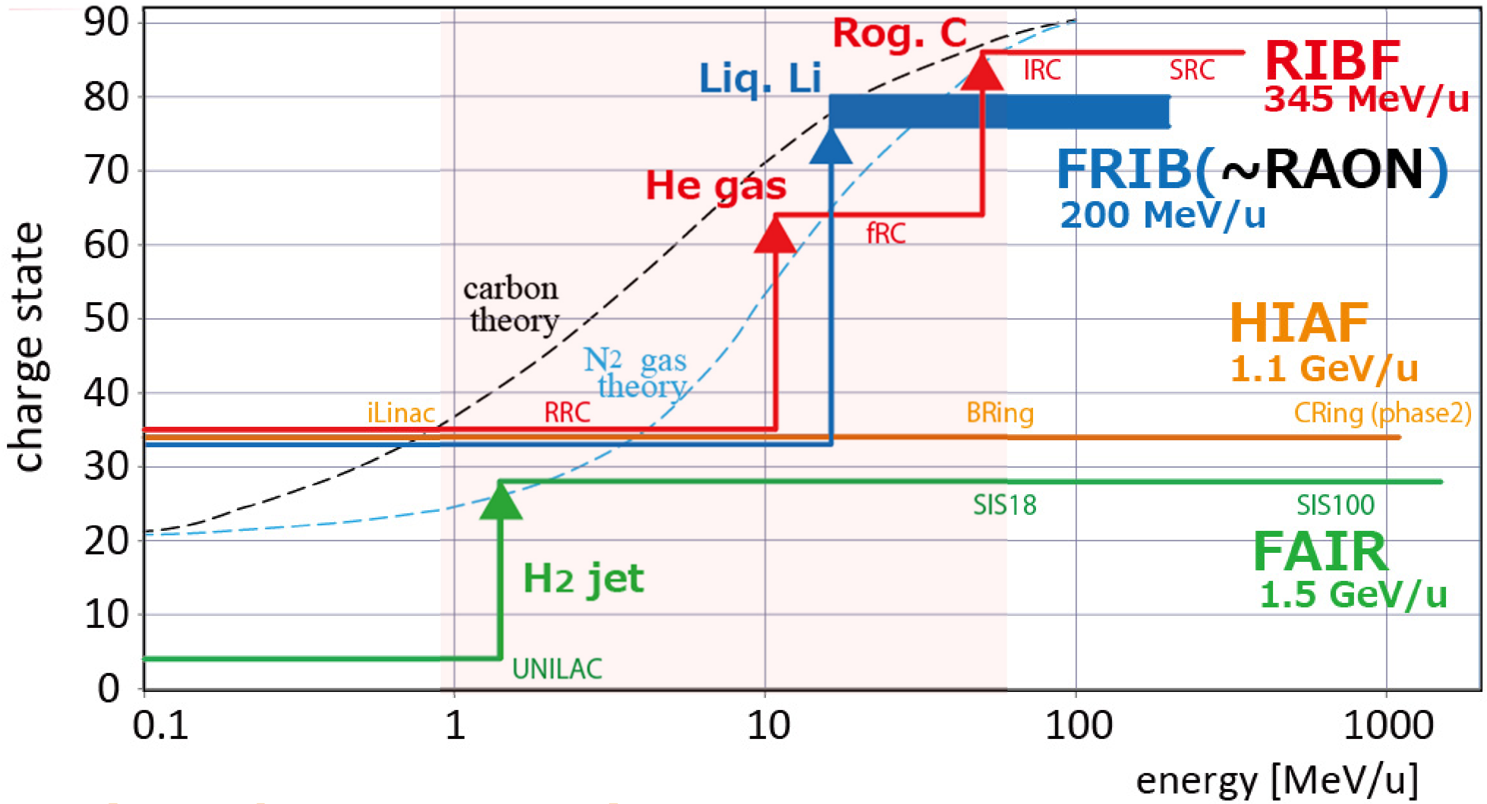
ASIA

Courtesy of L. Liang

N. America

1. Introduction

Acceleration scheme for ^{238}U



- **HIAF(Synchrotron, PLS)**
  U^{34+} No stripper (phase1), afterglow ECR, (planning U^{34+} ➡ U^{78+} in phase2)
- **FAIR(Synchrotron, PLS)**
  U^{4+} ➡ U^{28+}@1.4 MeV/u, lower charge state to reduce space charge effects
- **FRIB(SRF linac, DC), RAON(SRF linac, DC)**
  U^{33+}&U^{34+} ➡ U^{76+}-U^{80+} , multi-charge acceleration
- **RIBF(Ring cyclotron, DC)**
  U^{35+} ➡ U^{64+} & U^{64+} ➡ U^{86+}, two strippers, advantage of acceleration ability

Requirements for new strippers

- **Long lifetime**: heat load, radiation damage➡fluid, moving solid
- **High charge state**: low-density media such as gas provides lower charge state (density effect)➡ low-Z gas
- **High stripping efficiency**: shell effect, multi-electron process
- **Thickness uniformity and stability**: momentum spread
- **Safe handling**: explosion, pyrophoricity

Parameters of strippers for ^{238}U at FAIR, FRIB and RIBF

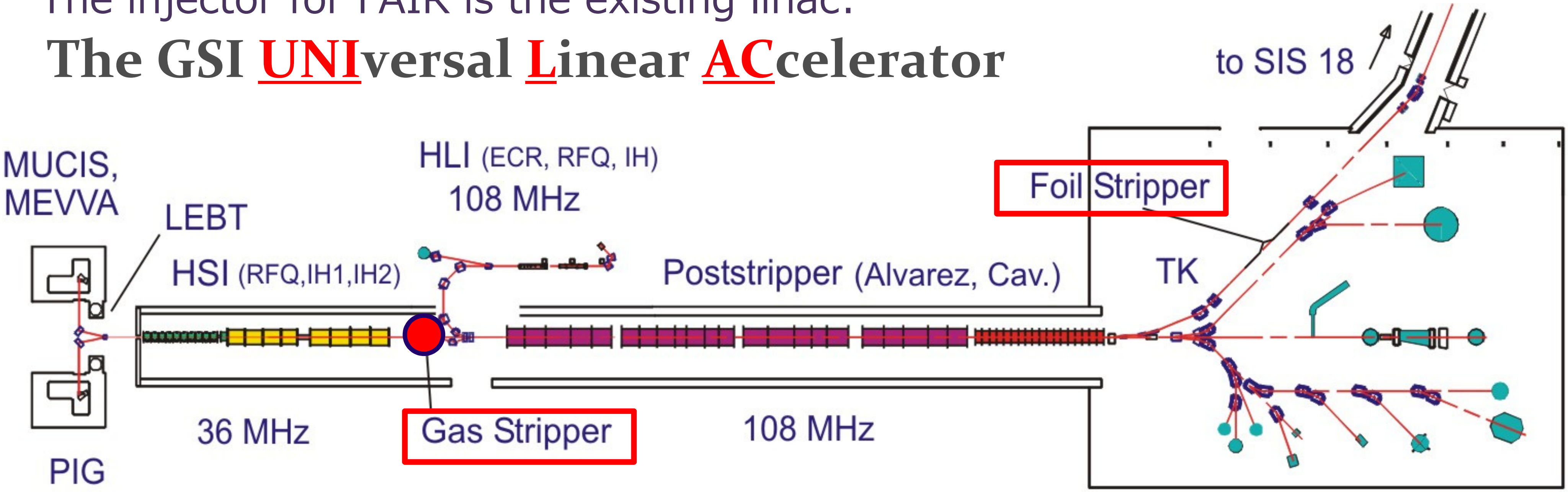
	FAIR (values at GSI)	FRIB (planning values)	RIBF (present values)	
media	H2 pulsed gas	Liq. Li	He gas	Rot. Disk
energy [MeV/u]	1.4	~20	10.8	50.8
input charge	4	33 + 34	35	64
output charge	28 or 29	76-80	64	86
intensity [pps]	1.2E+12	5.0E+13	1.0E+13	2.0E+12
thickness [mg/cm2]	0.03	0.5	0.7	14
energy loss [W]	10	700	180	270
key technology	pulse operation	safe operation of Li	windowless accumulation	uniform thickness strong material

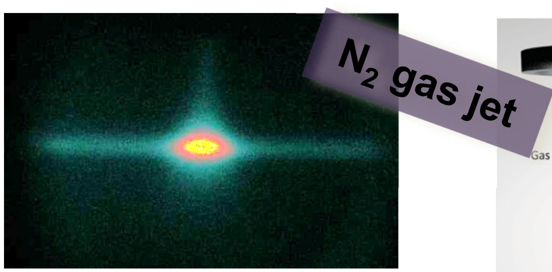
>10^{12}/s

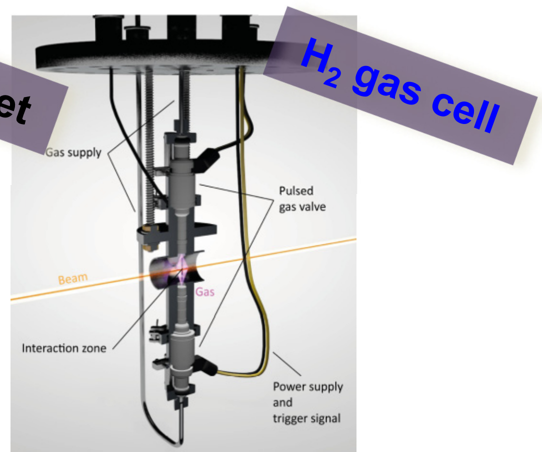
Gas stripper at UNILAC for FAIR

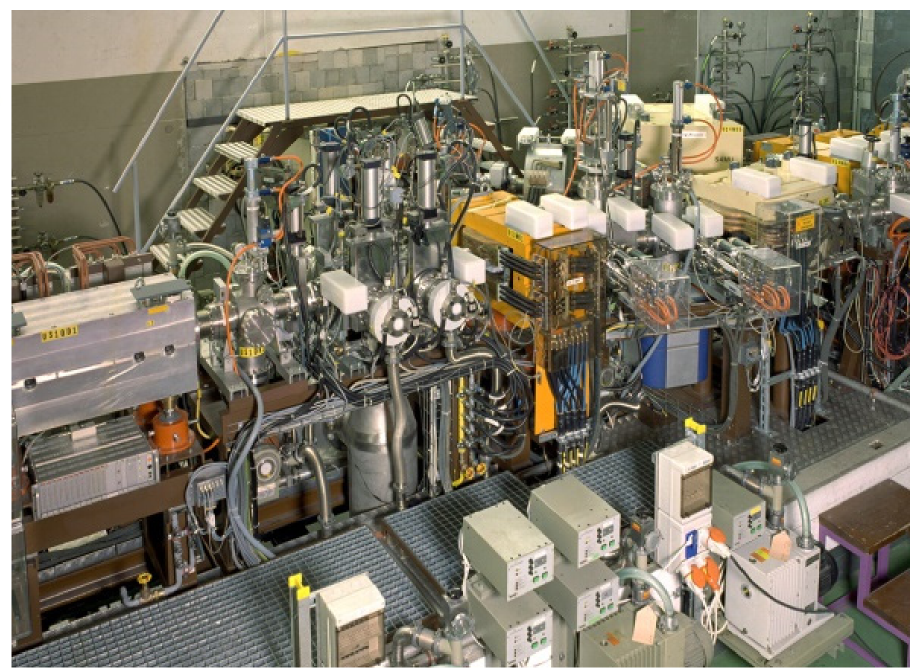
The injector for FAIR is the existing linac:

The GSI UNIversal Linear ACcelerator









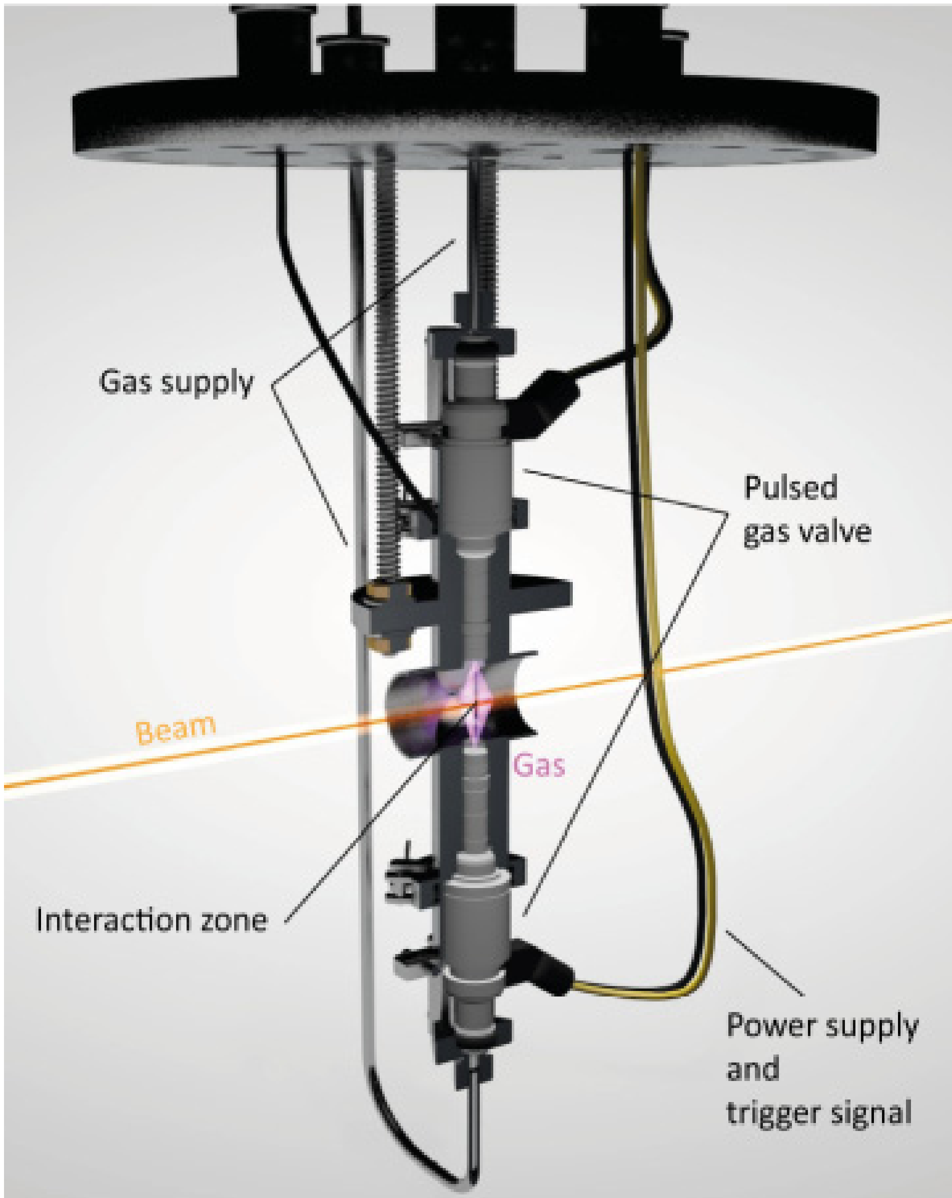
1.4 MeV/u

$U^{4+} \rightarrow U^{28+}$ or U^{29+}

~10 μg/cm^2

Courtesy of W. Barth (GSI)

Pulsed H_2 gas-cell stripper



Recent prominent work!

Duty cycle of injected beams : 100 μs/1 Hz

Pulsed gas stripper is effective to reduce gas load on 4-stage differential pumping system

Make thick low-Z gas target ($<100\ \mu g/cm^2$ for H_2) with the lower gas consumption rate

Pulsed gas valves with the leading time of 250 μs

Courtesy of W. Barth (GSI)

P.Scharrer et al., PRST-AB 20 043503 (2017)

2. World's activities: FAIR

Charge stripping efficiency

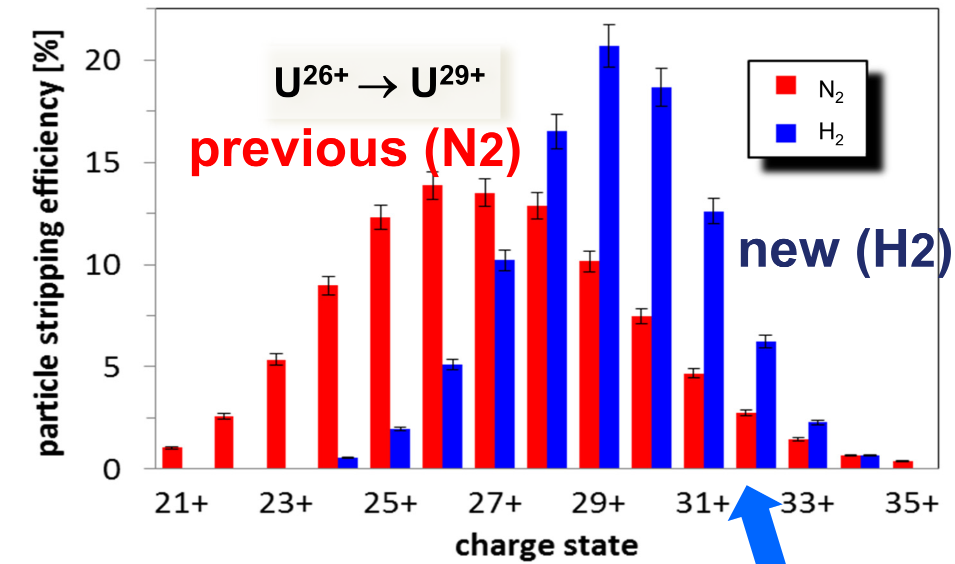
Very succeceful!!

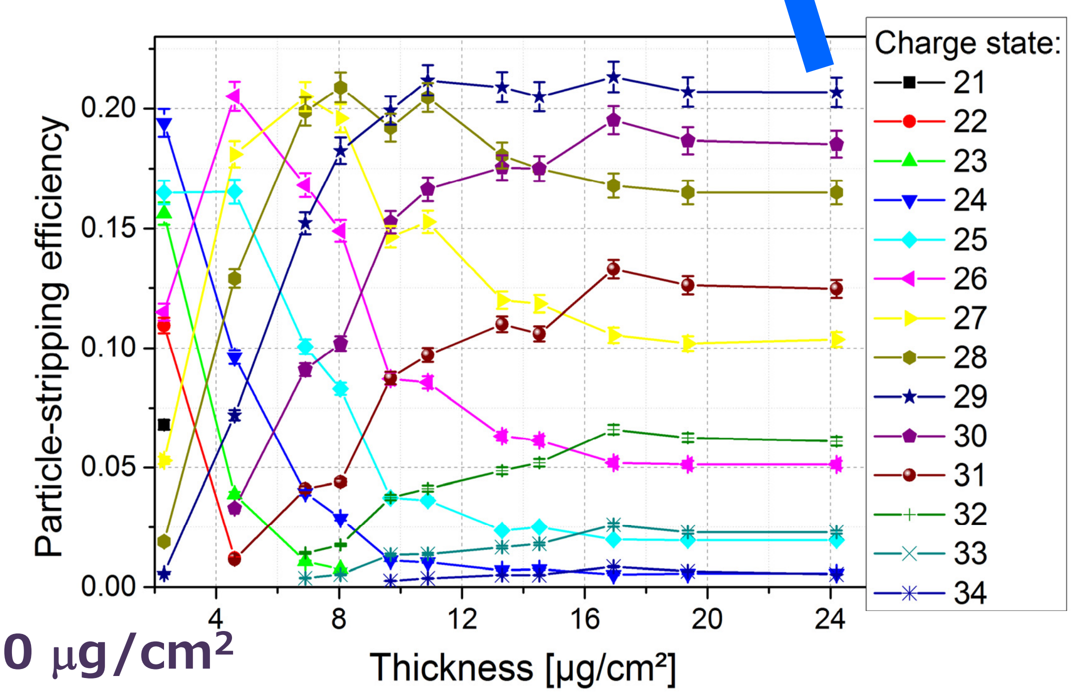
Beam Parameters:

	N_2-gas jet [8]	H_2- gas cell (pulsed)
Back-pressure	0.4 MPa	12.0 MPa
U^{4+}-current (HSI)	6.0 emA	7.4 emA
Stripping charge state	28+	29+
Stripping efficiency	12.7±0.5%	21.0±0.5%
Energy loss	14±5 keV/u	60±5 keV/u
Max. current	4.5 emA	11.5 emA
ε_x (90%, tot.) norm.	0.76 μm	0.51 μm
ε_y (90%, tot.) norm.	0.84 μm	0.96 μm
Hor. brilliance (90%)	5.32 mA/μm	20.29 mA/μm

Beam Energy Loss:

U^{28+}	N_2-jet (max.)	14±5 keV/u
U^{28+}	Pulsed H_2-stripper cell (7.5 MPa)	35±5 keV/u
U^{29+}	Pulsed H_2-stripper cell (12.0 MPa)	60±5 keV/u



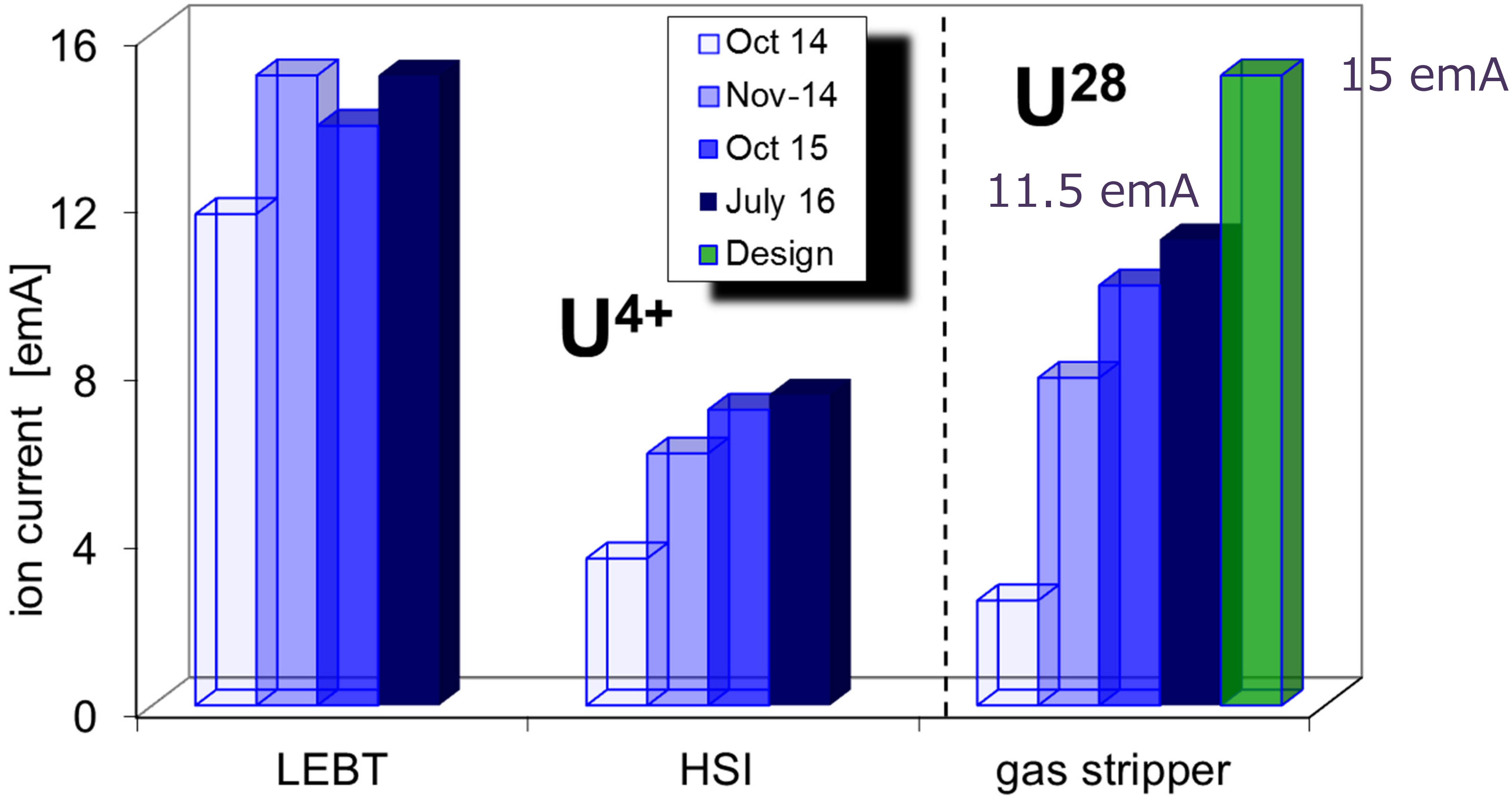


Thickness of H2 in measurement ~30 μg/cm²

Courtesy of W. Barth (GSI)

W.Barth et al., PRST-AB 20 050101 (2017)

Achieved output intensity



In FAIR, it is planned to use the pulsed H2 gas-cell stripper at 1.4 MeV/u. Beam qualities after the stripper should be measured and multi-turn injection to SIS18 should be verified.

Courtesy of W. Barth (GSI)

W.Barth et al., PRST-AB 20 050101 (2017)

Plasma stripper for FAIR

Plasma stripper is free from the thermal issues basically due to the heavy ion beams

High charge state: electron capture processes w/ free electrons are strongly suppressed

Frankfurt group working at GSI

- **Pinch plasma (pulse)**
- **High electron density up to $3.6\text{x}10^{16}$ /cm^3 (measured by Hβ broadning)**
- **Test experiments with Au^{26+} beams (3.6 MeV/u) at GSI**
- **Charge state enhancement:**

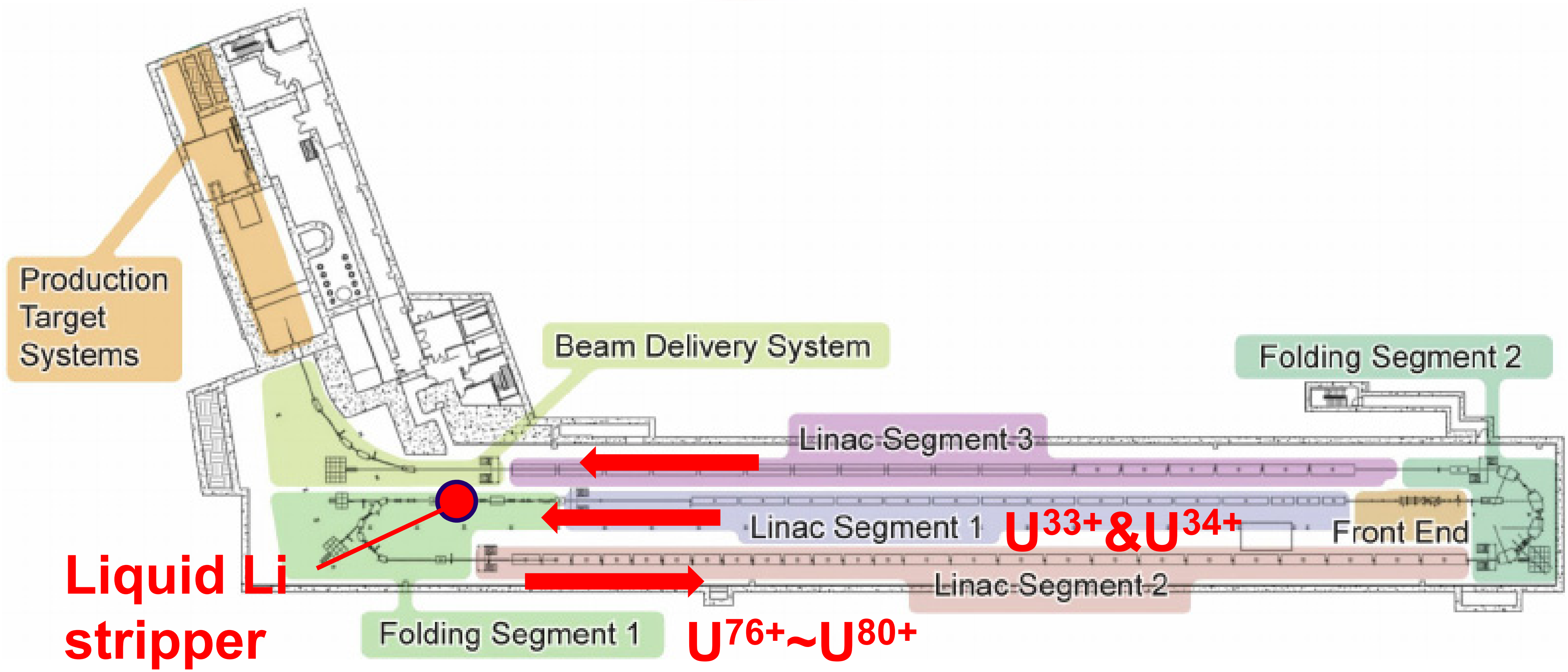
Hydrogenplasma (θ-pinch) : 27+-30+

H^2 gas: 26+-28+

Aiming the higher electron densities more than 10^{17} /cm^3

M. Iberler, et al., Proceedings of IPAC2016 TUPMR056
Ge Xu et al., PRL 119, 204801 (2017)

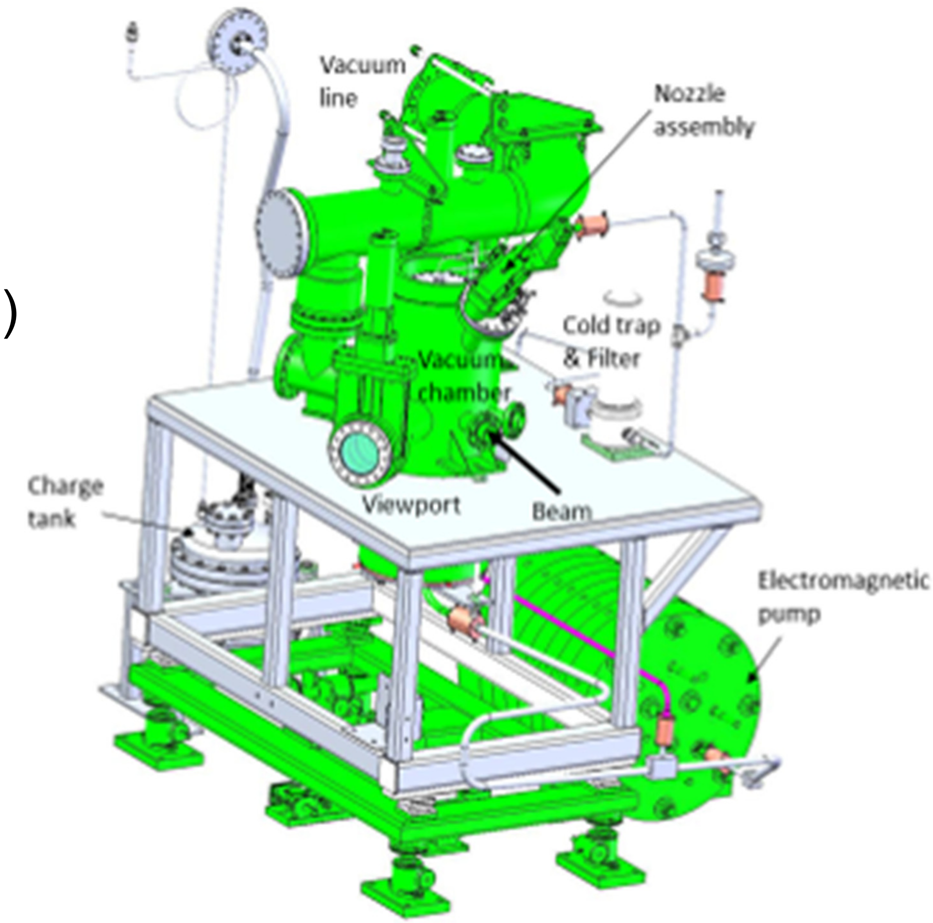
FRIB(USA): a folded linac



- SC Linac E/A≧200 MeV/u, 400 kW on target
- Liquid Li stripper at an energy of ～20 MeV/u
- Beam power at the stripper ～40 kW
- Energy deposit of ~700 W on thin Liq. Li film target (~10 μm)

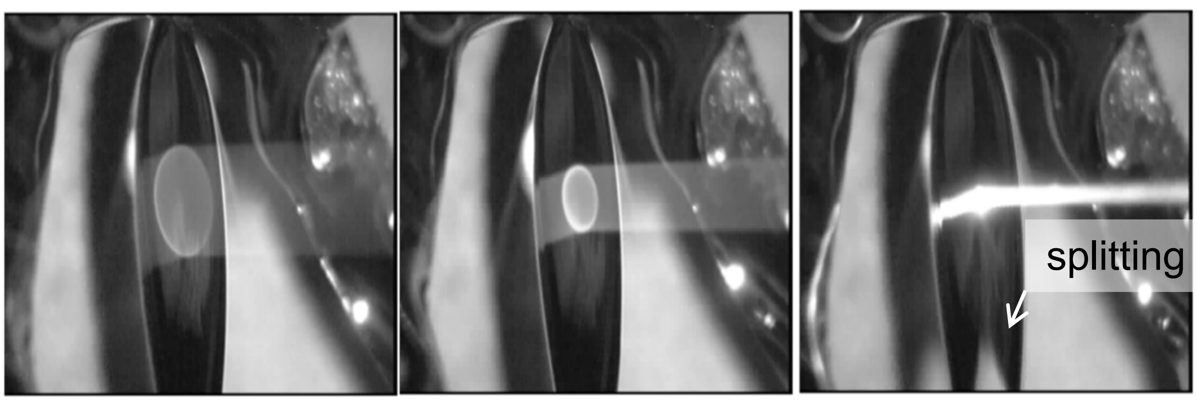
Liquid Li stripper for FRIB

- Liquid lithium stripper for FRIB has developed in collaboration between **MSU and ANL** (***J.Nolen et al.***)
- A high pressure lithium jet impinging on a deflector produces a thin lithium film (**~ 10 μm**) moving at high speed (**~ 50 m/s**)
- The lithium is circulated with an electromagnetic pump



Film break up or not by powerful beams?

Film stability demonstrated with a proton beam depositing similar power densities as an uranium beam at FRIB conditions



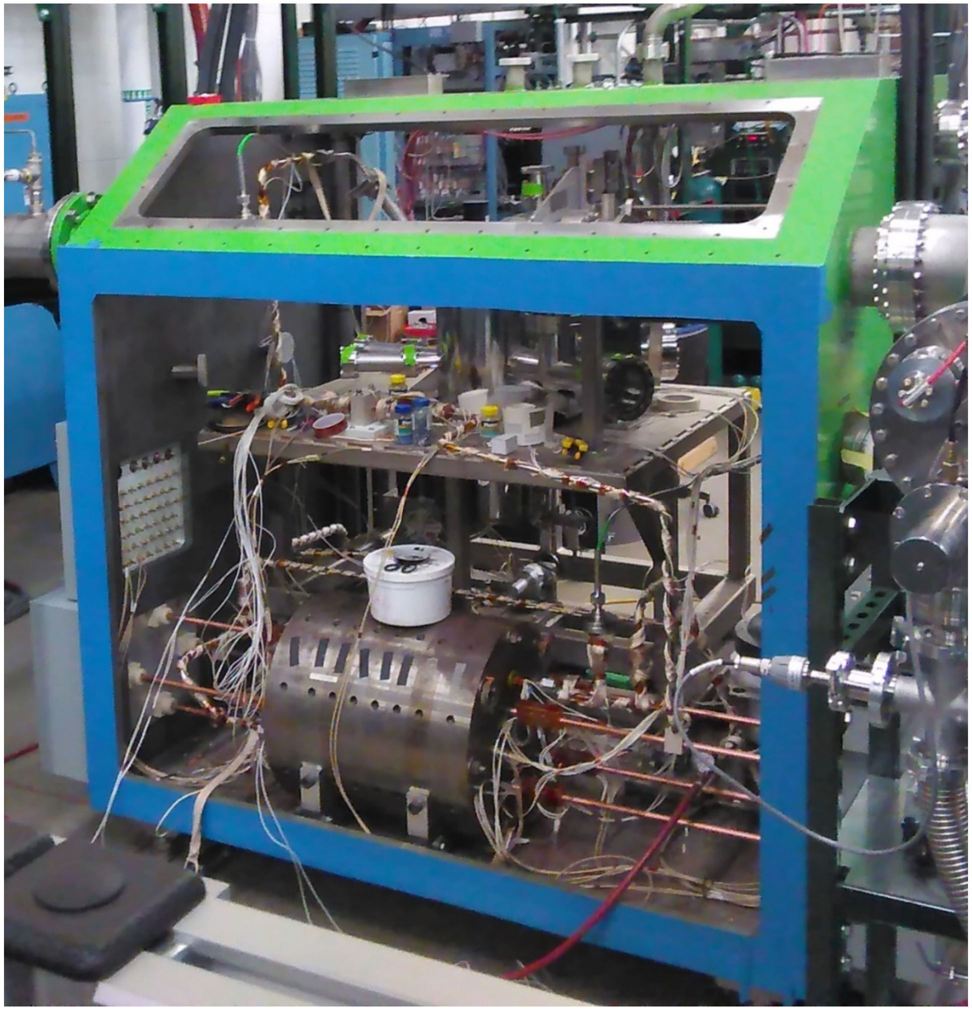
Y.Momozaki et al., JRNC, 305, 843 (2015)

Proton beam (65 kV, 4.6 mA, 300 kW, σ = 0.7 mm in the best focused condition) impinging on the liquid lithium film.

Beam power: 43% of FRIB
Power density: 250% of FRIB were proved

Courtesy of F. Marti (MSU)

Hazard mitigation



Complete lithium loop enclosed in a 2.5 cm steel vessel. Over one hundred temperature sensors included.

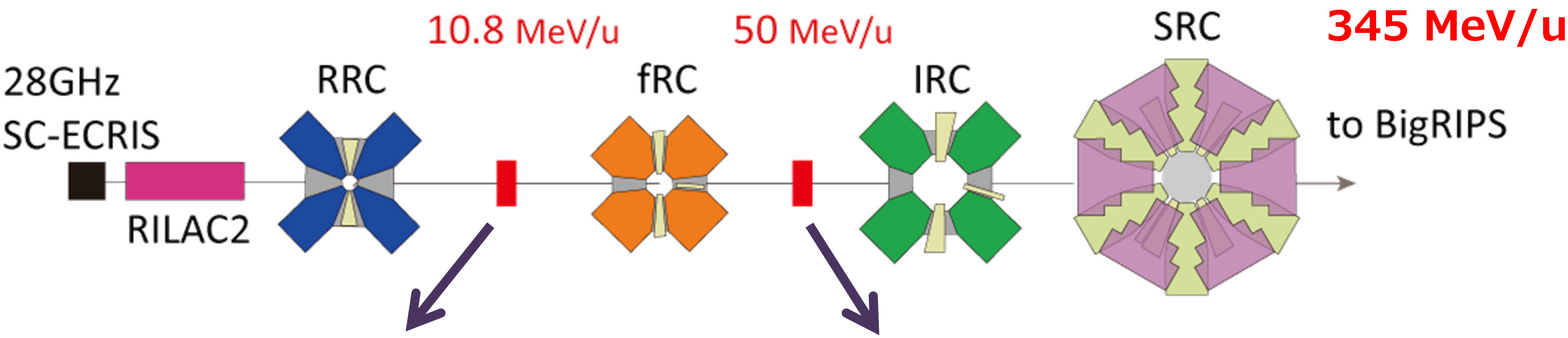
- Secondary vessel encloses the entire Li loop and provides a safety barrier. The vessel atmosphere is maintained as an argon environment during operation (i.e. when Li is not solid)
- Detection of abnormal situation (i.e. excessive pressure in vacuum chamber or in secondary vessel) triggers a shutdown of lithium pump and controlled shutdown of the system.
- System is ready to load lithium

started to load the lithium in the module

Courtesy of F. Marti (MSU)

3. Strippers at RIBF

Acceleration scheme of ^{238}U at RIBF

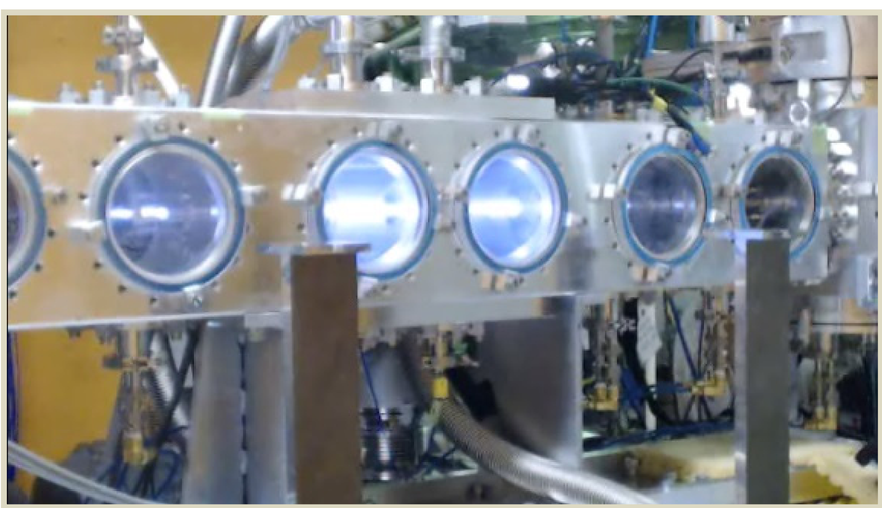


1． He gas stripper (since 2012)

35+⇒64+ (20%)

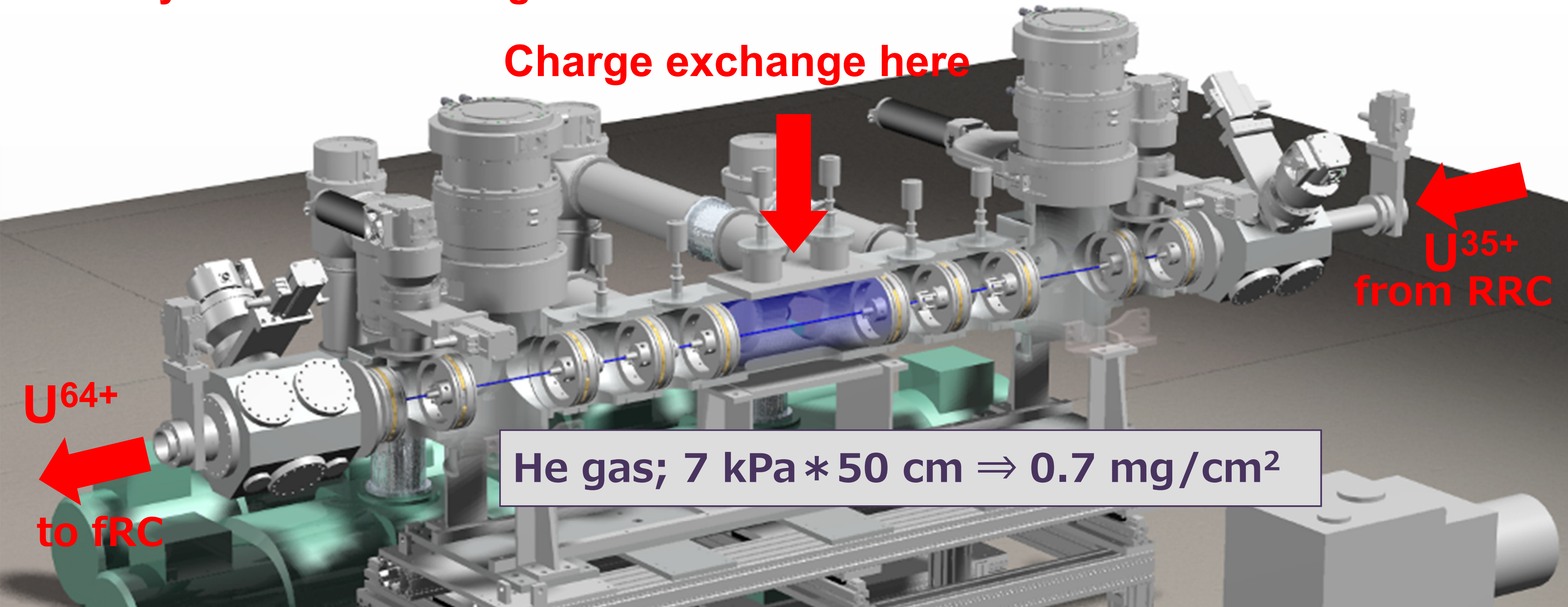
2． Rotating disk stripper (since 2012)

64+⇒86+ (30%)

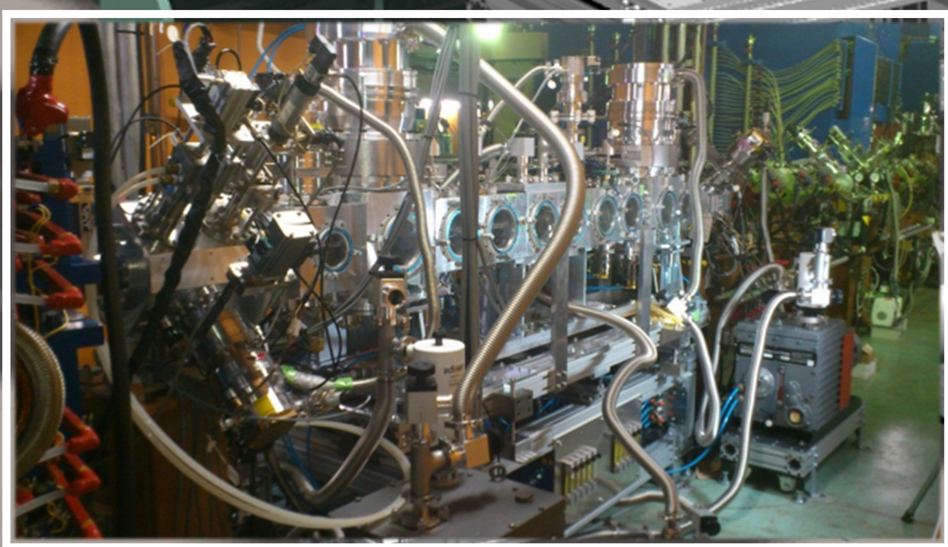


Recirculating He stripper

Primary technical challenge ➡ windowless accumulation of He

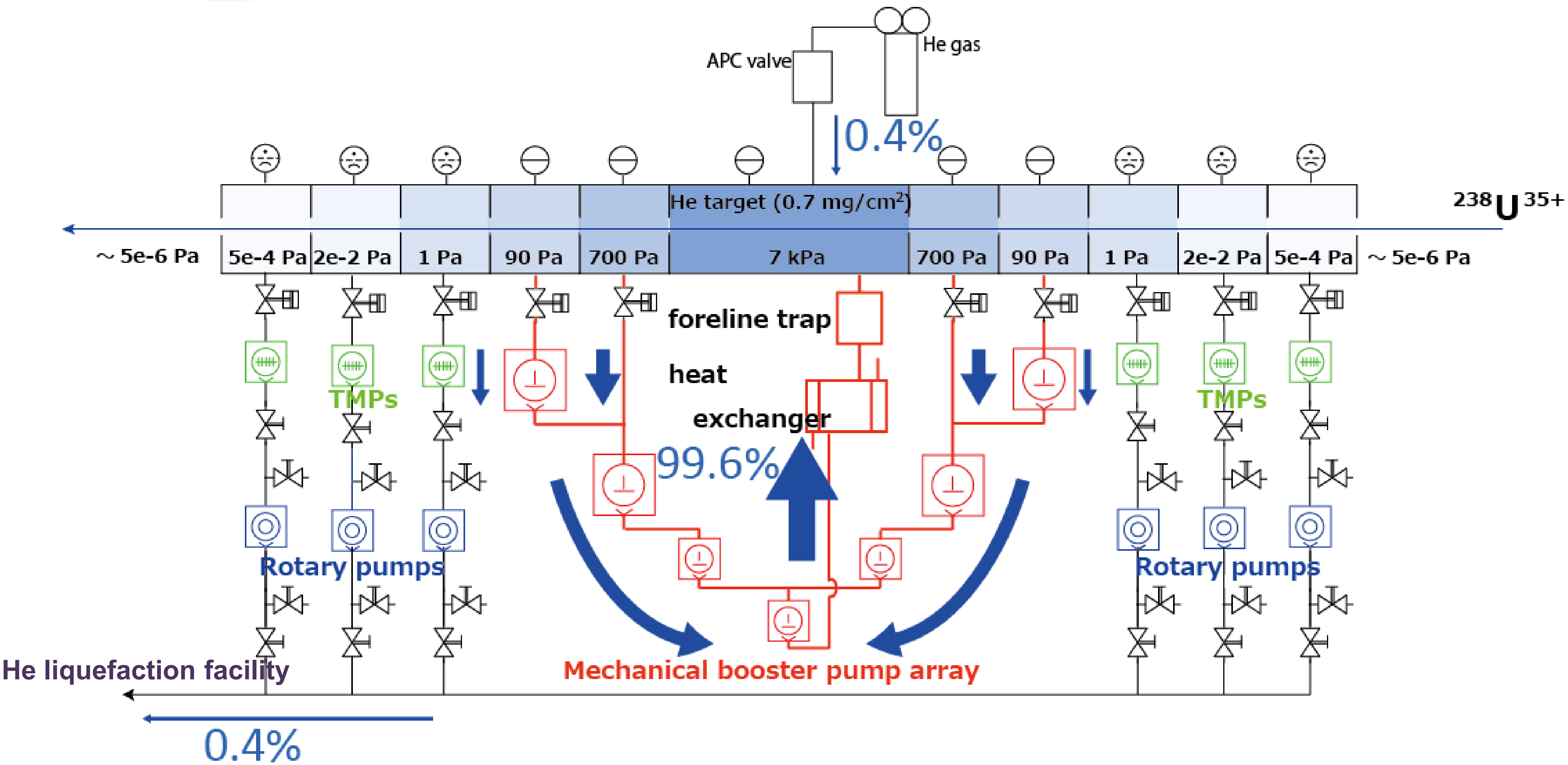


He gas; 7 kPa ∗ 50 cm ⇒ 0.7 mg/cm^2



- 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**

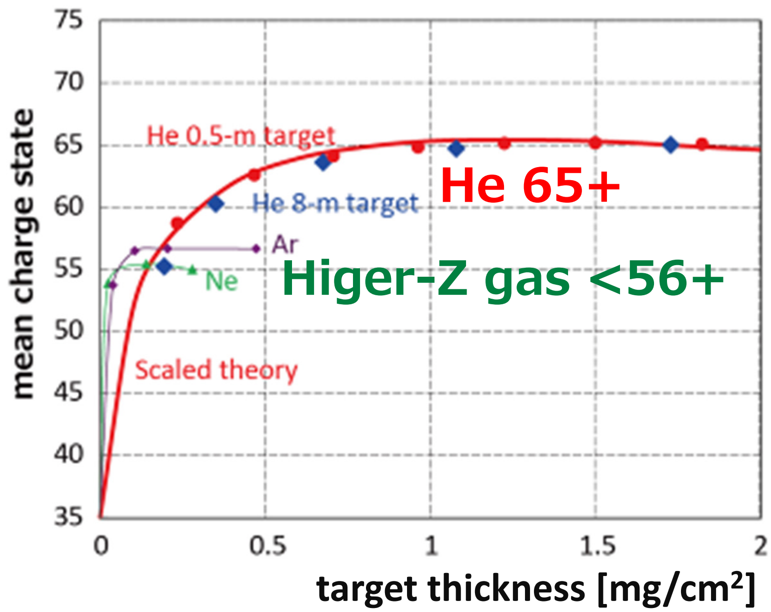
Recirculation system

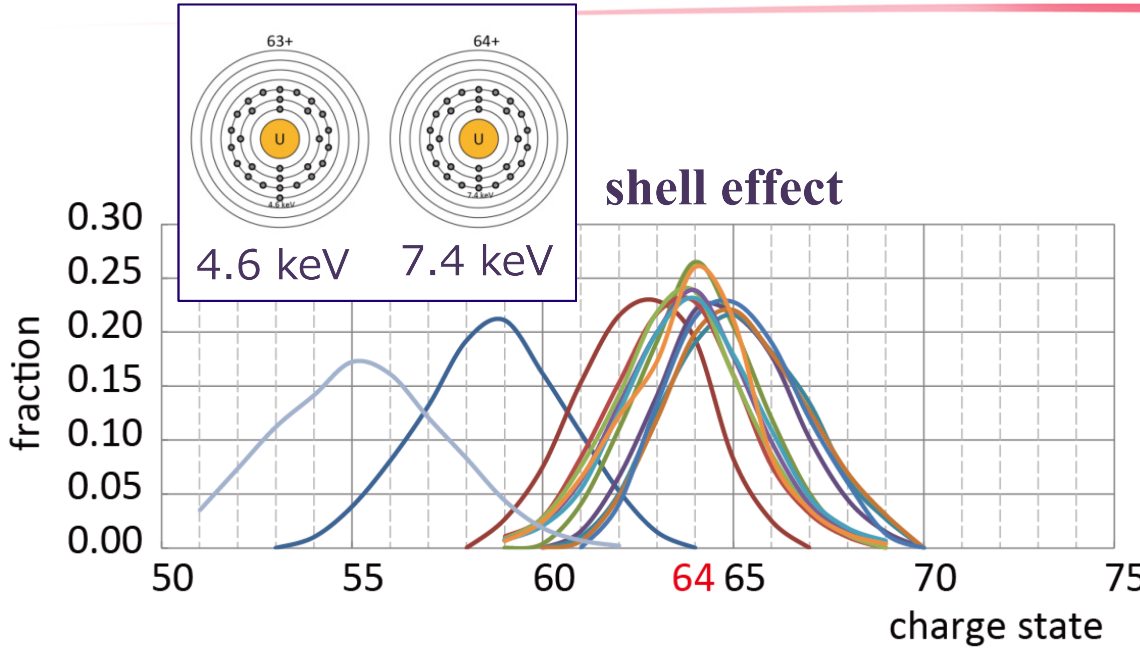


- **Multi-stage MBP array** (7 units, 12000 m^3/h)
- **Recycling rate < 99.6%**

Fundamental data

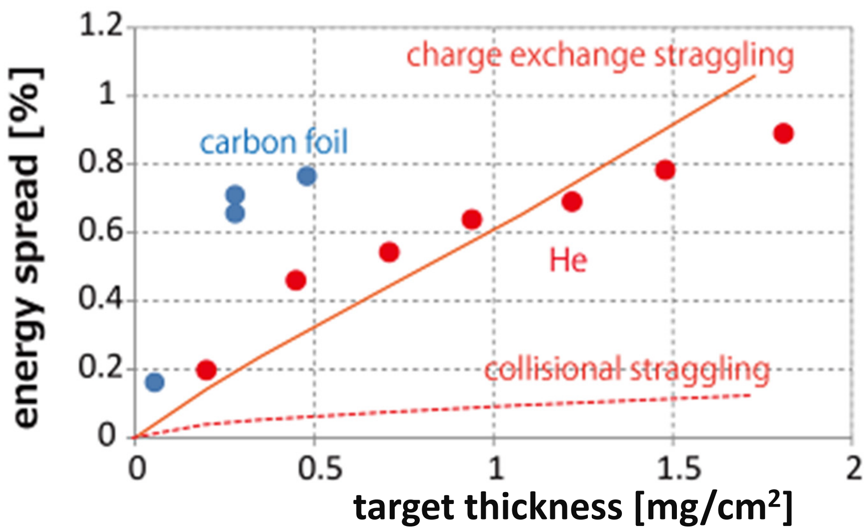
•Charge evolution



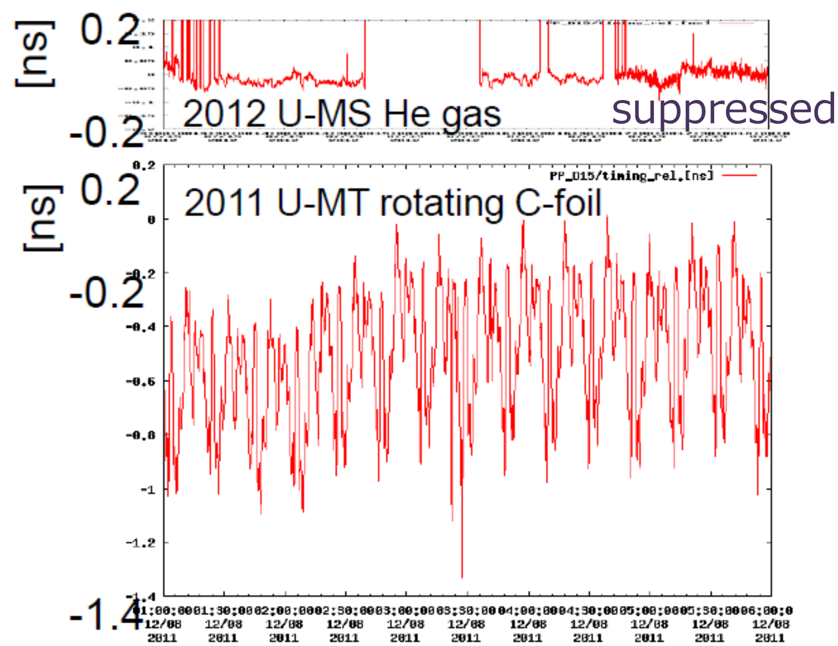


•Energy spread

Half of spread (thickness uniformity)



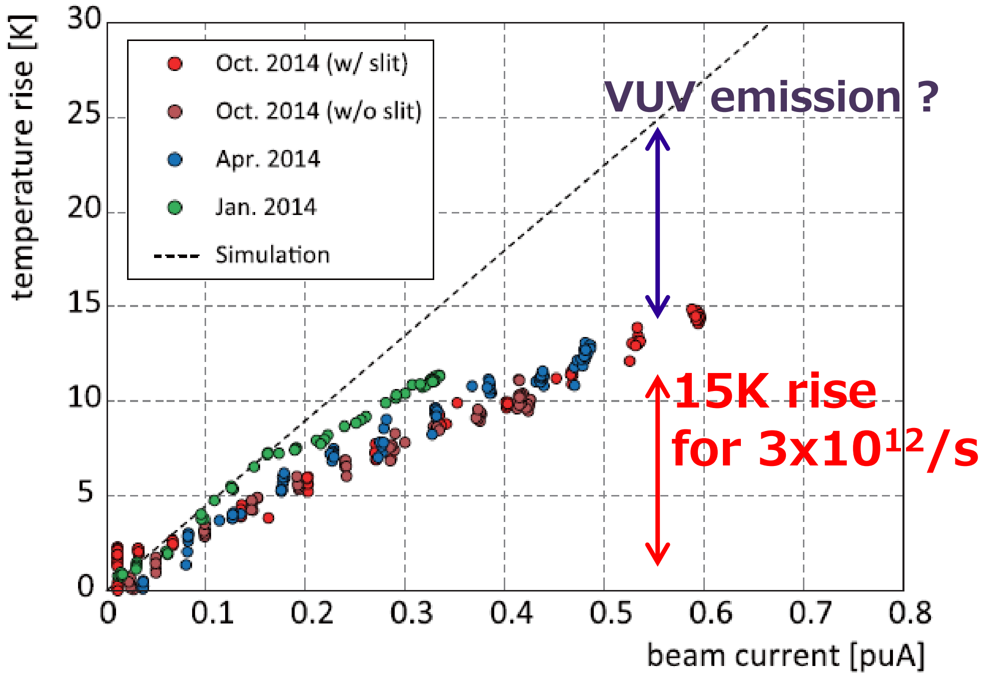
•Jitter of beam timing



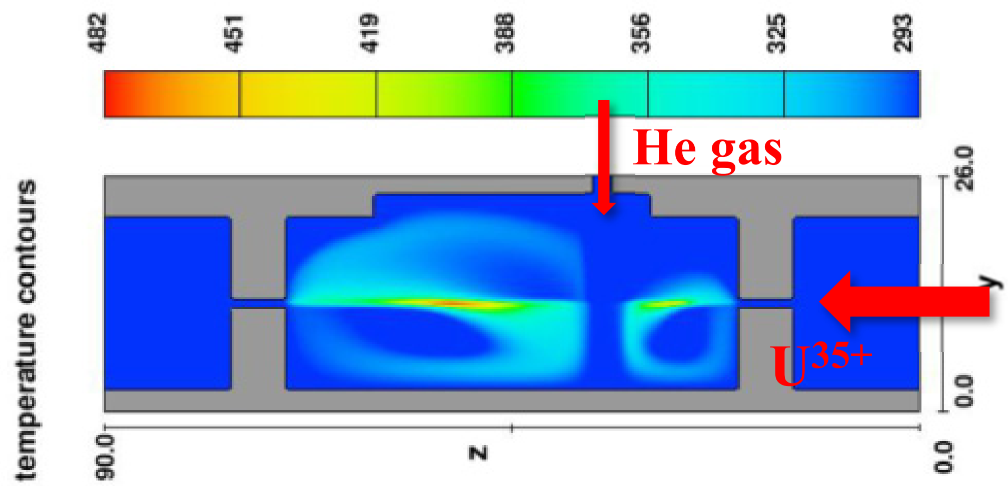
H. Imao et al., PRST-AB 15, 123501 (2012)

Target thinning

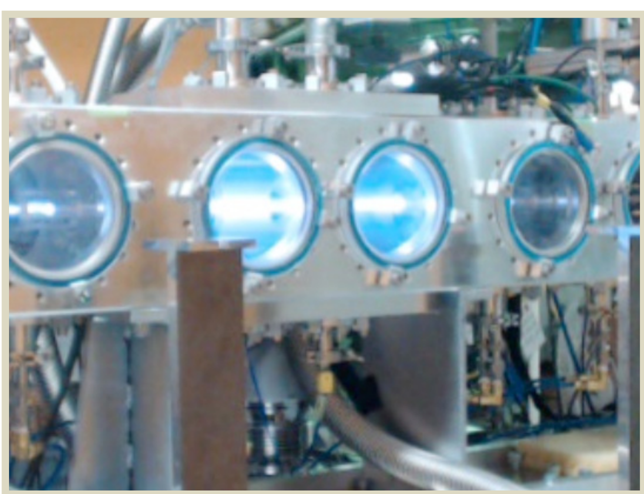
Powerful beams may make a hole even in gas stripper
Target thinning will determine the application limit of gas stripper



Measured TOF of U beams after stripper as a function of beam current



Calculation
- flow3D (K. Ogata)
- SW flow simulation (H. Imao)



Compared with CFD calculations, **the heating efficiency is about 50%**

VUV light emissions are a possible explanation

Not so serious at the present intensities

high-intensity operation

Problems with increasing intensities (>10^{13}/s)

1. Beam transmission

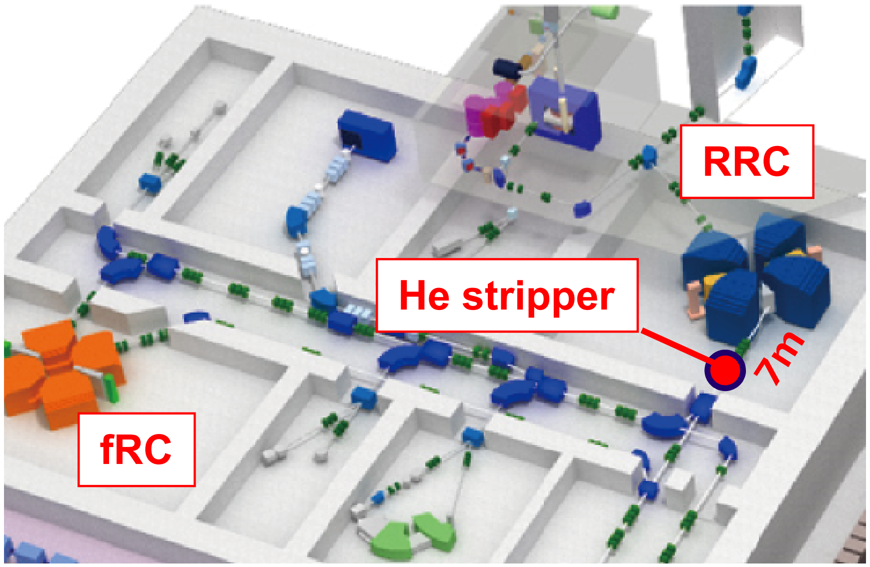
Small beam loss cause hardware trouble and radioactivites

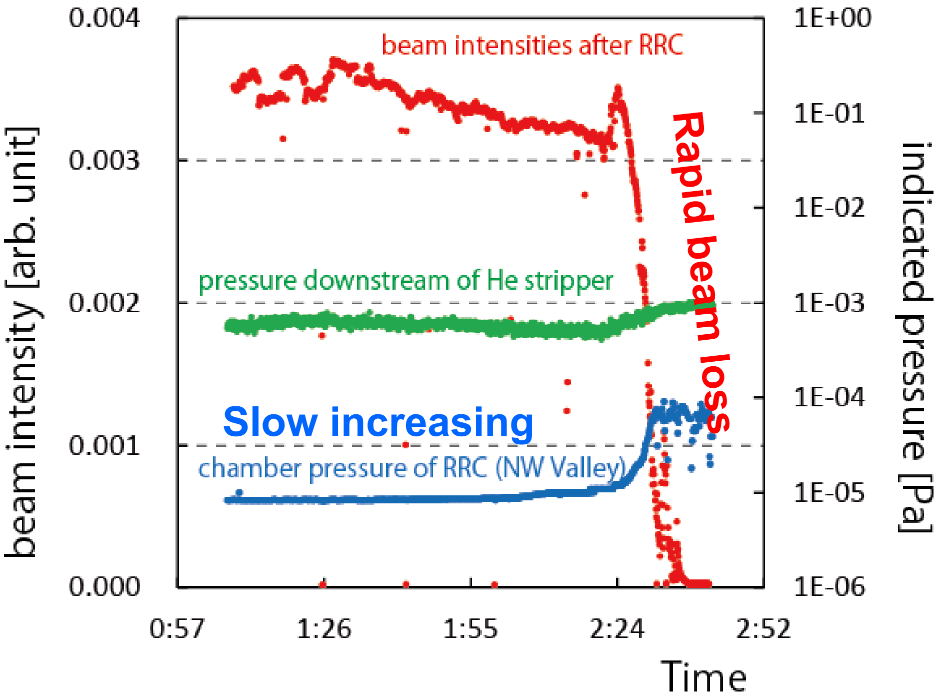
Beam quality becomes worse due to space charge

2. Dynamic vacuum in RRC

RRC have only cryopumps and low pumping power for He

Accumulation of He due to the stripper

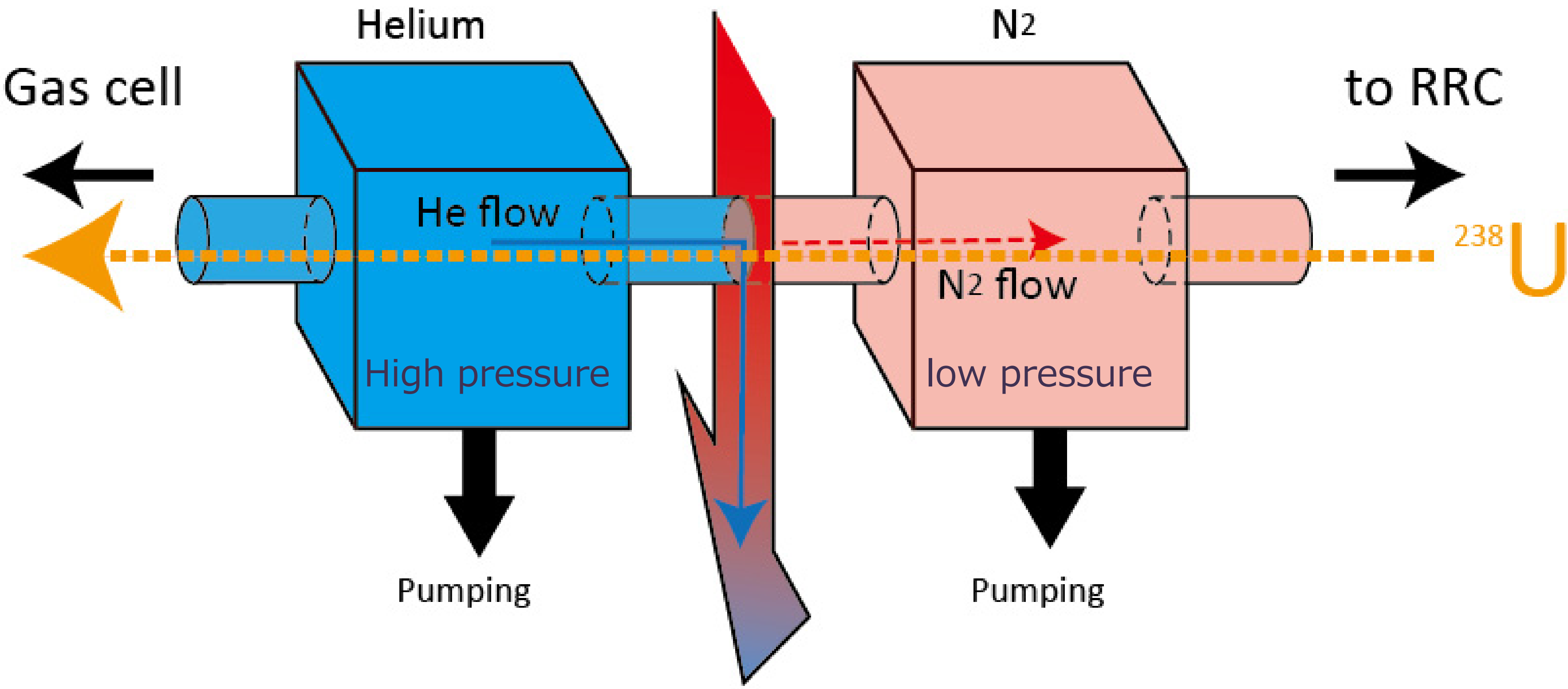




large apertures and high sealing performance for He at the same time

New concept of gas jet curtain

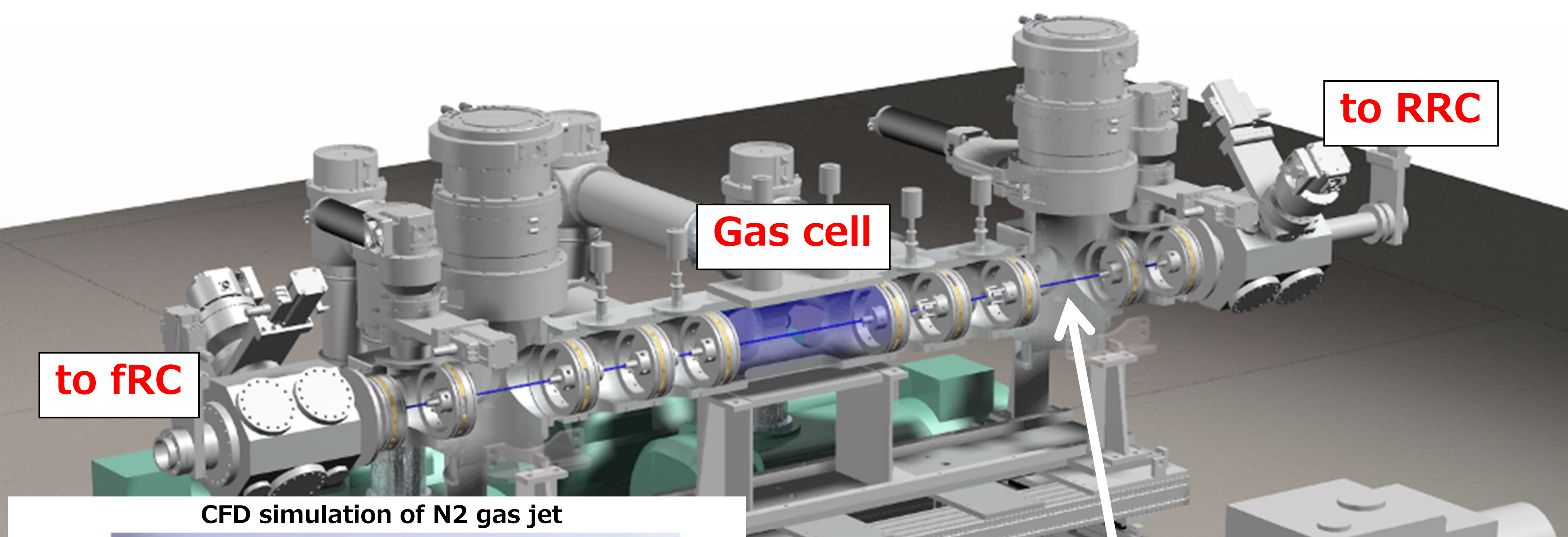
Curtain-like nitrogen-gas jet



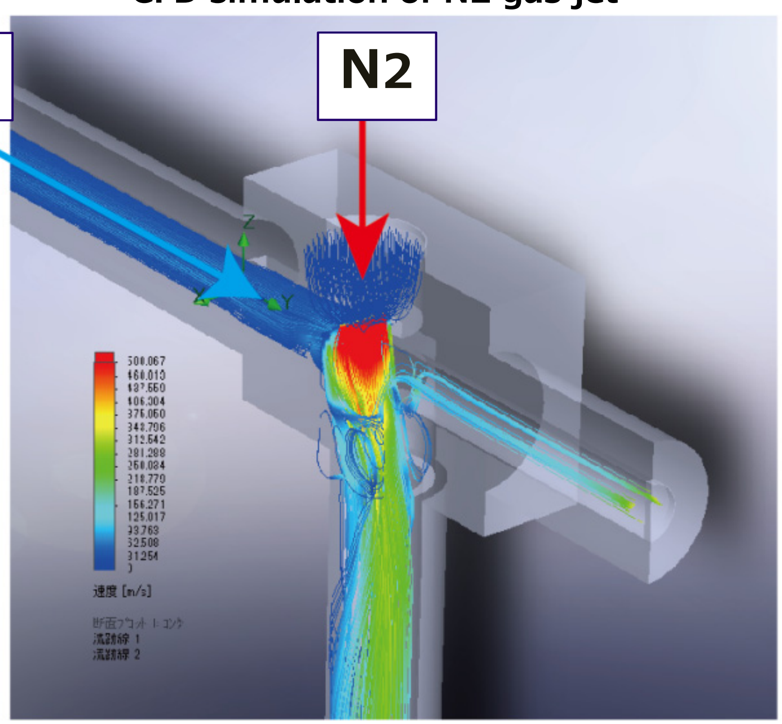
Block He flow and exchange gas species

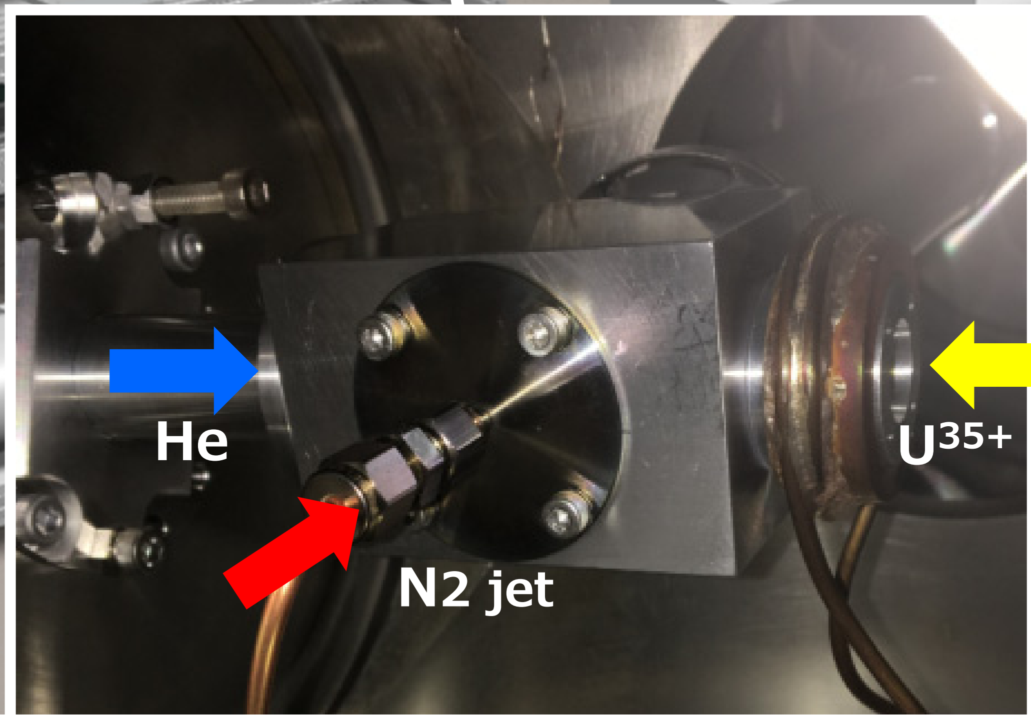
N_2 gas can be evacuated by cryopumps in RRC (120 m^3/s)

Installation of gas-jet curtain



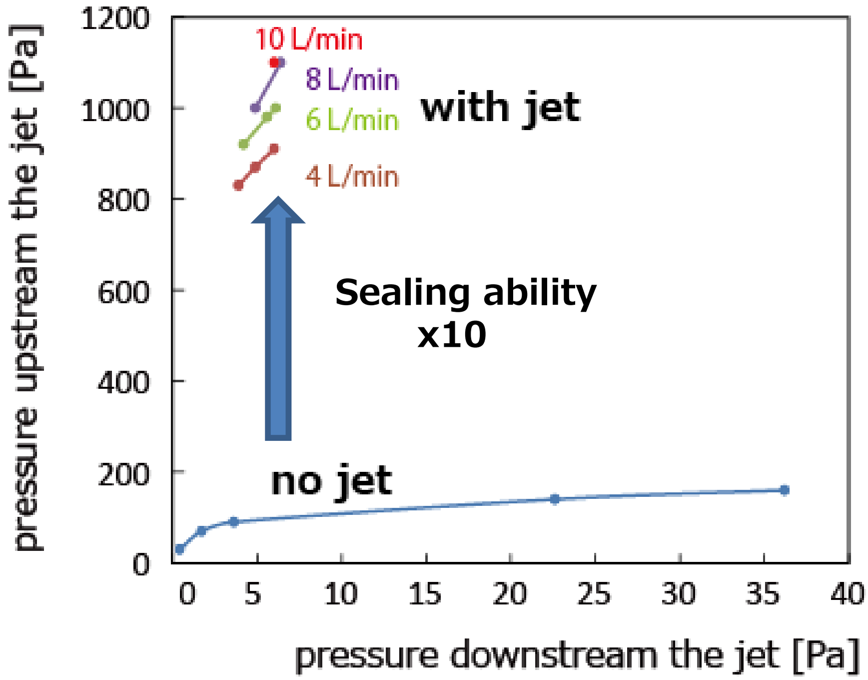
CFD simulation of N2 gas jet

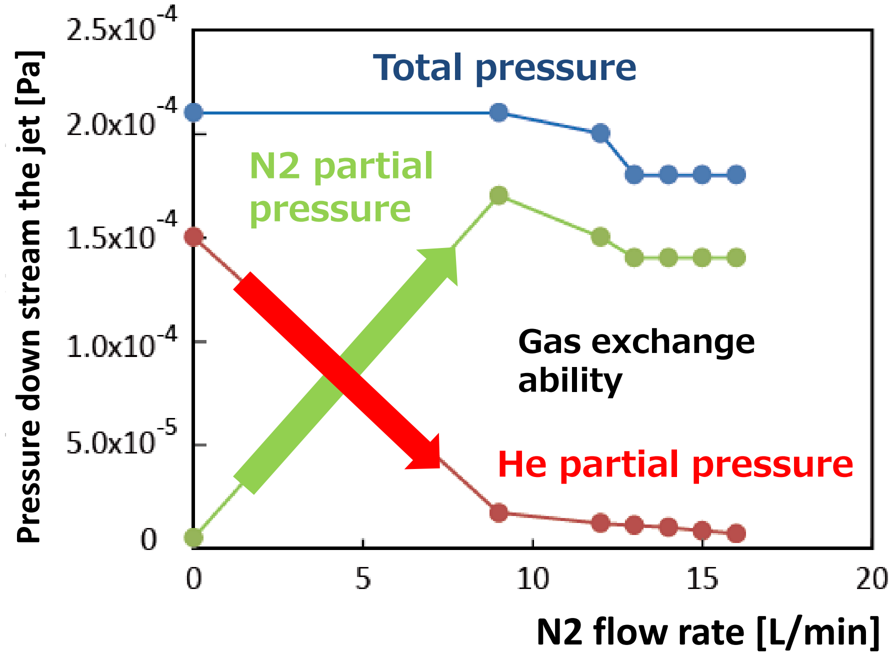




Performance

Performance of N_2 jet curtain excellent ***(patent pending)***

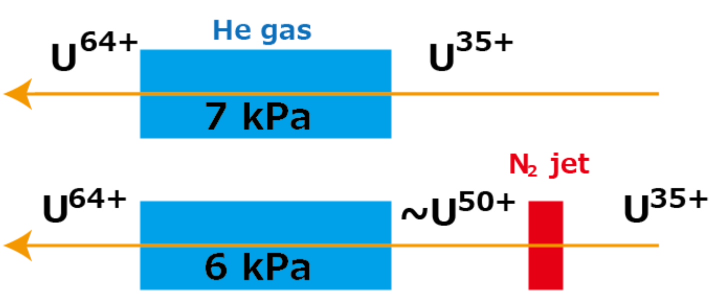




Three favorite effects

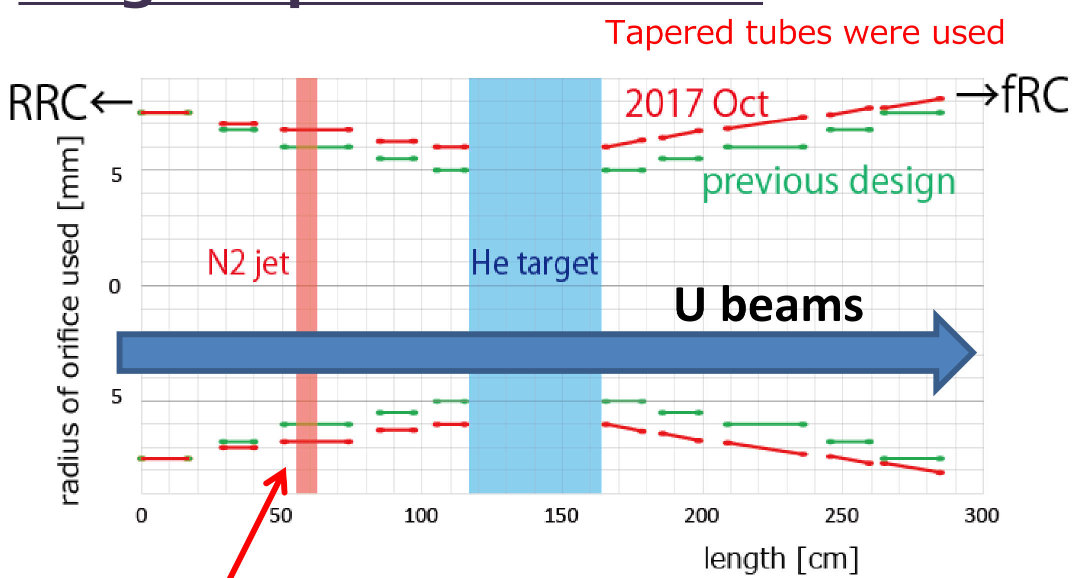
- Sealing ability ➡ **10 times higher**
- Gas exchange to N2 ➡ Cryo-pumps in RRC works well
- N2 pre-stripper ➡ **initial rapid stripping in N2** (30 μg/cm²)

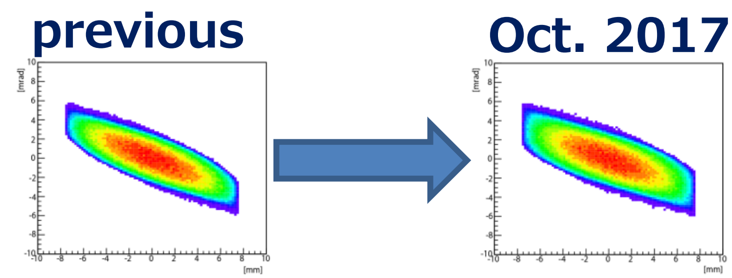
  reduce pressure of He (7kPa ➡ 6kPa)



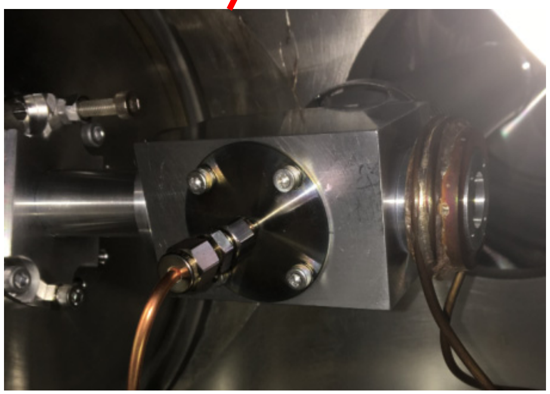
Operation in 2017

Larger-aperture orifices



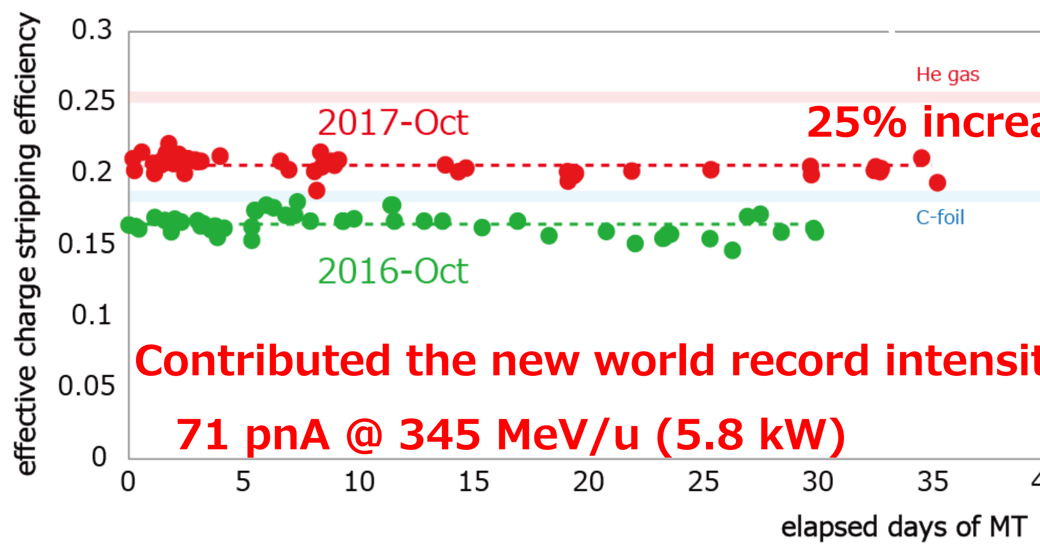


4D acceptance x 1.5



N2 gas jet system actually installed

Improvement of effective stripping efficiency



Contributed the new world record intensity in 2017

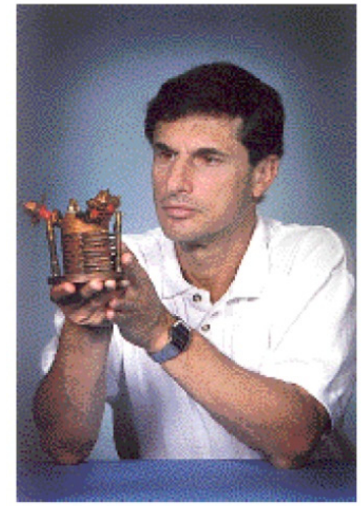
71 pnA @ 345 MeV/u (5.8 kW)

There is no pressure rise in RRC with N_2 gas-jet curtain

Plasma window

- Firstly developed by **Dr. Ady Hershcovitch (BNL)**

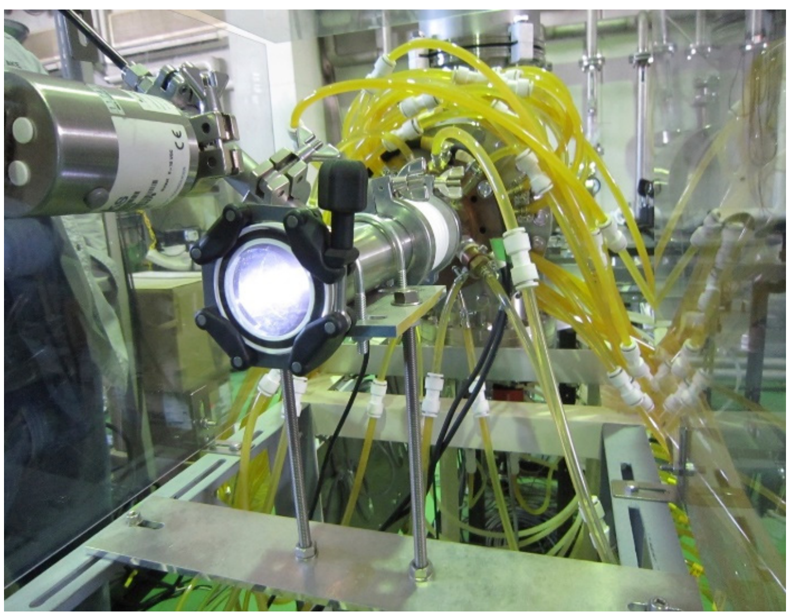
  Journal of Applied Physics, 78(9), 5283-5288 (1995)



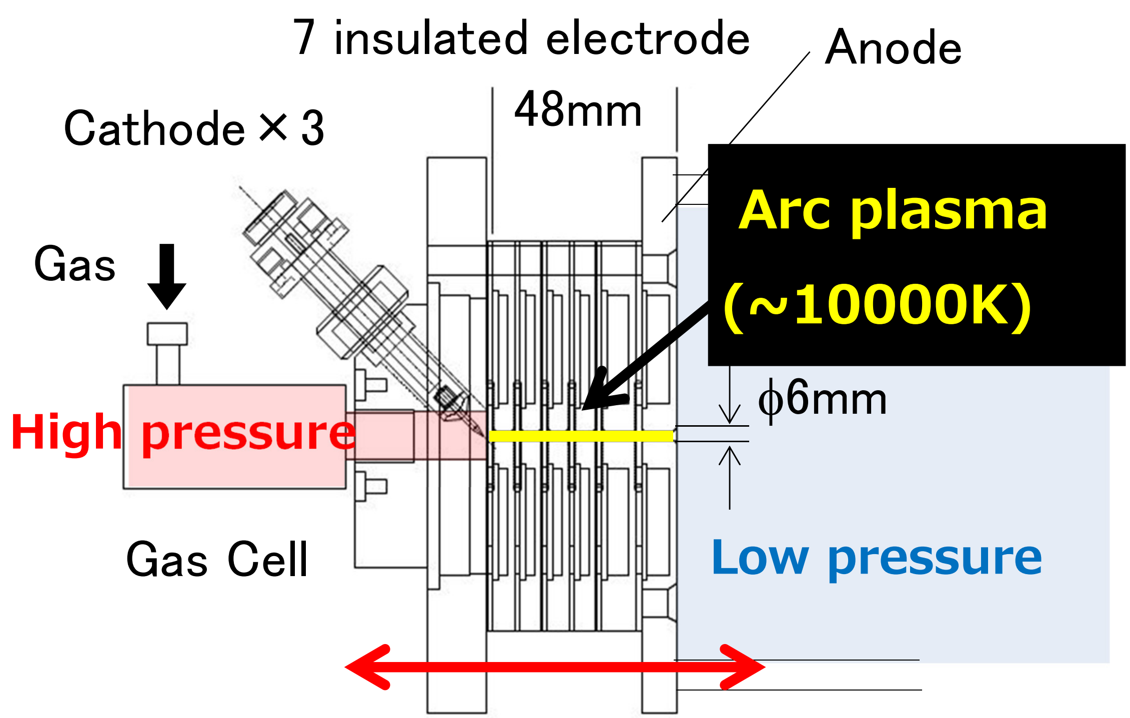
Principle

- **Arc plasma** compensates high density on high pressure side
- **Viscosity** of high-temperature gas in the plasma is increased

PW at RIBF (since 2011)



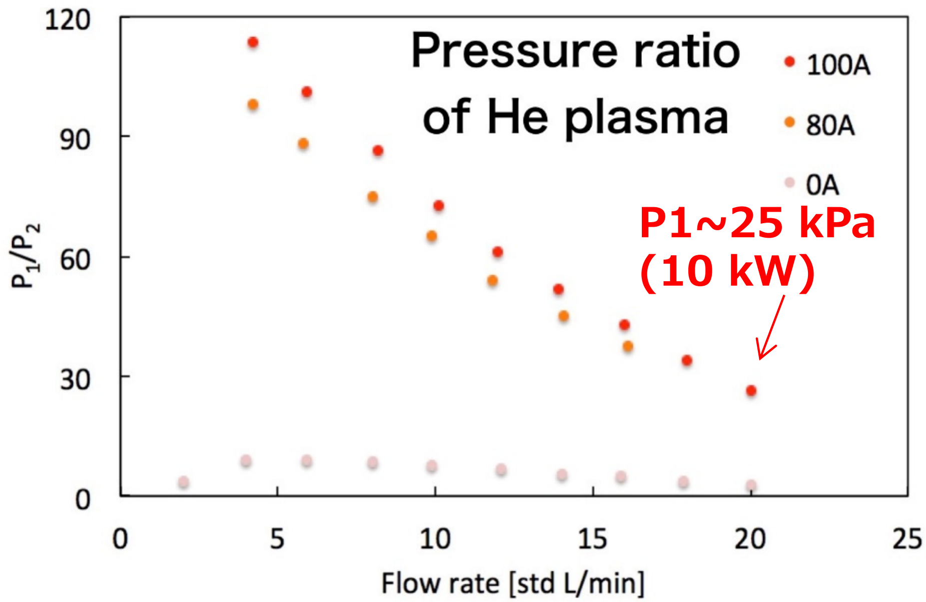
H.Kuboki et al., JRNC, 299, 1029 (2014)

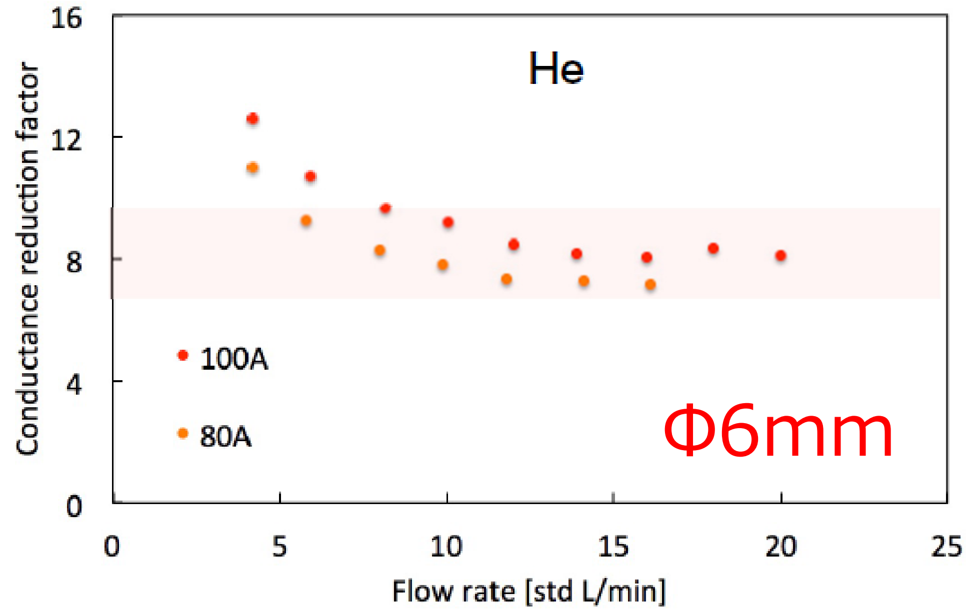


Make pressure difference

Courtesy of N.Ikoma (RIKEN)

Plasma window at RIBF





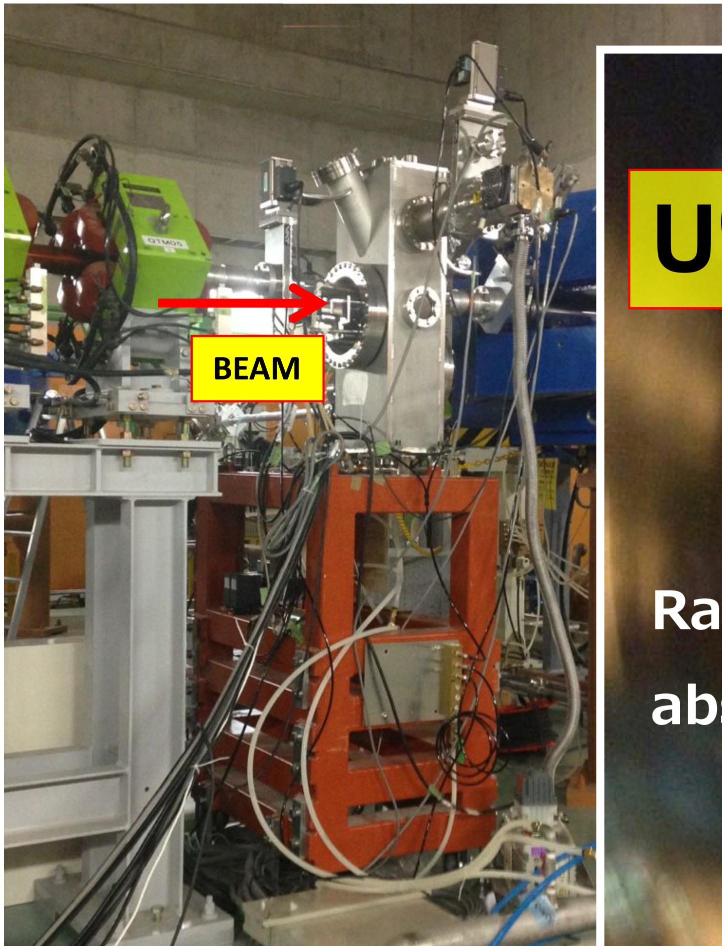
- Diameters of orifice up to Φ6mm are tested so far
- Conductance reduction factor at Φ6mm is around 8

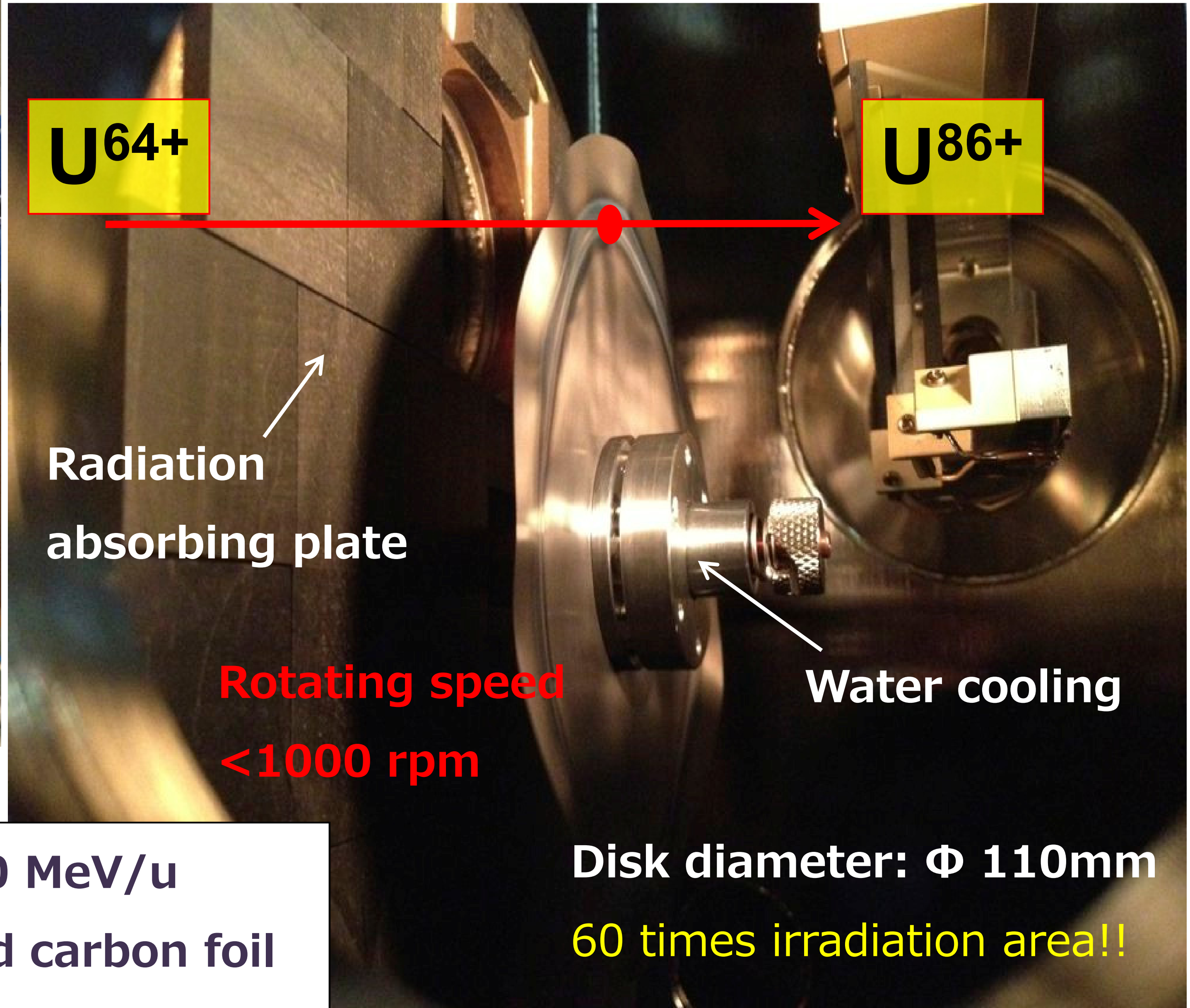
- Trying larger aperture more than 1cm
- Spectroscopy of arc plasma to know the temperature and the density

Courtesy of N.Ikoma (RIKEN)

3. Strippers at RIBF

Rotating disk for the 2nd stripper





2nd stripper at 50 MeV/u

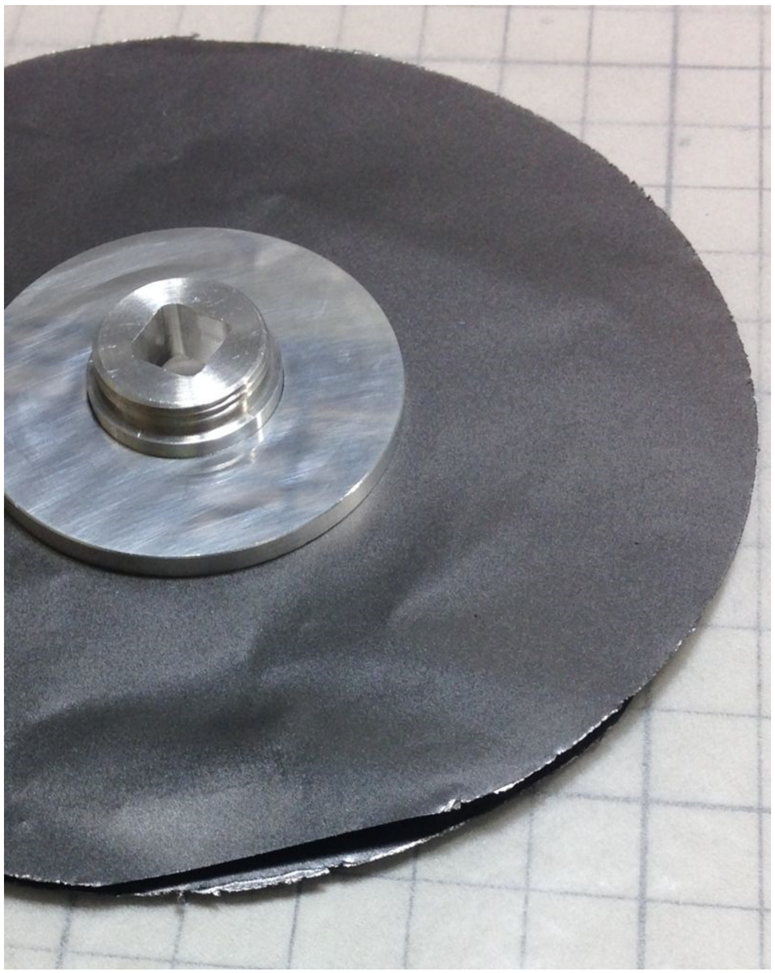
- 2011: fixed carbon foil
- 2012-14: Be disk
- 2015-: KNEKA GC

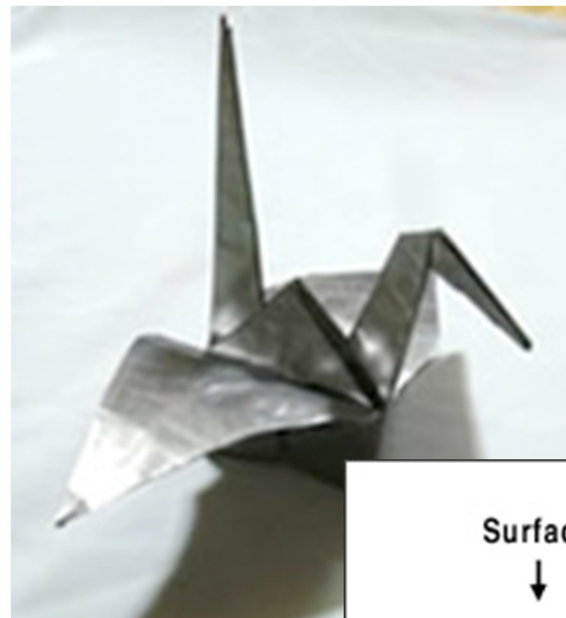
Courtesy of H. Hasebe (RIKEN)

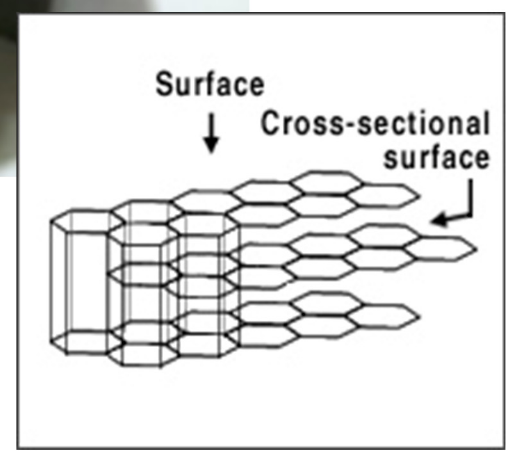
Graphite carbon of KANEKA

High Orientation Graphite Carbon Sheet
(KANEKA CORPORATION)

http://www.elecdiv.kaneka.co.jp/english/graphite/







Structure looks like layed graphene

A.Tatami et al., INTDS2016, O-3

Courtesy of H. Hasebe (RIKEN)

Properties of KANEKA GC

Typical properties

Properties

Silver ~400 W/mK
Beryllium ~200 W/mK

		Units	Test methods	Typical values	
				25μm	40μm
Thickness		μm	Micrometer	25	40
Thermal conductivity	In plane (XY axis)	W/mK	AC calorimeter method	1500	1500
	Thru plane (Z axis)		Laser flash method	5	5
Thermal diffusivity		cm^2/s	AC calorimeter method	9.0	9.0
Density		g/cm^3	Kaneka method	2.0	2.0
Tensile strength		MPa	ASTM-D-882	40	40
Bending		Cycles	JIS-C5016, R=2mm,135°	>10000	>10000
Electrical conductivity		S/cm	JIS K 7194	13000	13000
Heat resistance		°C	TG-DTA	500	500
Water absorption		%	JIS K 7209	<0.1	<0.1

These data are not guaranteed values but the measurement values at our company.

+ thickness uniformity

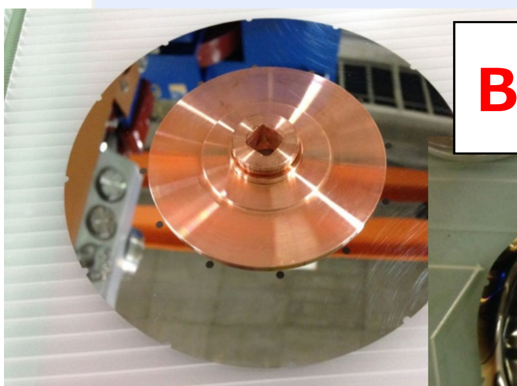
Courtesy of H. Hasebe (RIKEN)

Lifetimes of 2nd strippers at RIBF

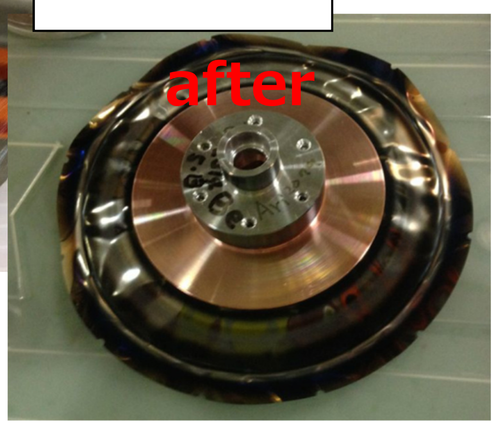
Performance of KANEKA GCS is remarkable!!

	Arizona graphite (fixed)	Be disk (rotation)	KANEKA GCS (rotation)
Period	2007-2011	2012-2014	2015-
Maximum beam intensity	2-3 eμA ~$2x10^{11}$/s 40 W loss	**12 eμA** **~$1x10^{12}$/s** **165 W loss**	**20 eμA** **~$2x10^{12}$/s** **270 W loss**
Lifetime	$7.12×10^{15}$ (71+) 9 hour	**$1×10^{18}$ (64+)** 20 days	**$2×10^{18}$ (64+)** 2×Beam Time **More than 40 days**

Be disk



before



Ductile above 400℃ and brittle below 400℃

H.Hasebe et al., INTDS2016, O-15

KANEKA GCS

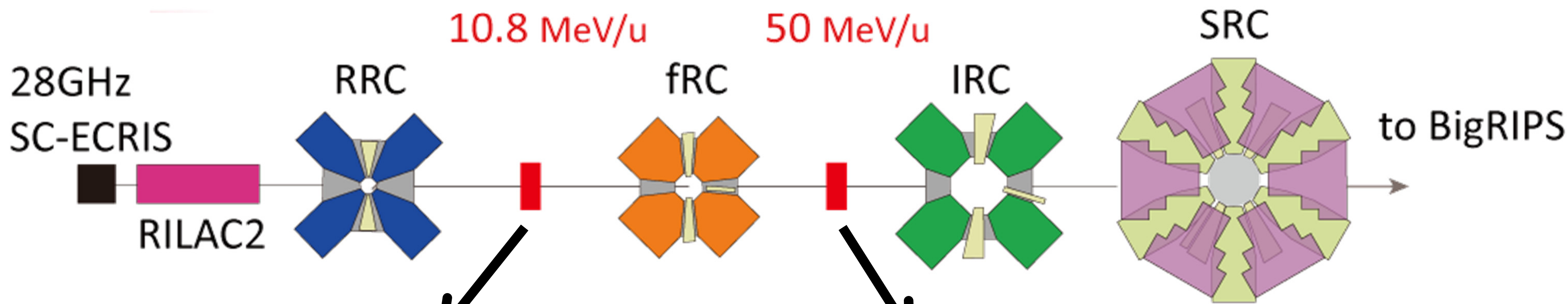
before

after

Courtesy of H. Hasebe (RIKEN)

3. Strippers at RIBF

Charge stripper ring



1． He gas stripper

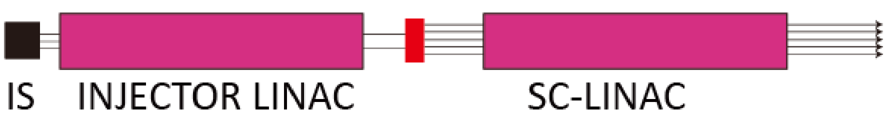
35+⇒64+ (20%)

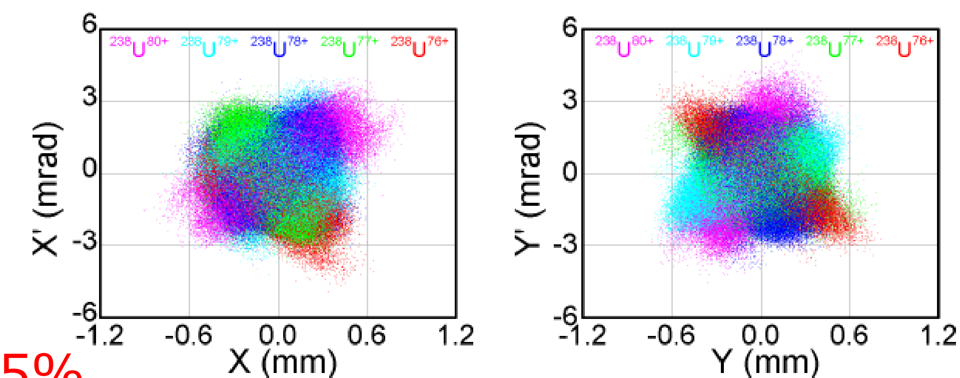
2． Rotating C-disk stripper

64+⇒86+ (30%)

Total charge conversion efficiency < 6%

FRIB uses multi-charge acc.

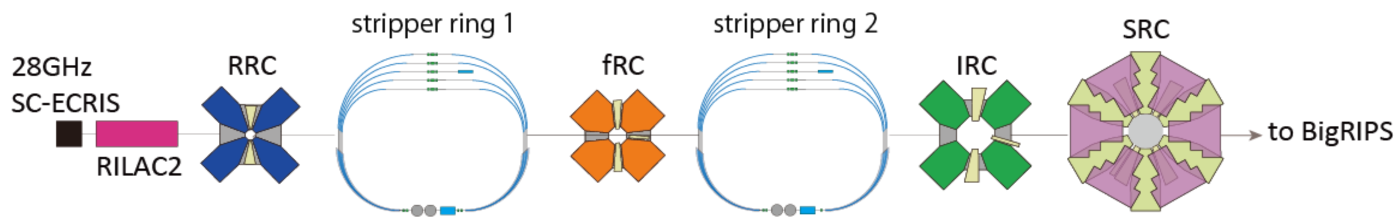




➡ aiming effective efficiency of 85%

Q. Zhao, HB2014

Charge stripper rings

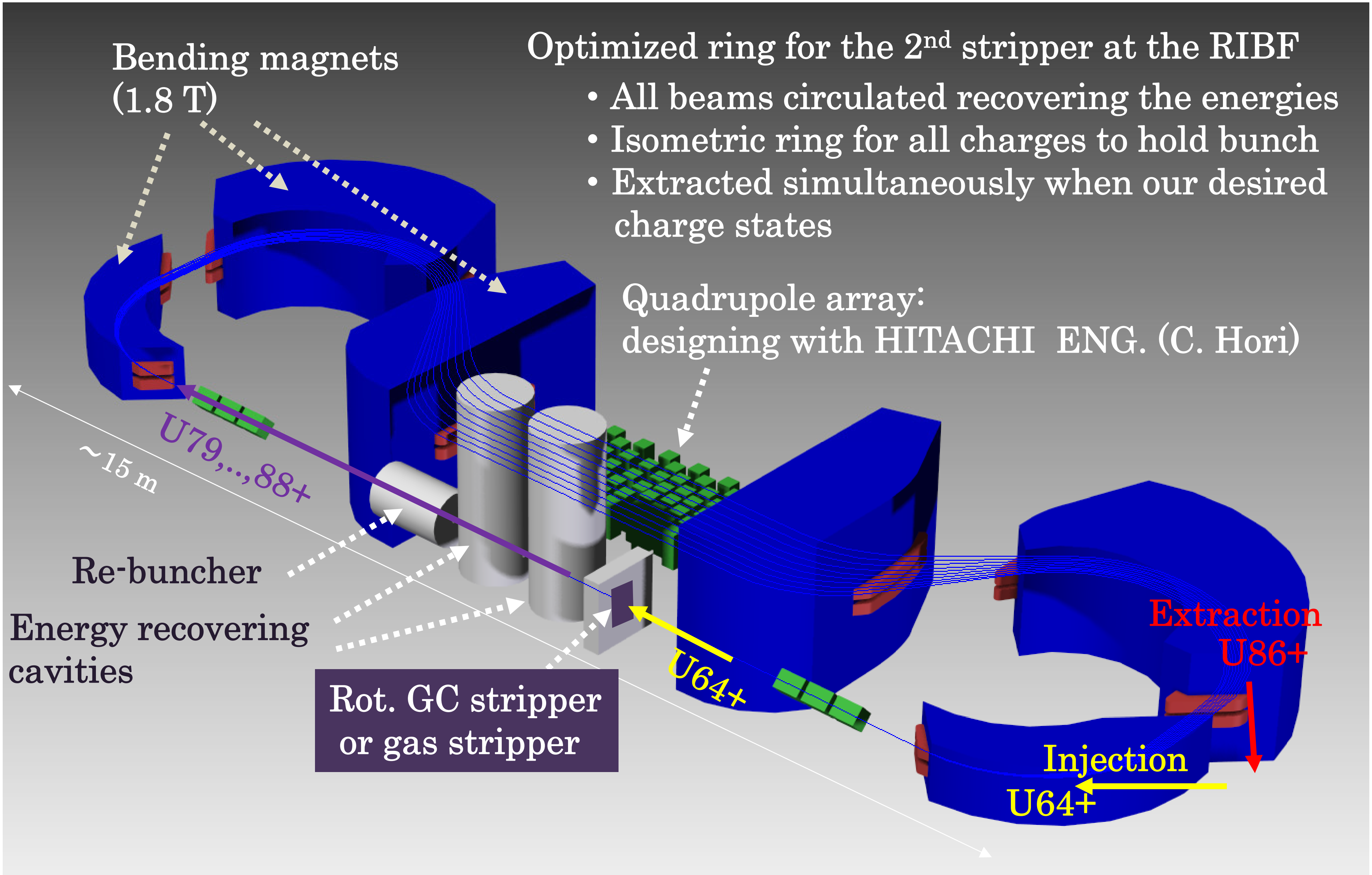


H. Imao et al., Cyclotron2016, TUC02

35+⇒64+ (90%???)

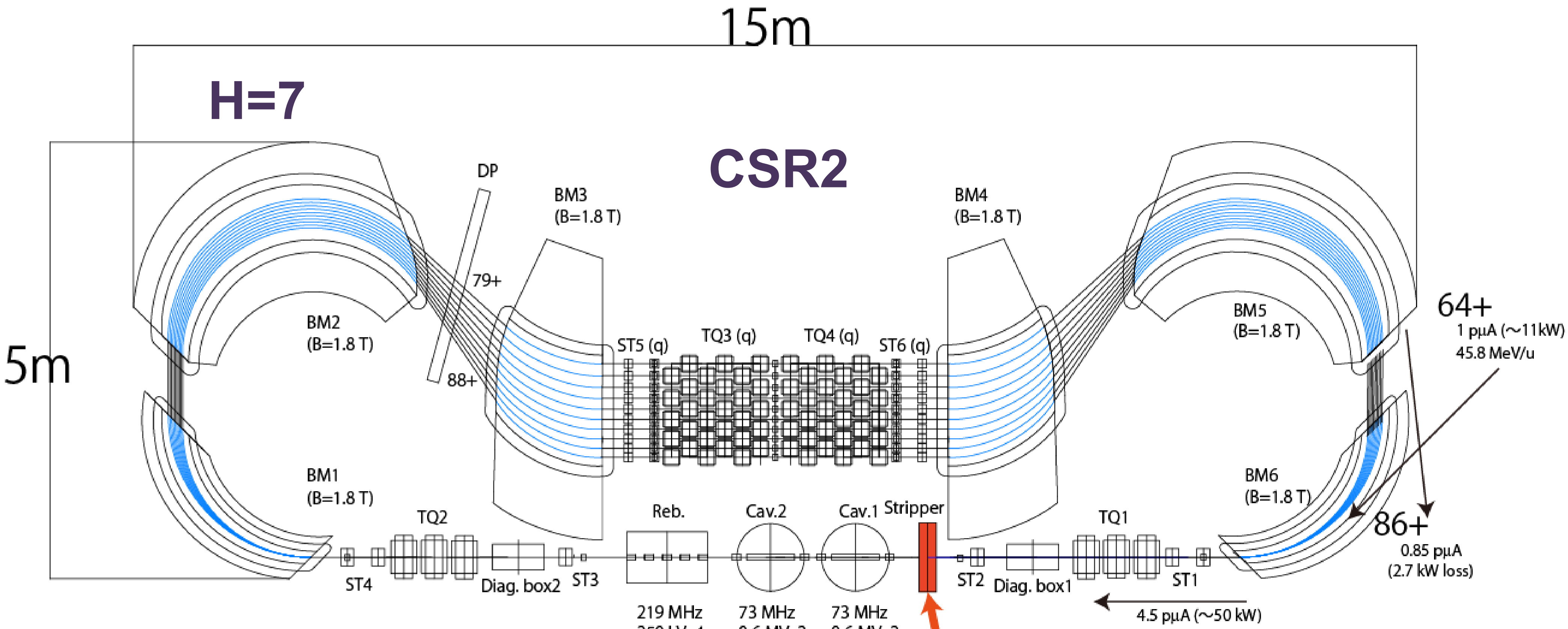
64+⇒86+ (90%???)

Design of stripper ring at 50 MeV/u



3. Strippers at RIBF

Longitudinal and transverse motions

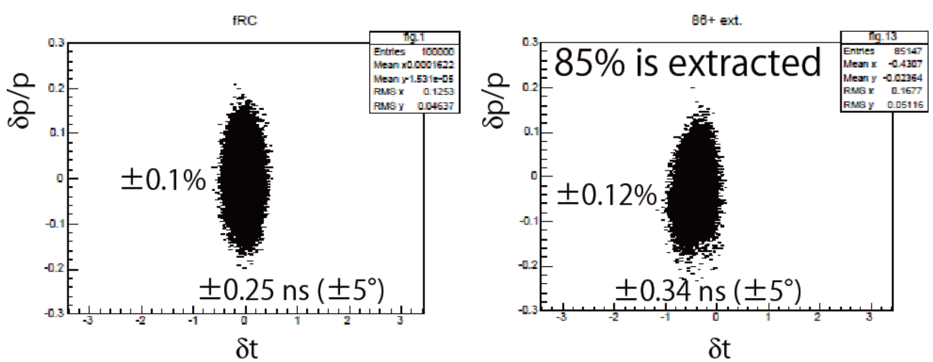


3 mg/cm² (13 μm)
energy loss ~900 W

Planning test experiment in autumn

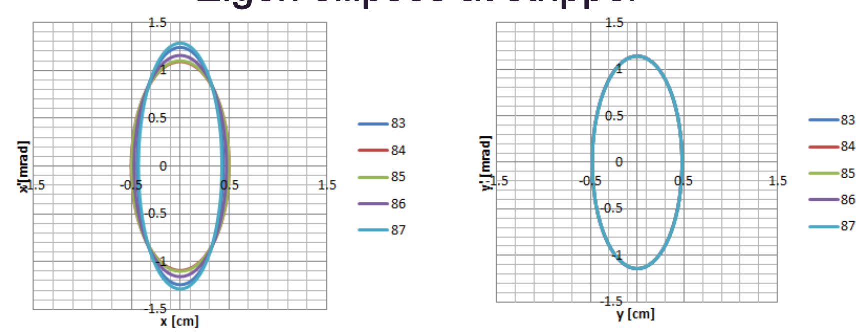
Longitudinal motions

initial beam at fRC — 86+ beams at extraction



Transverse motions

Eigen ellipses at stripper



4. Summary and future prospects

Various non-traditional strippers for world's in-flight RI beam facilities are being developed

- H2 gas-cell stripper at GSI is almost ready for FAIR
- MSU finished principle verification of liq. Li stripper and developing actual machines matching to FRIB operation
- He gas stripper and rot. GC-disk stripper have been developed at RIBF and are working well

- Studies for further advanced strippers and techniques, plasma strippers, gas-jet curtain, plasma windows and stripper rings, are also undergoing and will become strong tools in near future