Review of high power-cyclotrons for heavy-ion beams

September 6, 2010

Cyclotrons 2010, Lanzhou

A. Goto

RIKEN Nishina Center

Outline

1. Introduction

2. Overview of facilities worldwide that operate high-power heavy-ion cyclotrons

3. Some technological issues related to high-power heavy-ion beams

4. Summary

Introduction

- **Cyclotrons producing a wide range of heavy-ion beams were developed in the 1980s.**
- **Heavy ions → large magnetic rigidity**

  ↓

  Two types of cyclotrons: 1) Superconducting AVF cyclotrons

  2) Separated-sector cyclotrons or Ring cyclotrons

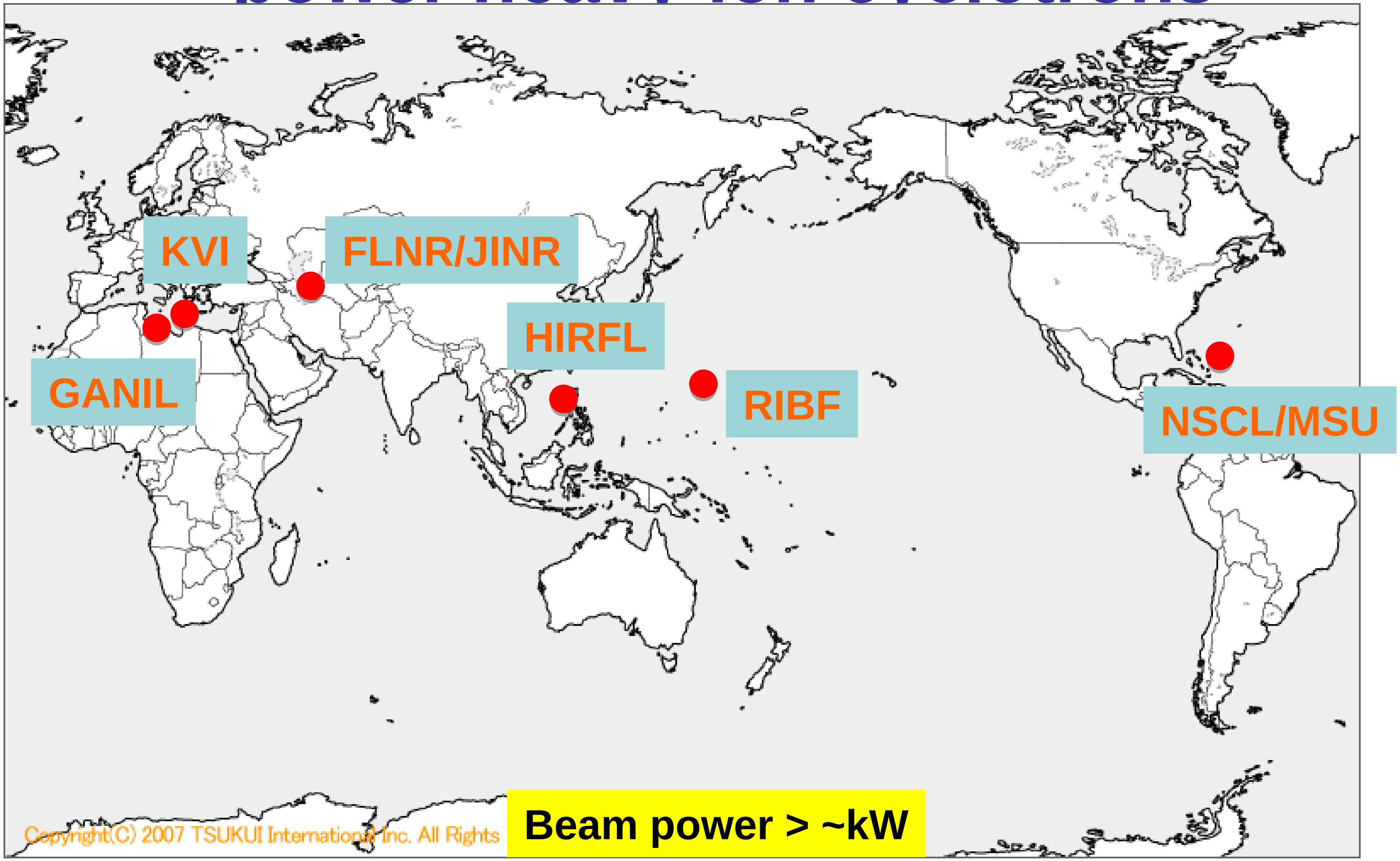
- **Requirements for RI beams**

  → **The intensities as well as energies of heavy-ion cyclotrons have been remarkably increased.**

  ↑ **Development of ECR ion sources that are able to produce highly-charged heavy ions**

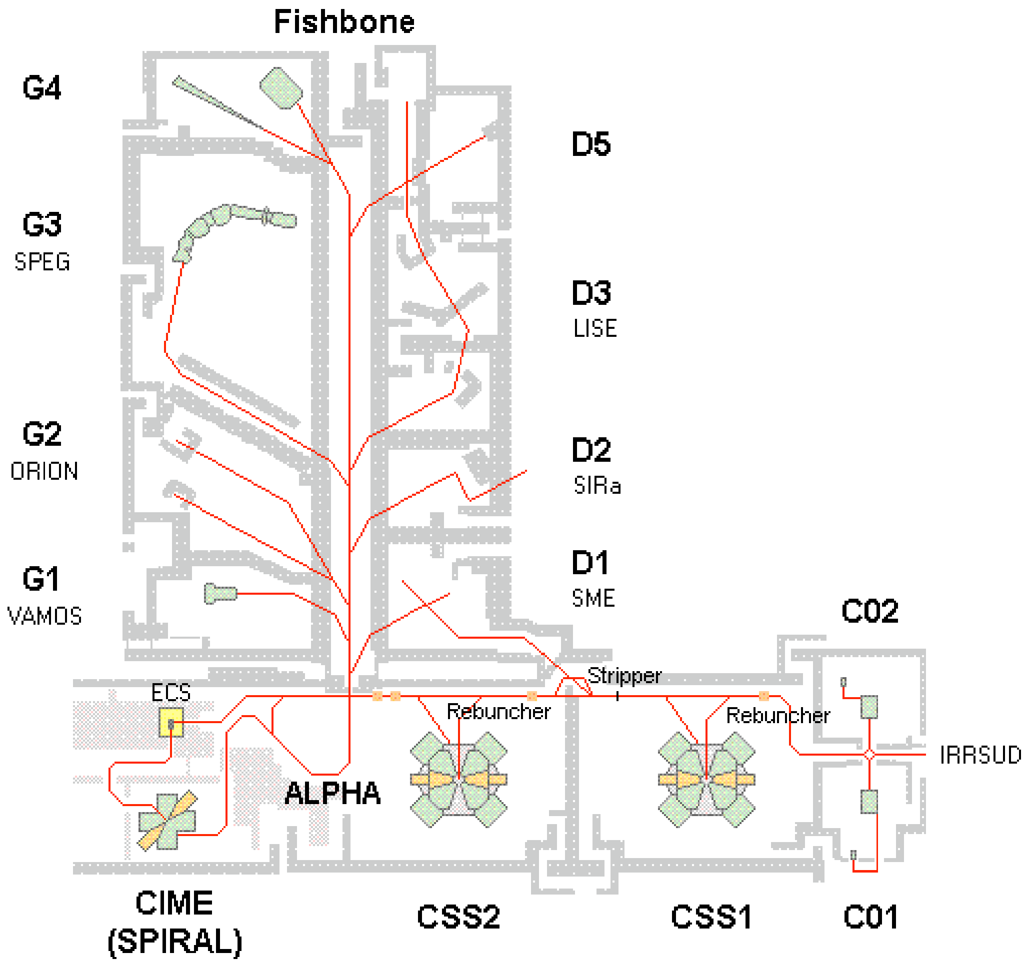
- **Now several high-power heavy-ion cyclotrons worldwide are operational.**

Six facilities that operate high-power heavy-ion cyclotrons



GANIL

(Grand Accelerateur National d'Ion Louds)



1982	First beam from CSS2
Mid-1980	OAE project
1998	First beam from CIME

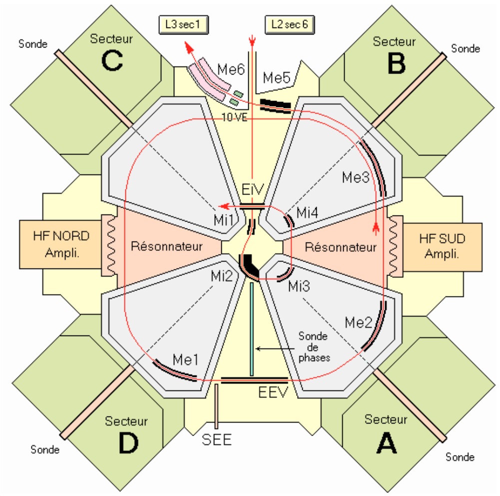
Beam energy

- **CSS1:** 5.5 ~ 13.7 MeV/u
- **CSS2:** 24 ~ 95 MeV/u

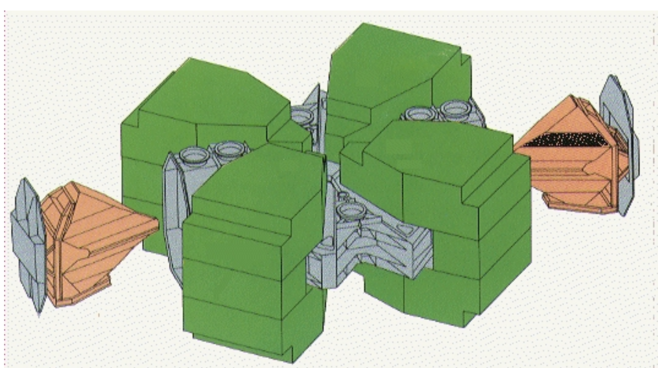
RI beams

- ISOL method
- Projectile fragmentation

GANIL



K-value	**380 MeV**
No. of sectors	**4**
Extraction radius	**3. 0 m**
Max. mag. field	**1.6 T**
No. of resonators	**2**
Magnet weight	**1,700 t**



CSS1 & 2

CSS2 beams

Beams	Energy (MeV/u)	Intensity (pnA)	Power (W)
$^{12}C^{6+}$	95	3,200	3,600
$^{13}C^{6+}$	75	3,000	2,900
$^{14}N^{7+}$	95	2,140	3,400
$^{16}O^{8+}$	95	2,000	3,000
$^{18}O^{8+}$	75	290	400
$^{20}Ne^{10+}$	95	1,570	2,400
$^{22}Ne^{10+}$	80	1,500	2,600
$^{24}Mg^{12+}$	95	1,670	3,800
$^{36}S^{16+}$	78	690	1,900
$^{36}Ar^{18+}$	95	1,330	4,600
$^{48}Ca^{19+}$	60	240	700
$^{58}Ni^{56+}$	75	150	700
$^{76}Ge^{30+}$	61	120	500
$^{78}Kr^{34+}$	70	210	1,200
$^{124}Xe^{44+}$	50	50	300

NSCL/MSU

(National Superconducting Cyclotrons Laboratory)

1982 First beam from K500

1988 First beam from K1200

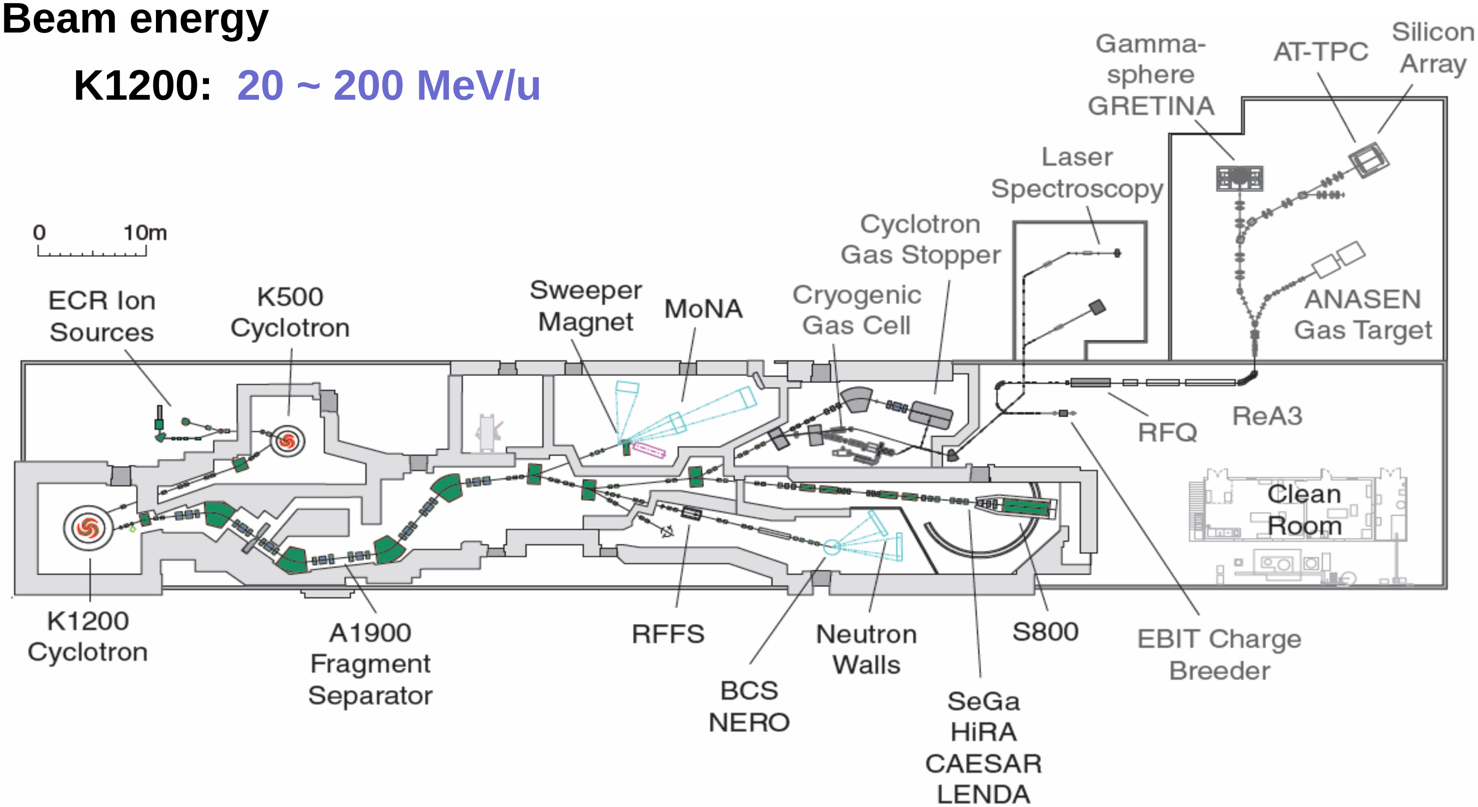
2000 First beam from the coupled cyclotrons

RI beams

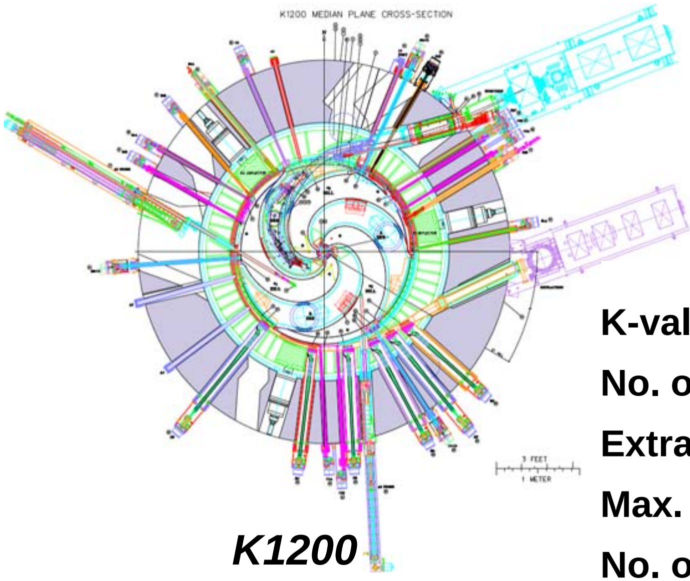
Projectile fragmentation

Beam energy

K1200: 20 ~ 200 MeV/u



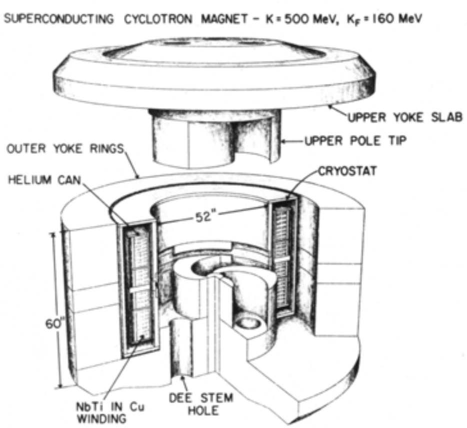
NSCL



K1200

K-value	**1,200 MeV**
No. of sectors	**3**
Extraction radius	**1. 01 m**
Max. mag. field	**6.1 T**
No. of resonators	**3**
Magnet weight	**260 t**

Supercnducting



K500

K1200 beams

Beams	Energy (MeV/u)	Intensity (pnA)	Power (W)
^{16}O	150	500	1,200
^{18}O	120	500	1,080
^{22}Ne	150	220	730
^{24}Mg	170	200	820
^{36}Ar	150	150	810
^{40}Ar	140	200	1,120
^{40}Ca	140	70	390
^{48}Ca	140	140	940
^{58}Ni	160	40	370
^{76}Ge	130	50	490
^{78}Kr	150	100	1,170
^{112}Sn	120	10	120
^{124}Xe	140	25	430
^{208}Pb	85	4	70
^{238}U	80	0.3	6

FLNR/JINR

(Flerov Laboratory of Nuclear Reactions)

1978 First beam from U400

1991 First beam from U400M

2002~ DRIBs project

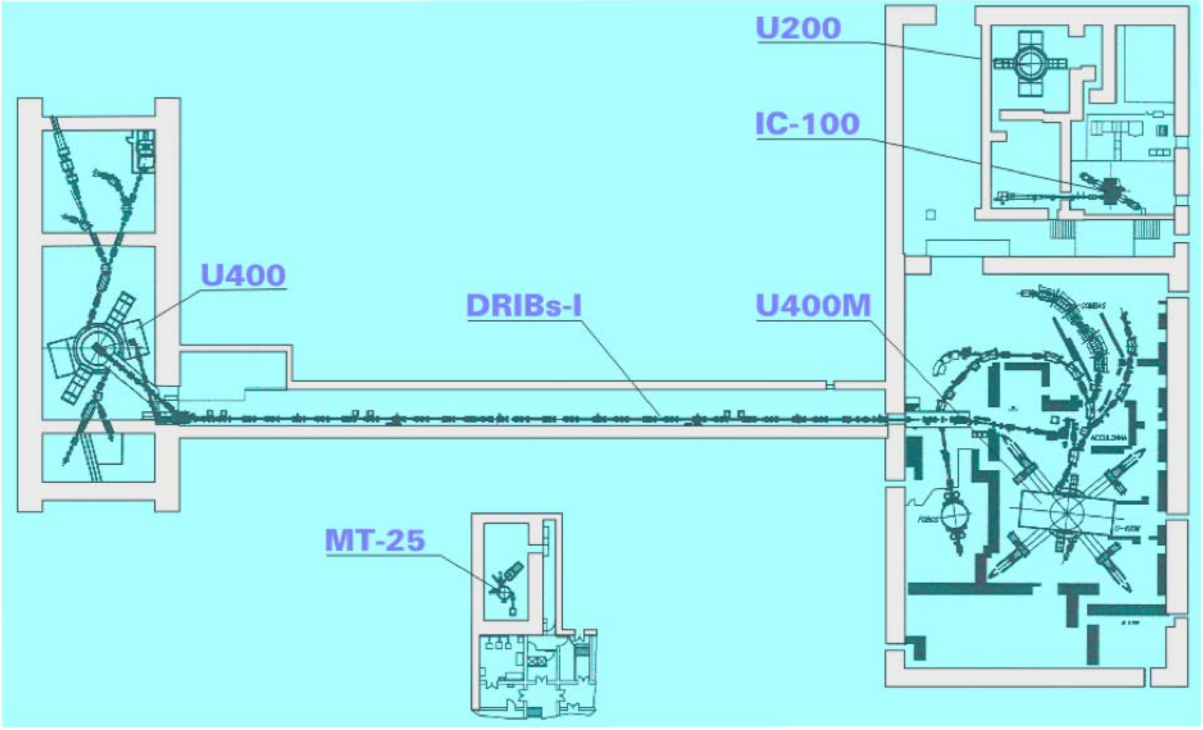
Beam energy

U400: 3 ~ 20 MeV/u

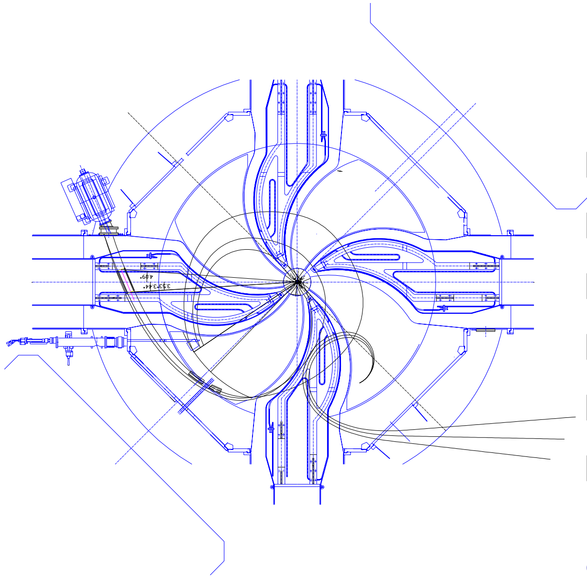
U400M: 30 ~ 50 MeV/u

RI beams

ISOL method



FLNR/JINR

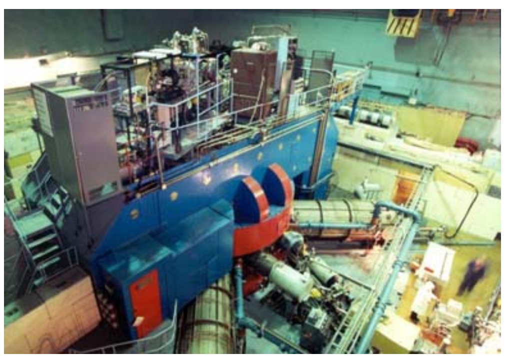


K-value	550 MeV
No. of sectors	4
Extraction radius	1.6 m
Max. mag. field	2.6 T
No. of resonators	4
Magnet weight	2,300 t

Stripping extraction

U400 beams

Beams	Energy (MeV/u)	Intensity (pnA)	Power (W)
$^{16}O^{2+}$	7.9	5,000	630
$^{18}O^{3+}$	15.8	4,400	1,250
$^{40}Ar^{4+}$	5.1	1,700	350
$^{48}Ca^{5+}$	5.3	1,200	310
$^{48}Ca^{9+}$	17.7	1,000	850
$^{50}Ti^{5+}$	5.1	400	100
$^{58}Fe^{6+}$	5.4	700	220
$^{84}Kr^{8+}$	4.4	300	110
$^{136}Xe^{14+}$	6.9	80	80



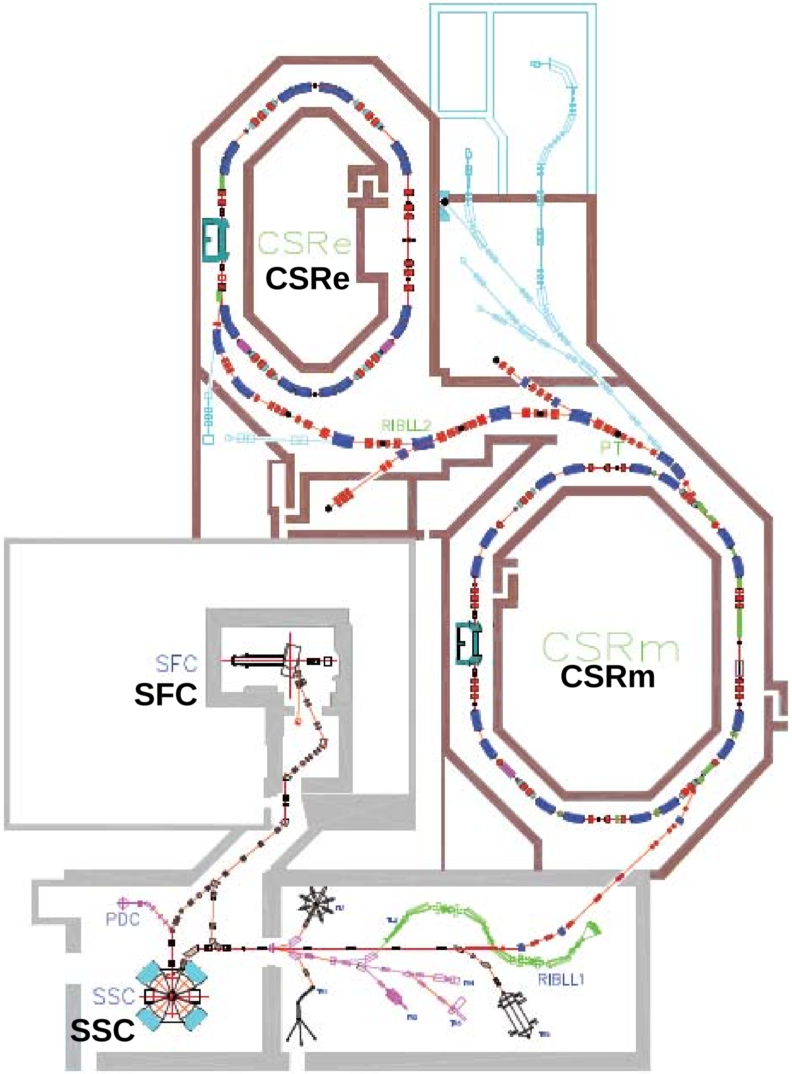
U400M

About 66 % of the total operation is used for the acceleration of ^{48}Ca ions to synthesize new super-heavy elements.

Upgrade project of the U400 is underway: to increase the beam intensity up to 2.5 ~ 3 pμA and to increase the energy variation for ^{48}Ca, ^{50}Ti, etc.

HIRFL

(Heavy Ion Research Facility in Lanzhou)



1988	First beam from SSC
Early-2000	Refurbishment of SFC & upgrade of SSC
2007	First beam from CSRm

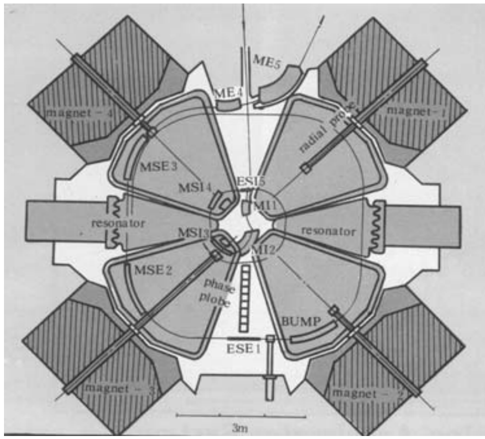
Beam energy

- **SFC:** < 10 MeV/u
- **SSC:** < 100 MeV/u
- **CSRm:** 1,100 MeV/u for C ions
  520 MeV/u for U^{72+} ions

RI beams

- In-flight fission of U ions
- Projectile fragmentation

HIRFL



K-value	450 MeV
No. of sectors	4
Extraction radius	3.21 m
Max. mag. field	1.6 T
No. of resonators	2
Magnet weight	2,000 t

SSC

SFC beams

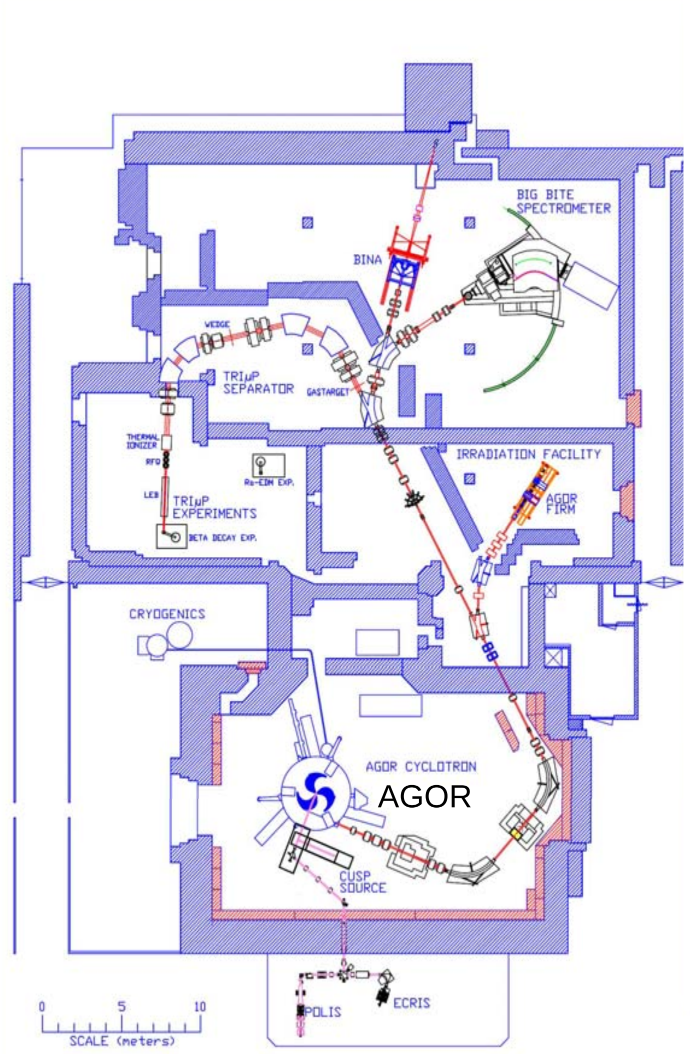
Beams	Energy (MeV/u)	Intensity (pnA)	Power (W)
$^{12}C^{4+}$	7.0	3,750	320
$^{16}O^{6+}$	8.0	3,000	260
$^{20}Ne^{7+}$	7.2	1,710	250
$^{26}Mg^{8+}$	6.5	250	43
$^{40}Ar^{8+}$	2.4	1,880	180
$^{78}Kr^{19+}$	4.0	470	150
$^{129}Xe^{27+}$	3.0	260	100
$^{238}U^{26+}$	0.8	13	2.5

SSC beams

Beams	Energy (MeV/u)	Intensity (pnA)	Power (W)
$^{12}C^{6+}$	100	50	60
$^{22}Ne^{10+}$	70	50	77
$^{36}Ar^{8+}$	7.2	440	350
$^{58}Ni^{22+}$	6.5	9	26
$^{129}Xe^{27+}$	2.4	28	70
$^{209}Bi^{31+}$	5.8	10	20

KVI

(Kernfysisch Versneller Instituut)



1996 First beam from AGOR

Beam energy

AGOR: 35 ~ 90 MeV/u for Q/A=0.5

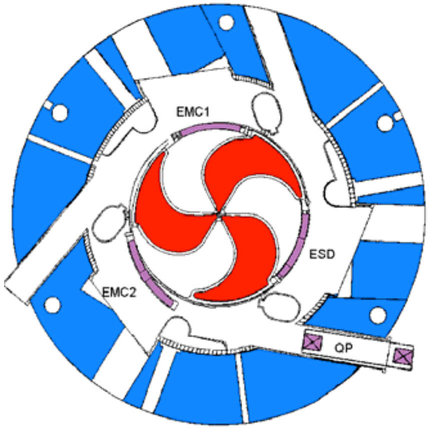
10 ~ 30 MeV/u for Q/A=0.25

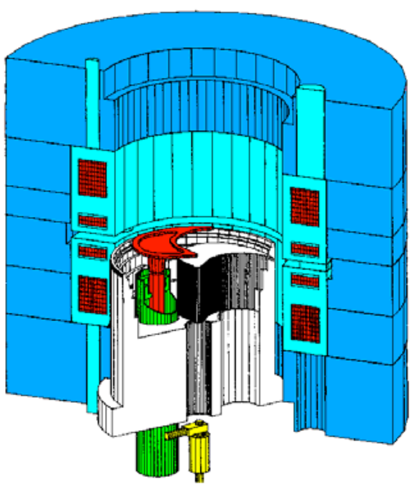
6 MeV/u for Q/A=0.1

RI beams

Inverse kinematics method

KVI





AGOR

K-value	600 MeV
No. of sectors	3
Extraction radius	0.89 m
Max. mag. field	5.1 T
No. of resonators	3
Magnet weight	390 t

Superconducting

AGOR beams

Beams	Energy (MeV/u)	Intensity (pnA)	Power (W)
$^{11}B^{3+}$	19	160	30
$^{12}C^{4+}$	23	1,000	280
$^{19}F^{4+}$	11	330	70
$^{20}Ne^{6+}$	23	2,200	1,000
$^{36}Ar^{10+}$	30	500	540
$^{40}Ca^{14+}$	45	160	290
$^{82}Kr^{19+}$	25	160	330
$^{208}Pb^{27+}$	9.2	40	80

Upgrade project of the AGOR *is underway:* to increase the beam intensity in order to obtain a beam power of ~1 kW for all beams up to Pb.

RIBF

(RI Beam Factory, RIKEN Nishina Center)

1986 First beam from RRC

Mid-1990 Upgrade of the pre-injector of RILAC

2006 First beam from SRC

RI beams

In-flight fission of U ions

Projectile fragmentation

Beam energy

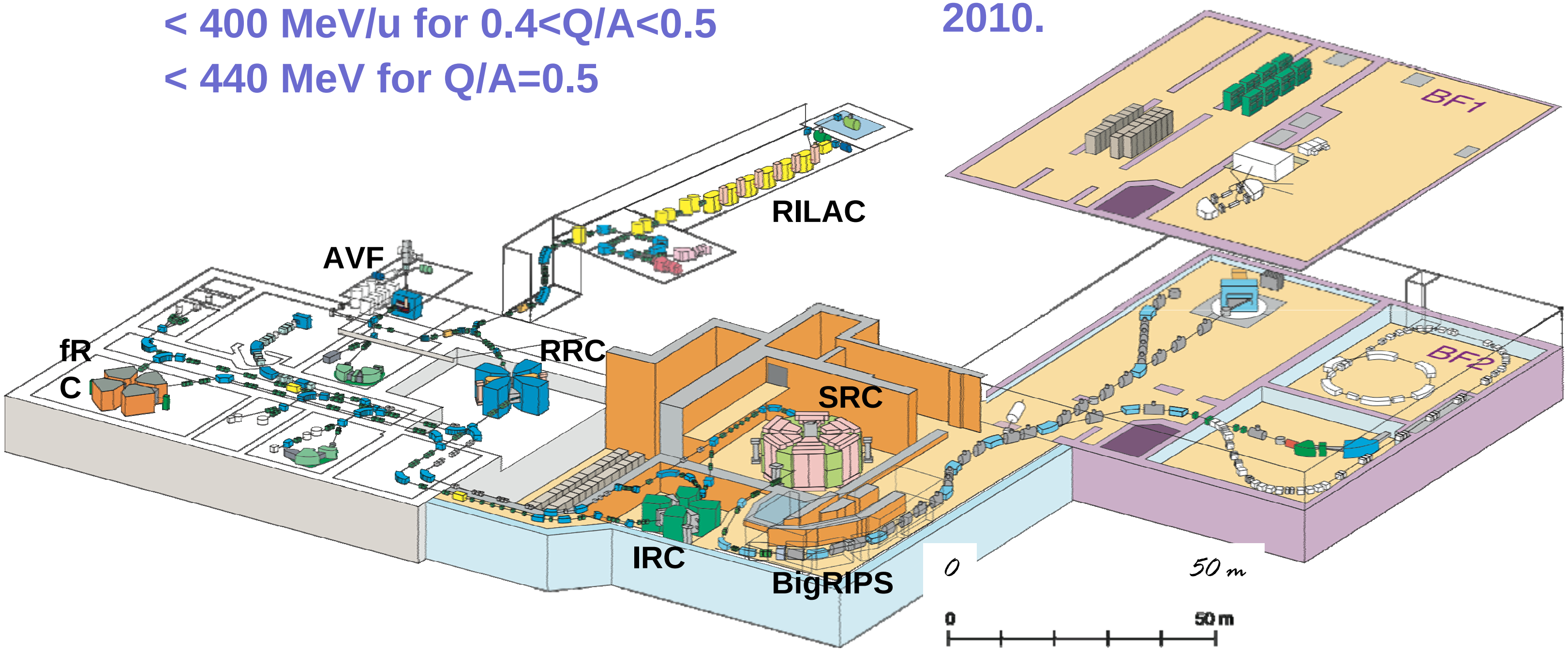
RRC: 7 ~ 135 MeV/u for heavy ions

SRC: 345 MeV/u for all heavy ions

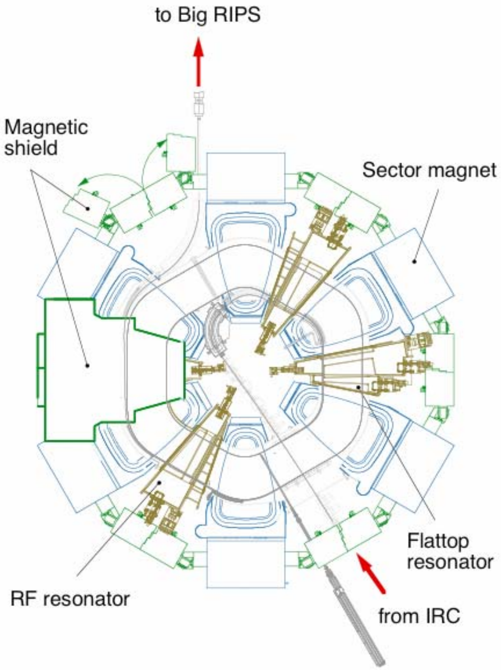
< 400 MeV/u for 0.4<Q/A<0.5

< 440 MeV for Q/A=0.5

New injector linac, RILAC2, will be ready for commissioning by the end of 2010.



RIBF



K-value	2,600 MeV
No. of sectors	6
Extraction radius	5.36 m
Max. mag. field	3.8 T
No. of resonators	4
Magnet weight	8,100 t

Superconducting

SRC

Goal: 1pμA for 345 MeV/u ^{238}U ions

(80 kW)

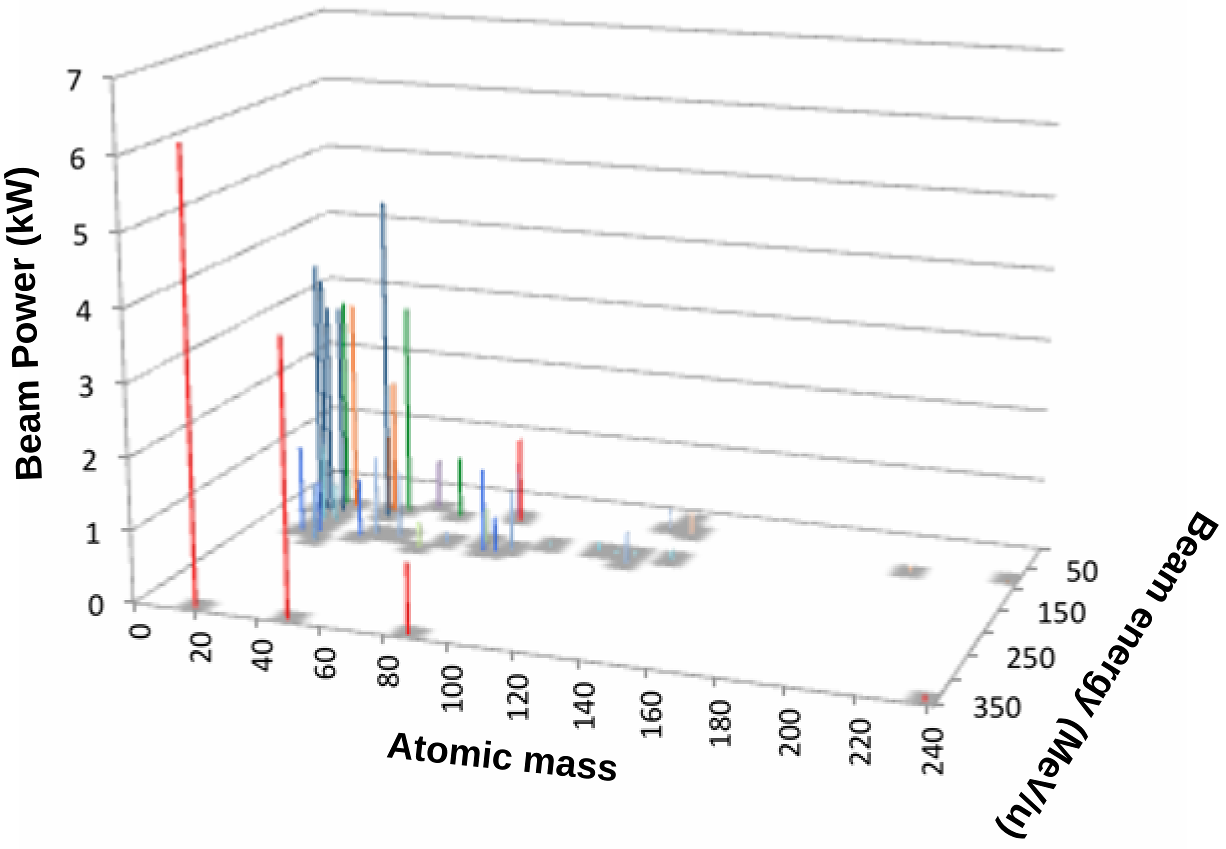
RRC beams

Beams	Energy (MeV/u)	Intensity (pnA)	Power (W)
$^{12}C^{6+}$	135	770	1,250
$^{14}N^{7+}$	135	710	1,340
$^{18}O^{8+}$	100	590	1,060
$^{22}Ne^{10+}$	110	360	870
$^{36}Ar^{17+}$	115	80	330
$^{40}Ar^{15+}$	63	800	2,020
$^{48}Ca^{17+}$	63	140	420
$^{56}Fe^{247+}$	90	8	40
$^{86}Kr^{30+}$	63	80	430
$^{136}Xe^{20+}$	11	15	22

SRC beams

Beams	Energy (MeV/u)	Intensity (pnA)	Power (W)
$^{18}O^{8+}$	345	1,000	6,210
$^{48}Ca^{20+}$	345	230	3,810
$^{86}Kr^{34+}$	345	33	980
$^{238}U^{86+}$	345	0.8	66

Statistics for the beam power of heavy-ion beams obtained from high-power cyclotrons so far



Some technological issues related to high-power heavy-ion beams

- **ECR ion sources**
- **LEBT**
- **Extraction**
- **Charge strippers**
- **Beam diagnostics/safety system/stability**
- **Availability**
- **Space charge effect**

ECR ion sources

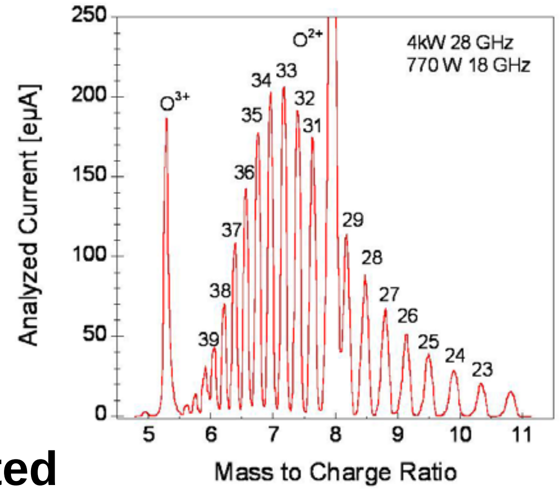
- **At RIBF**

  Goal: 1 pμA 345 MeV/u uranium beam

  → > 500 eμA U^{35+} from the ion source is required.

- **VENUS and SECRAL of 3rd generation ECR ion sources have achieved good performance.**

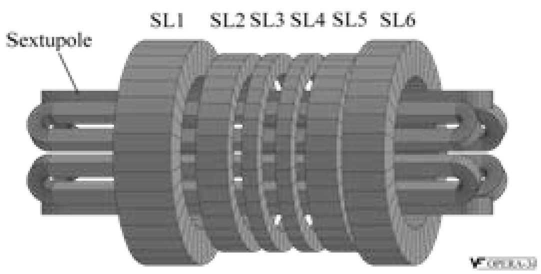
  Ex.: 180 eμA U^{35+} from VENUS



- **RIKEN 28 GHz SC-ECRIS has been newly constructed and expected to produce such 500 eμA U^{35+} ions.**

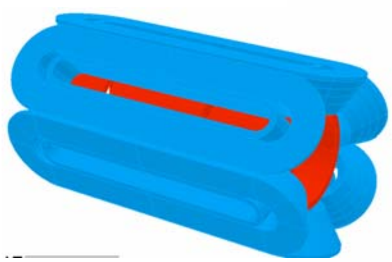
  - Large ECR-zone size

  - Gentle field gradient



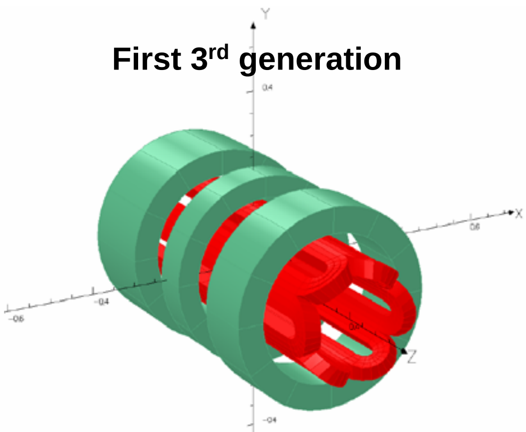
RIKEN SC-ECRIS

Solenoid coils set inside sextupole coils



SECRAL

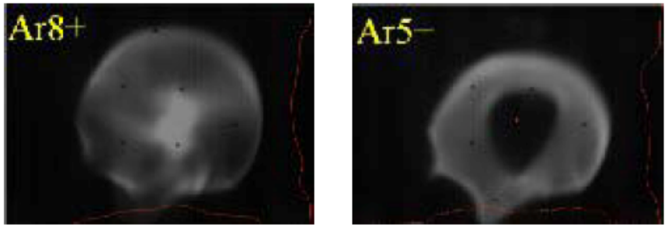
First 3rd generation



VENUS

LEBT

- To control the quality of beams in the LEBT is very important to obtain good net transmission efficiency.



- At NSCL
  - Study has been carried out intensively using BaF$_2$-coated viewing plates and an Allison-type emittance scanner.

    To deal with hollow beams

    → A solenoid lens was replaced with an electrostatic lens.
  - The net beam transmission efficiency was improved by 400 % from 2003 to 2006.

	~2003 SOURCE OUT → K1200 OUT	~2006 SOURCE OUT → K1200 OUT	GAIN
^{40}Ar	2280 → 58	1920 → 222	4.5
^{48}Ca	1275 → 32	1400 → 160	4.6
^{76}Ge	690 → 17	725 → 63	3.5
^{78}Kr	2640 → 22	2760 → 79	3.4

[*J. Stetson et al, Cyclotrons 2007 (2007) 340*]

- A more detailed study involving both simulations and experiments still has to be carried out to further elucidate the mechanism of beam motion.

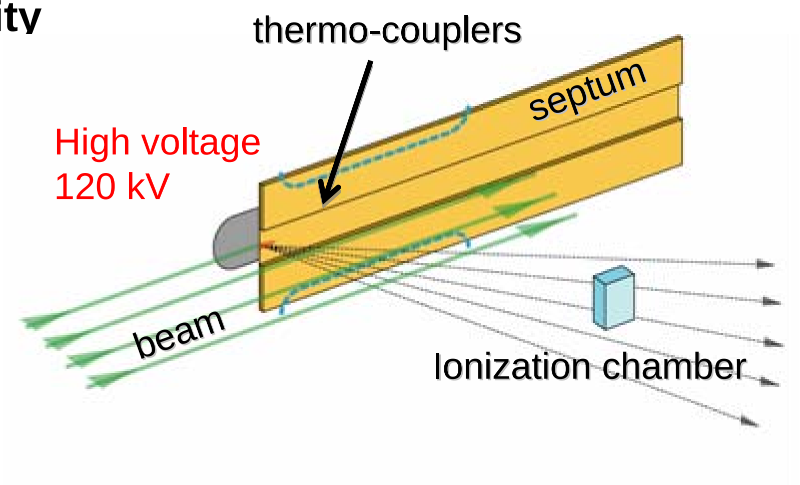
  Unknown factor: neutralization

  initial condition at the extraction of the ion source

Extraction

- *Beam loss at electrostatic deflectors*

  ➡ **limits cyclotron output beam intensity**



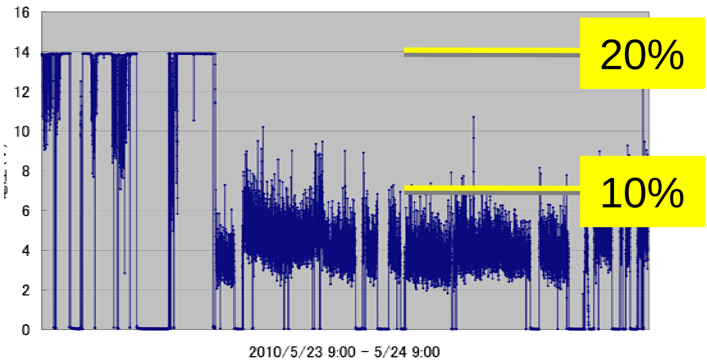
- **At RIBF**
  - **Beam loss at the SRC-EDC is monitored by measuring:**

    - temperature of the septum electrode

    - radiation with an ionization chamber
  - **Heat load limit: 300 W**

    (corresponds to 10 % of the total power for 345 MeV/u ^{48}Ca beam)

Signal from the ionization chamber



- **How to deal with the problem:**

  - increase of RF voltage

  - use of flattop resonator

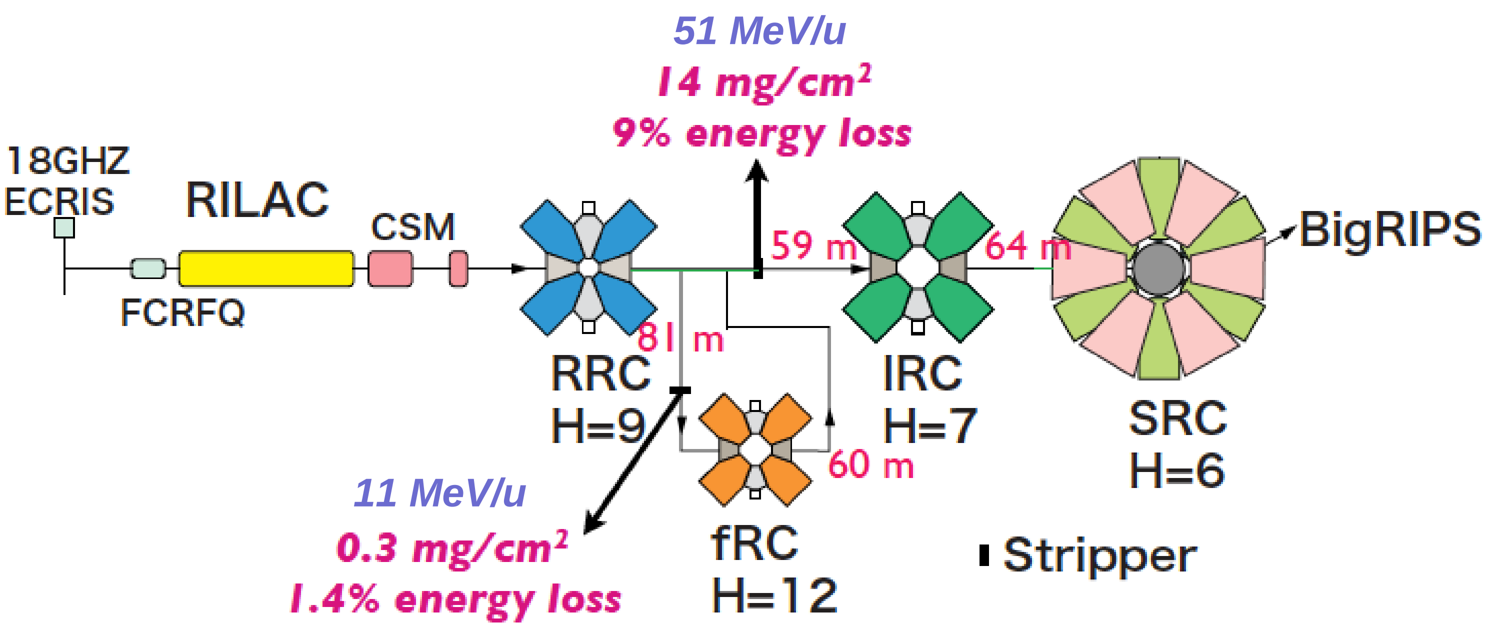
  - collimation of the beam

  - development of a deflector that endures higher values of beam loss, say 1 kW

Charge strippers

- Charge stripper problems are very serious for very heavy ions like U.
- At RIBF
  - For the acceleration of a U beam, two carbon-foil charge strippers are used.
  - A problem occurs with the first stripper.

Acceleration scheme of a uranium beam at RIBF

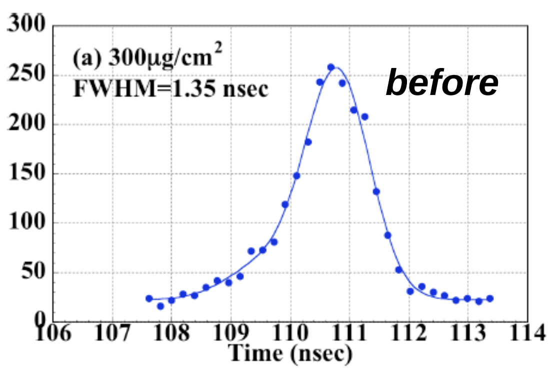


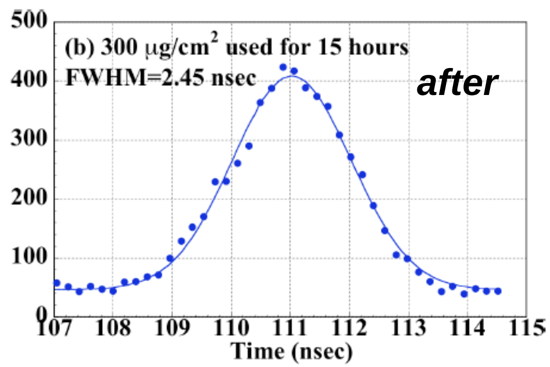
Charge strippers

- **At RIBF (cont'd)**
  - **Lifetime: ~ 10 h with a beam intensity of 80 pnA (3 W loss)**
  - **The lifetime is determined by the decrease of beam intensity due to energy spread after irradiation. (The foils are not necessarily broken.)**
  - **Non-uniformity of thickness is 30 %.**
  - **The target intensity of 1 pμA is about 1,000 times higher than what is currently available.**

→ Development of other types of charge strippers such as a gas stripper or a liquid stripper are essential for higher intensity beams.

TOF signal measured downstream the charge stripper





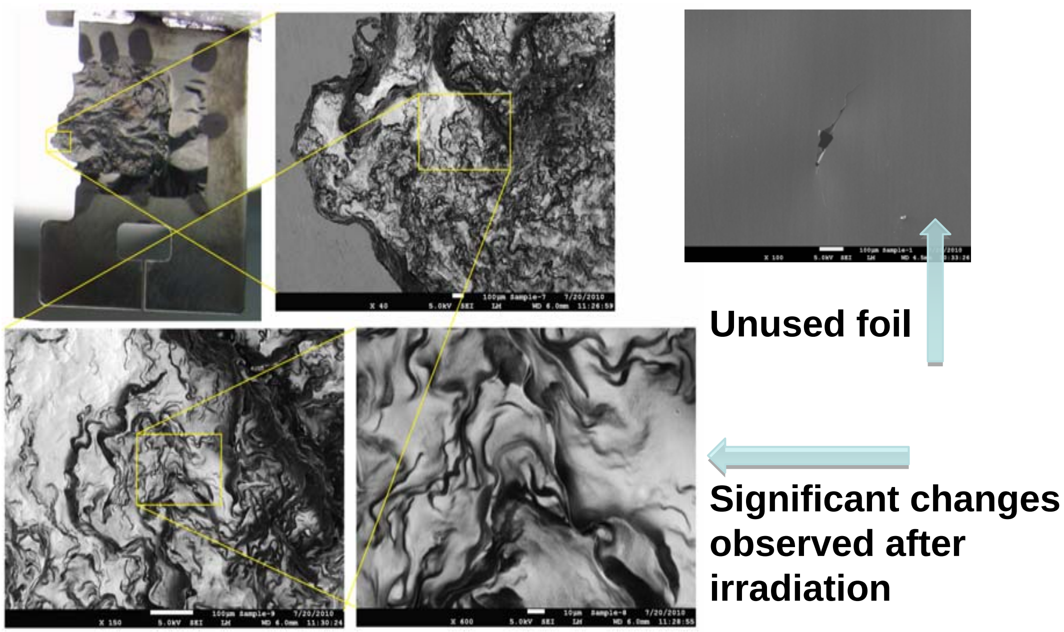
before

after

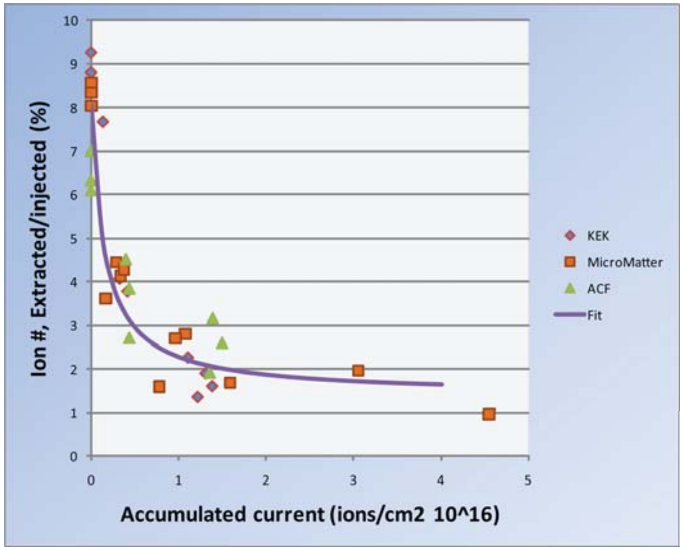
Charge strippers

- **At NSCL**
  - **Experiment performed in the K1200 with a Pb beam**
  - **Significant decay observed at 10^{14} ions in 4 mm^2 in the cyclotron**
  - **Not practical to use at the present time**

SEM photographs of Pb irradiated foil



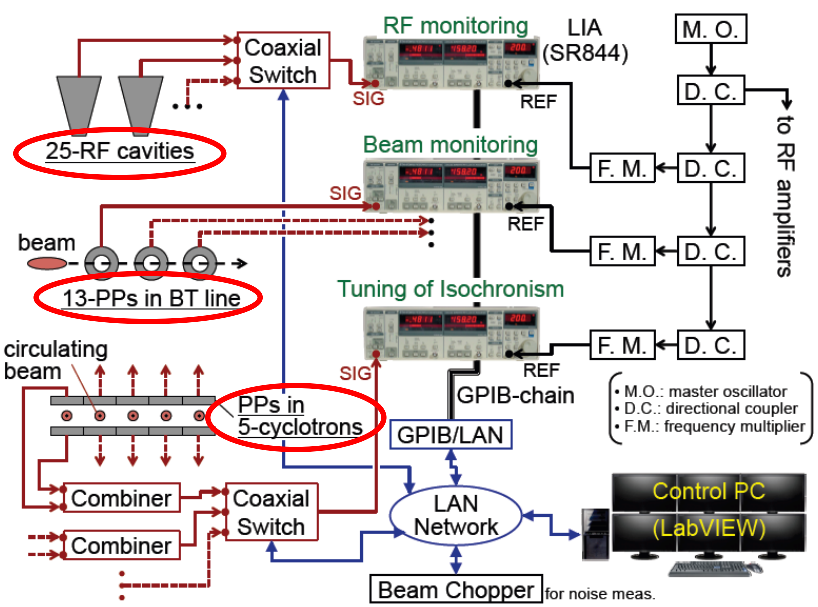
Accumulated current dependency of beam transmission efficiency



Beam diagnostics/safety system/stability

- **Non-destructive beam diagnostic devices are indispensable for high-intensity operations.**
- **At GANIL**
  - **The machine is tuned step-by-step by reducing the beam-chopping rate.**
  - **Interceptive diaphragms and current transformers**
  - **The beam loss is continuously monitored and if it exceeds a threshold, the safety system works.**
- **At RIBF**
  - **A monitoring system of beam phases and RF fields using lock-in amplifiers (LIAs) has recently been developed.**
- **An automated beam alignment system using inductive beam position monitors (BPMs) is also useful.**

Monitoring system using LIAs at RIBF



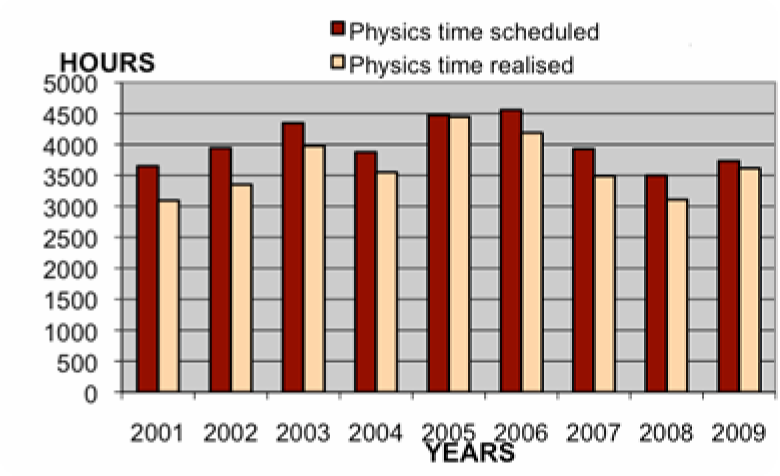
Availability

- **Availability =** $\dfrac{\textbf{Delivered beam time}}{\textbf{Scheduled beam time}}$

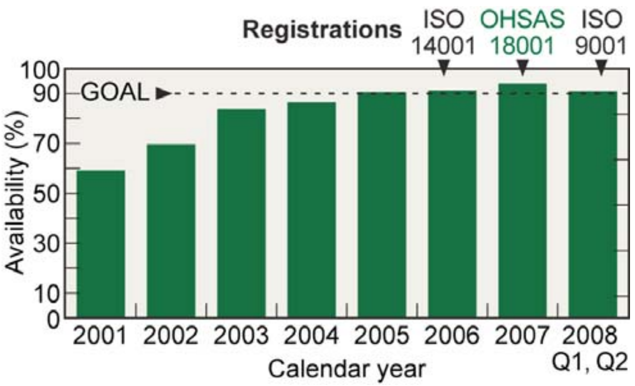
- **The availability is now as high as ~ 90 % at every facility.**

345 MeV/u 48Ca, May 22 ~ June 9, 2010

RIBF



GANIL



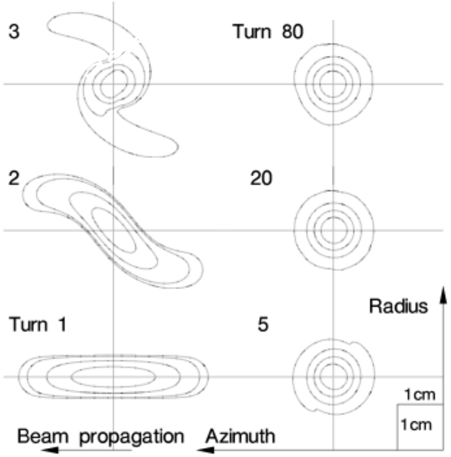
NSCL

Space charge effect

- **Little study on the space charge effects in heavy-ion cyclotrons;**

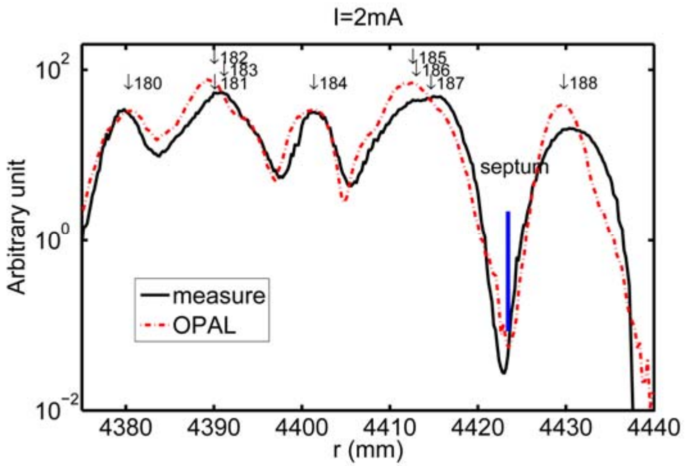
  cf. considerable research has been devoted to those in high-intensity proton cyclotrons such as PSI cyclotrons.
- **However, it has become necessary to take these effects into account in simulations even for heavy-ion cyclotrons.**
- **In the PSI proton cyclotron, "round beam" formation was observed and has been studied intensively.**

"Round beam" formation in the PSI Injector II



[*Calculation by S. Adam*]

Beam patterns in the PSI Ring cyclotron



[*Calculation by Y. J. Bi and A. Adelmann*]

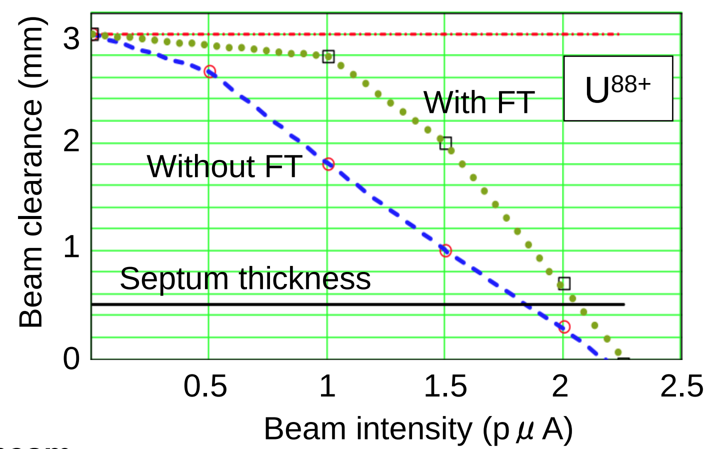
Space charge effect

- **“Round beam” formation and the matching condition for it are studied for heavy ion beams.**

  [*P. Bertran et al., Cyclotrons 2001 (2001) 379*]

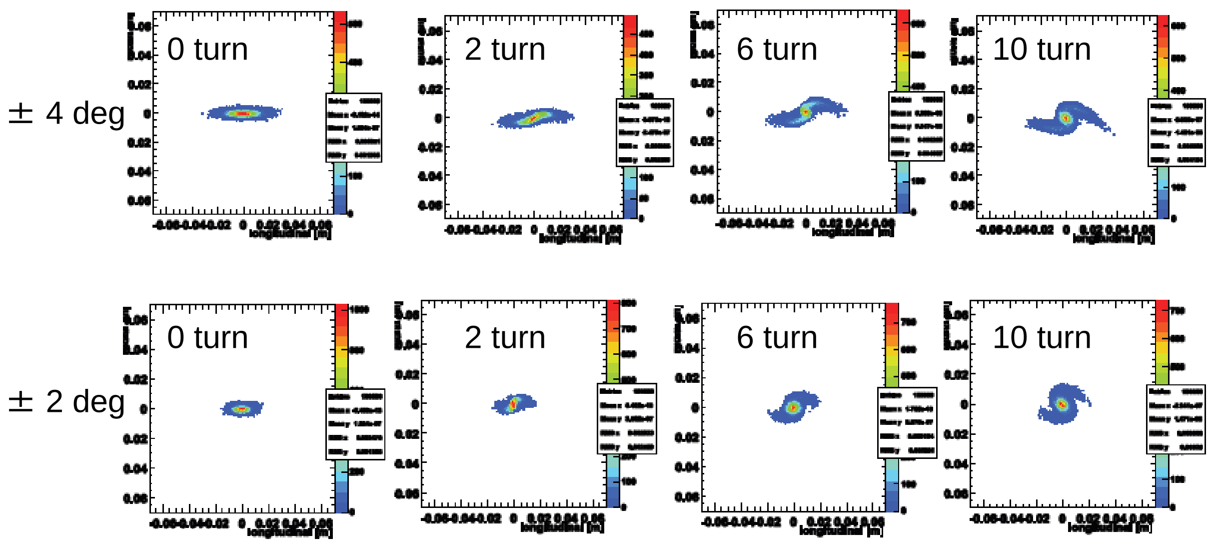
- **Some simulations for RIBF cyclotrons**
  - **“Round beam” in the RRC**
  - **Intensity limit due to the longitudinal space charge effect in the SRC**

Intensity dependence of beam clearance in the SRC



[*Calculation by S. Vorozhtsov*]

“Round beam” formation in the RRC at 0.5 mA for a U^{35+} beam



[*Calculation by H. Okuno*]

Summary

- High-power cyclotrons for heavy-ion beams have played essential role in RI beam sciences.

- Six facilities worldwide that operate high-power heavy-ion cyclotrons were overviewed.

  The beam power of up to several kW have been obtained for ions lighter than around Ar.

- Some technological issues related to high-power heavy-ion beams were discussed on the basis of the experiences of the above cyclotrons.

  There are still challenging technological issues to be solved to meet great targets.

- High-power heavy-ion cyclotrons are expected to be more and more useful for RI beam sciences.

Acknowledgement

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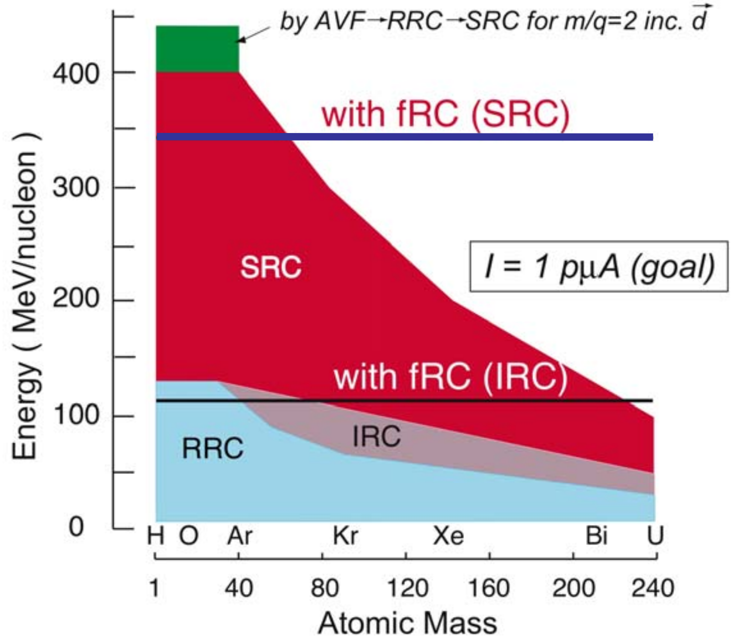
Thanks for members of the Accelerator Group, RIKEN Nishina Center.

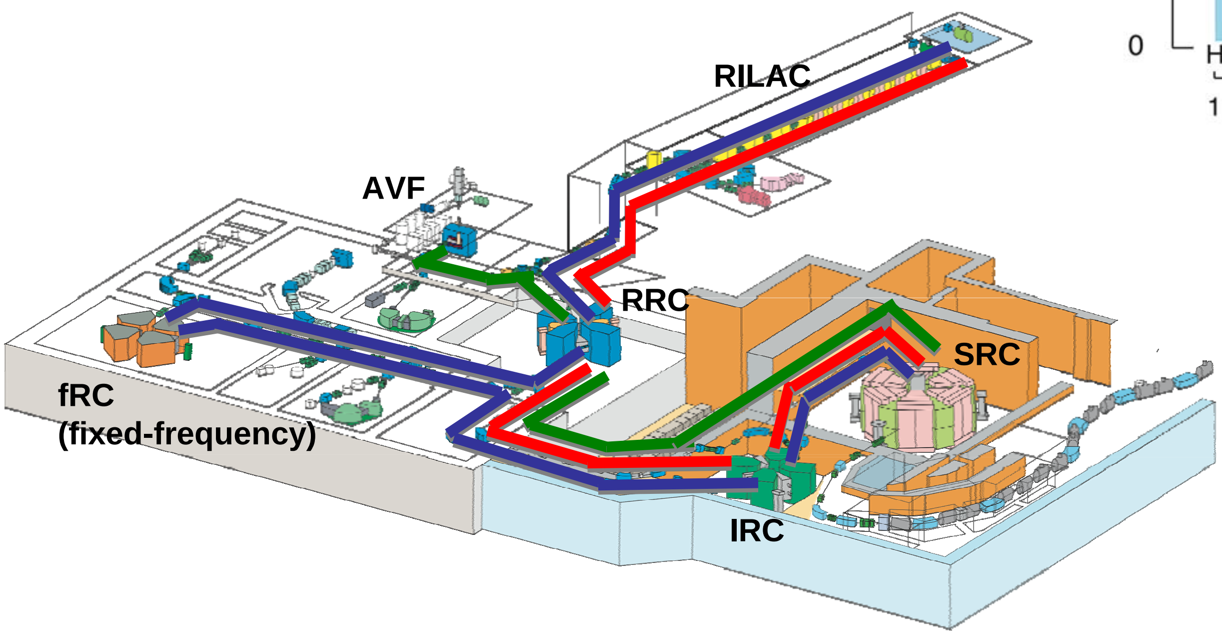
Thank you for your attention!

RIBF

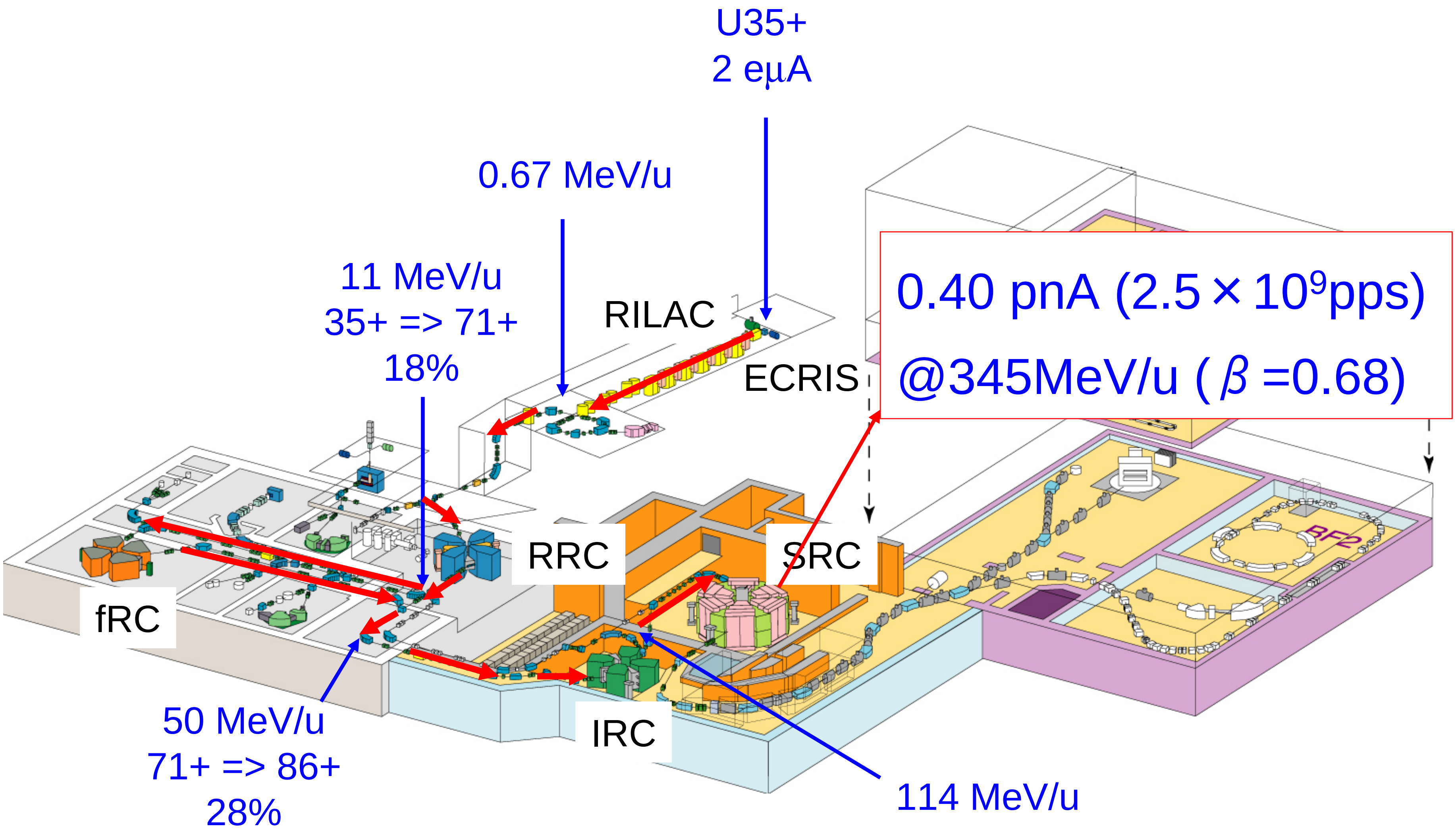
Three acceleration modes

- Fixed-energy mode (345 MeV/u)
- Variable-energy mode (< 400 MeV/u)
- AVF-injection mode (< 440 MeV/u)

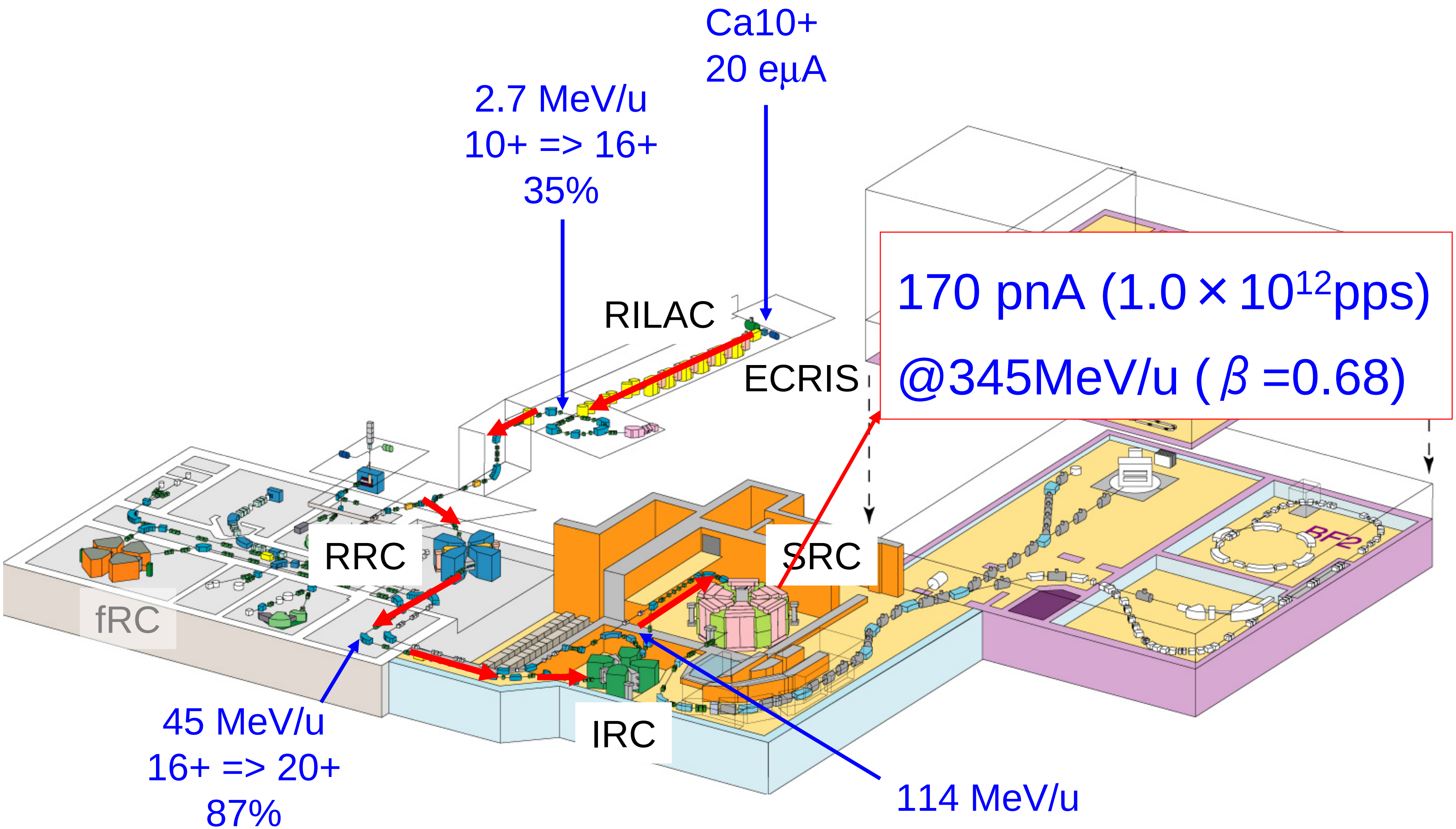




Acceleration of ^{238}U beam



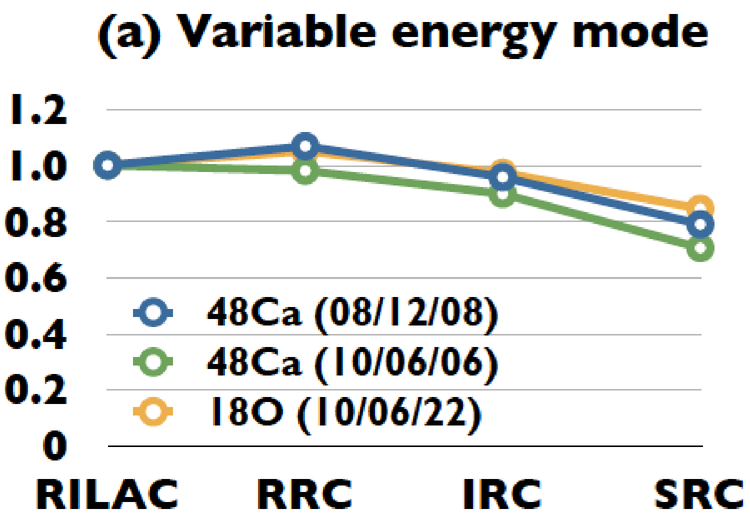
Acceleration of ^{48}Ca beam

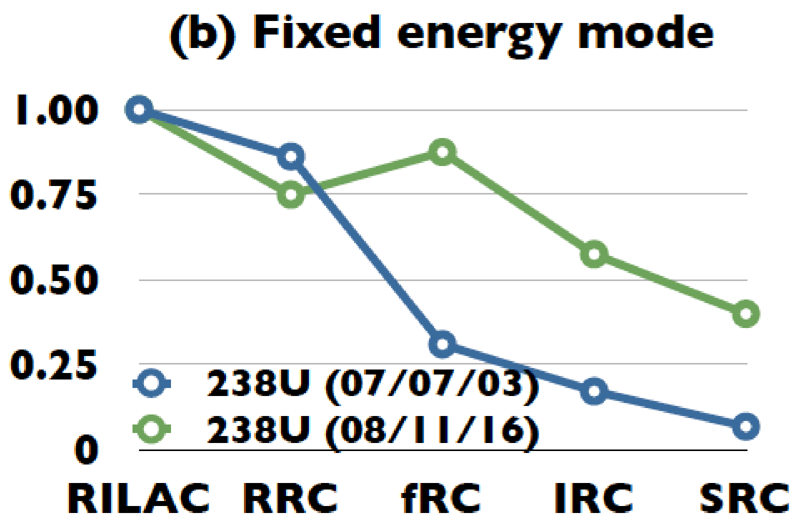


Beam transmission efficiency

Ex.: Beam transmission efficiencies at RIBF

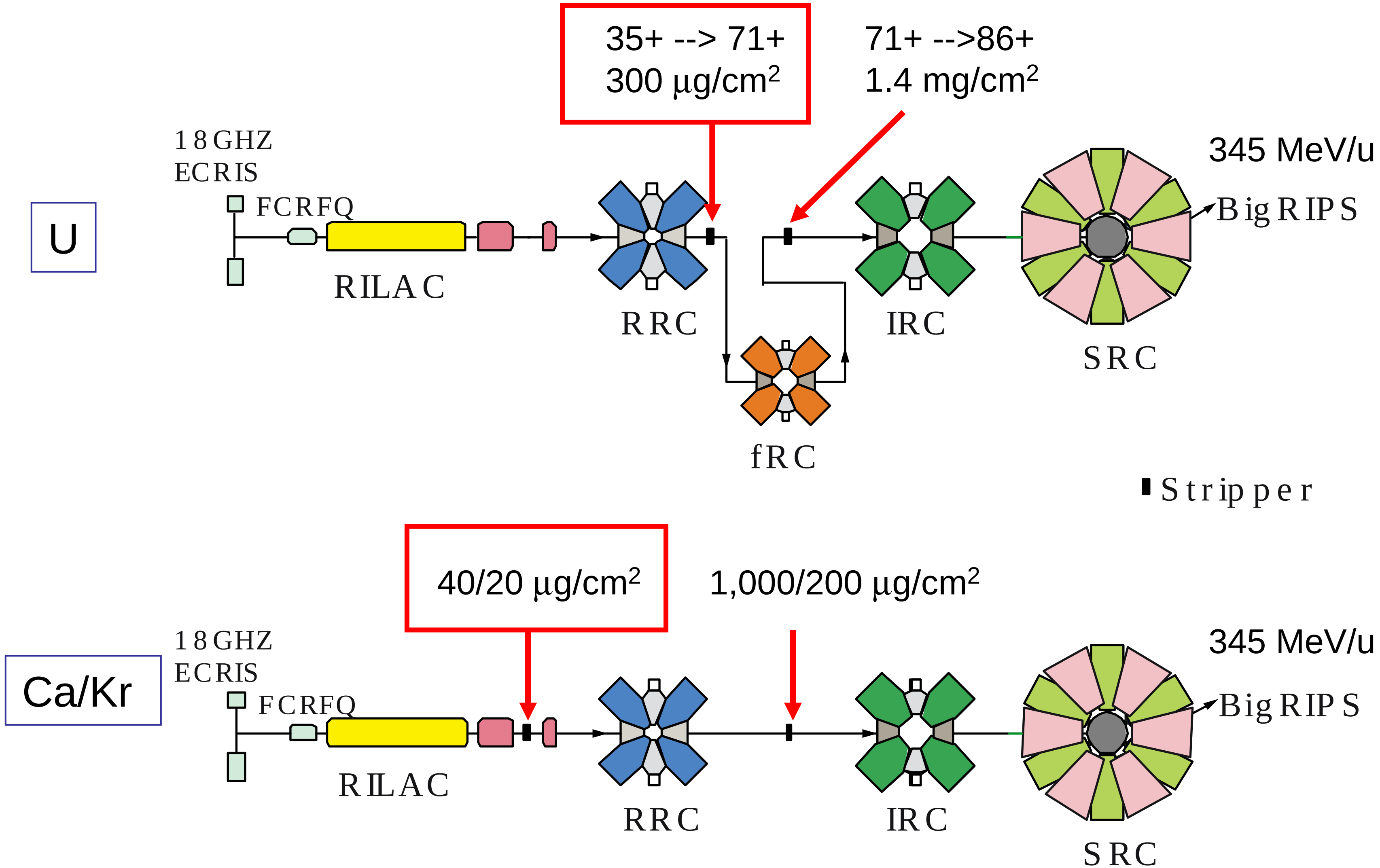
- **85 %** in variable-energy mode (three cyclotrons: RRC-IRC-SRC)
- **40 %** in fixed-energy mode (four cyclotrons: RRC-fRC-IRC-SRC)





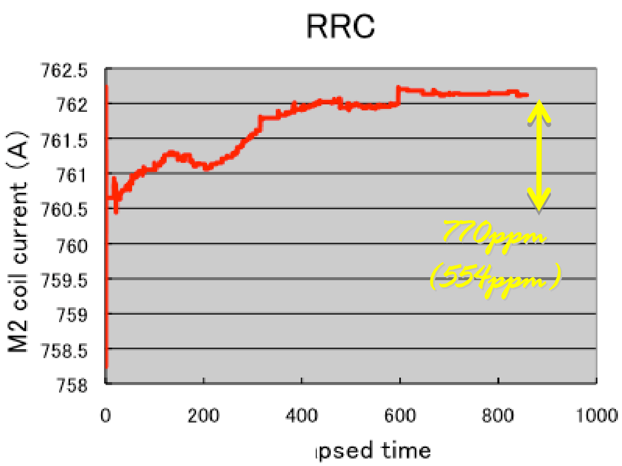
Note: charge stripping efficiencies (30% for ^{48}Ca and 4.4% for ^{238}U) are excluded.

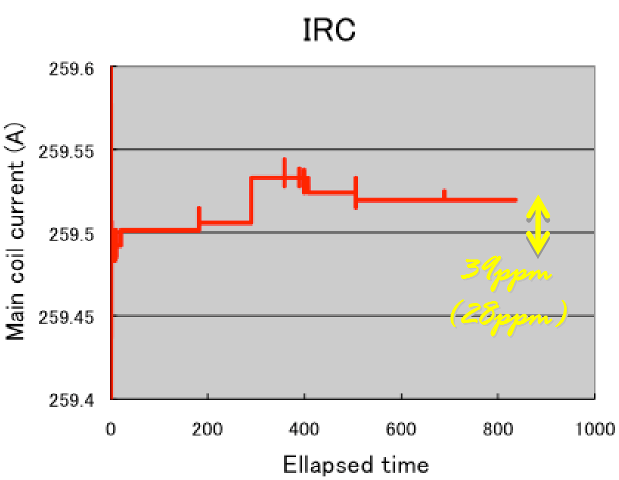
Charge strippers in RIBF

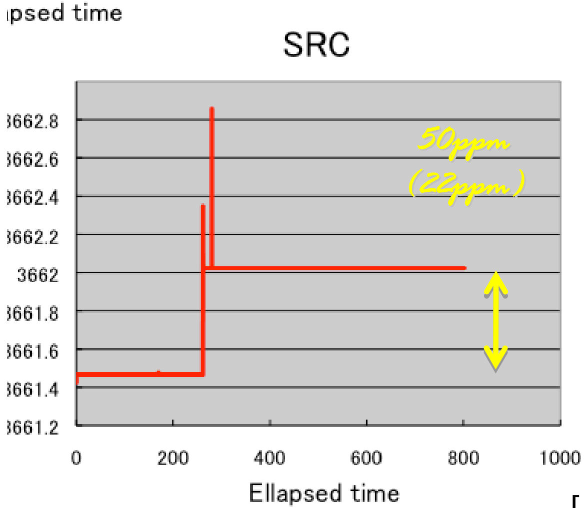


Stability

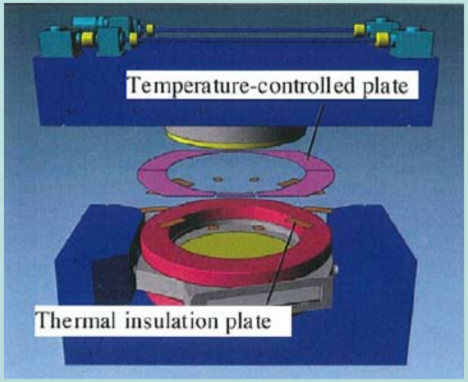
- **At RIBF**
  - **Drift of the magnetic field of the RRC: 1 ppm/h for the first 600 h**

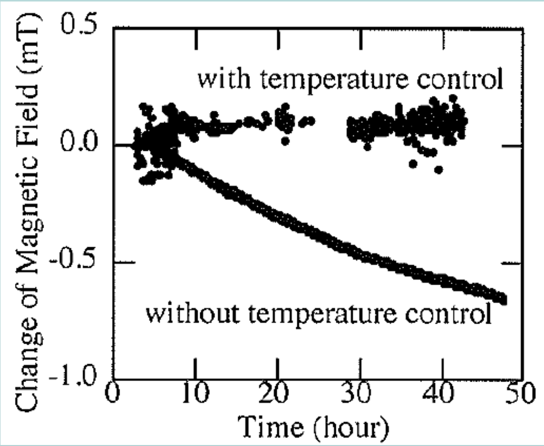






Temperature control of Takasaki AVF cyclotron magnetç





[*S. Okumura et al, Cyclotrons 2001 (2001) 330*]

Availability/reliability

- An electric power cogeneration system (CGS) with the output electric power of 6.5 MW is operated at RIBF.
- To increase the reliability and overall energy efficiency of the power supply of the entire facility.
- It powers apparatus requiring continuous operation such as the He refrigerator of the SRC.
- When the CGS stops, the equipment is immediately switched over to the commercial power grid.

CGS at RIBF