# RI Beam Factory
# and
# Other Radioactive Isotope Beam Facilities

(1)report the present status of RIBF
(2)outline the worldwide RI beam facilities in the near future

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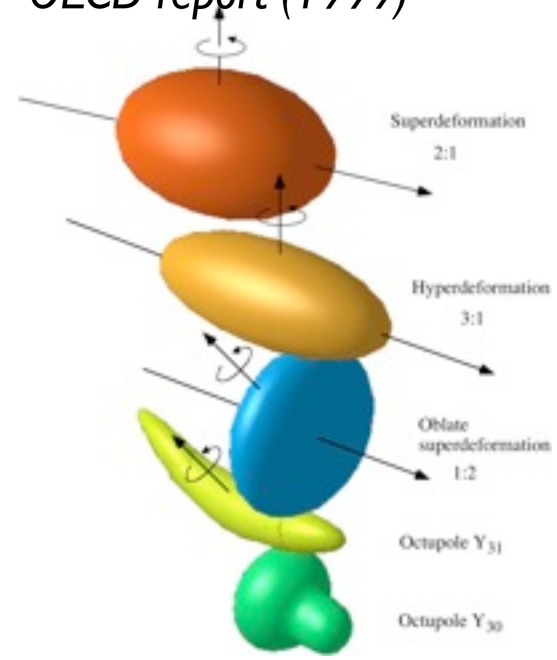
# Radioactive Isotope Beam

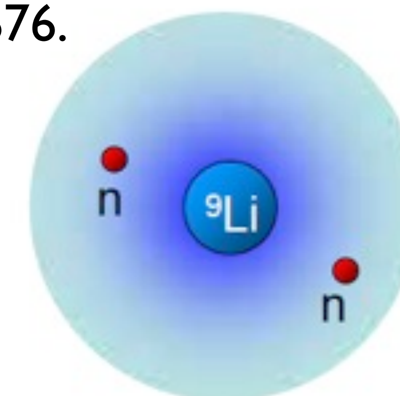
**Discovery science**
- **Nuclear Structure**
  - *halo, skin, super-heavy elements*
- **Nuclear Astrophysics**
  - *r-process, neutron star, supernovae*
- **Fundamental symmetries**
  - *electric dipole moment search in RI*

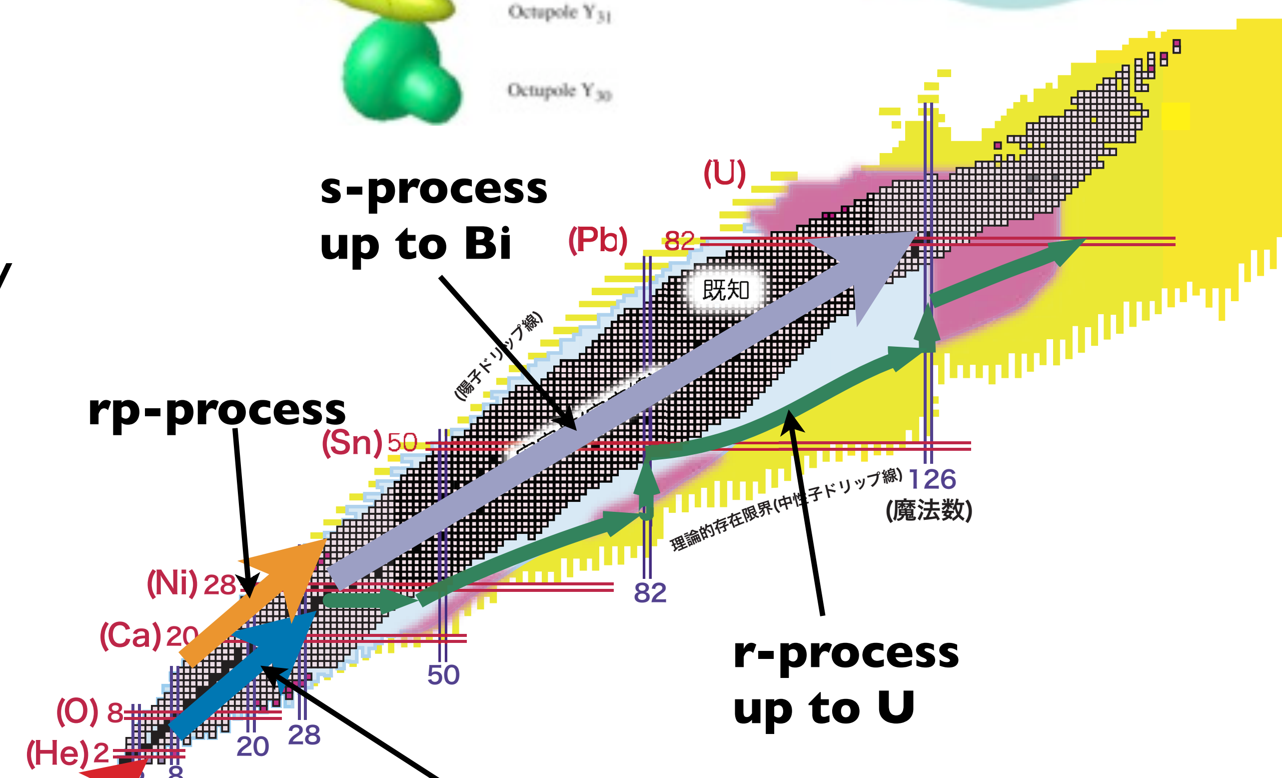
**Application**
- **Nuclear energy**
  - *neutron cross section relevant to ATW*
- **Medicine and Biology**
  - *imaging, targeted therapy, radiotracer*
- **Industry**
  - *RI as in-situ detectors*
- **National Security**

**Exotic nuclei?**
*OECD report (1999)*




**$^{11}$Li neutron halo**
Pioneering work,
I. Tanihata, PRL 55 (1985) 2676.



# ISOL technique

**(1+ → n+ schme)**

↓ **Driver beam (p,d)**

**Production target** — fission, spallation, fragmentation

↓ **RI (neutral)**

**Ion Source** — Surface IS, Plasma IS, Laser IS

↓ **RI (1+)**

**Analyzer magnet** — Mass separation

↓ **RI (1+)**

**Charge state breeder** — ECR, EBIT

↓ **RI (n+)**

**Post accelerator**

O. Kofoed-Hansen, K. O. Nielsen, Phys. Rev. 82, (1951) 96.

# In-flight separation

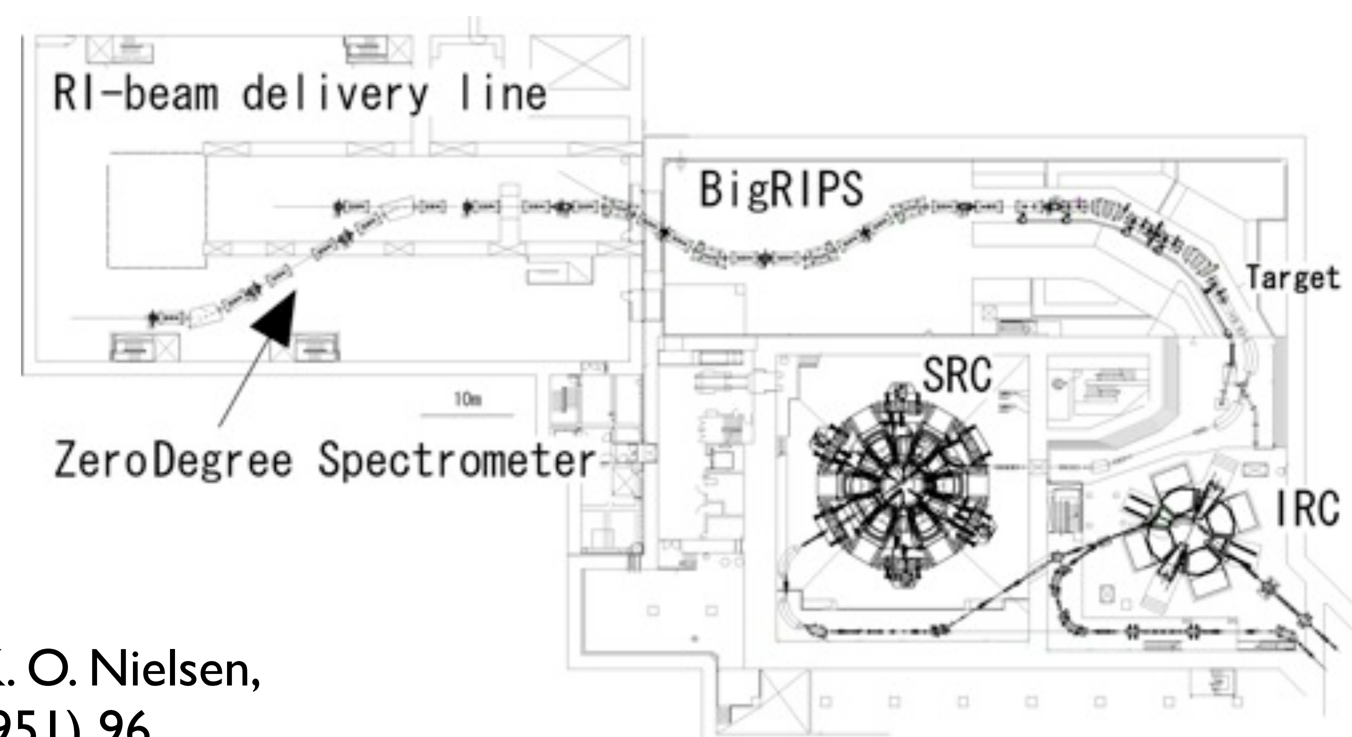
↓ **Driver beam (high-energy heavy ion)**

**Production target** — projectile fragmentation, projectile fission

↓ **RI (n+)**

**fragment separator**
**Bρ**
**TOF**
**ΔE**

T. M. J. Symons, 4th Int. Conf. on Nuclei far from Stability, CERN 81-09 (1981) 668.

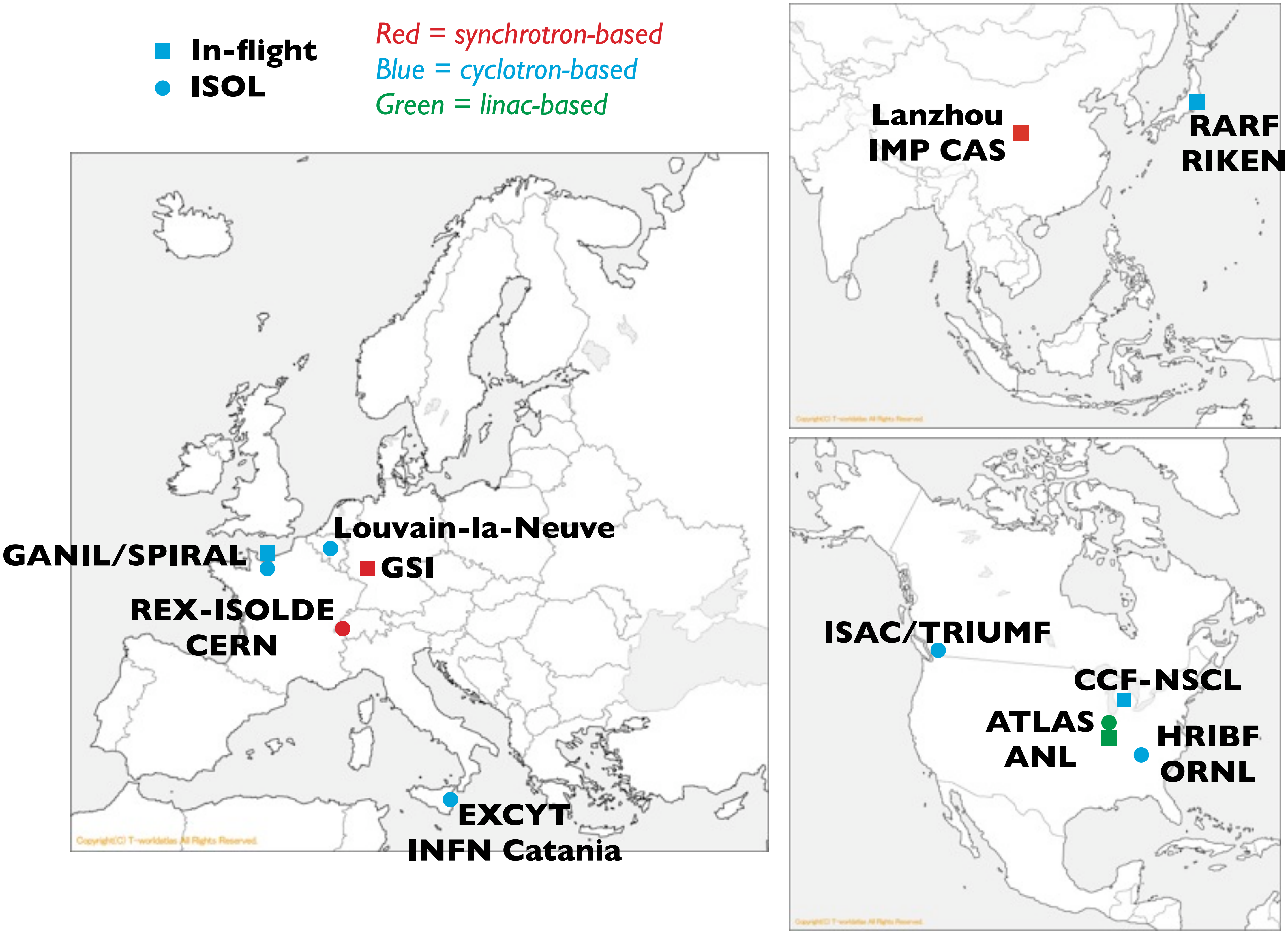


# ISOL vs in-flight

## thought to be complementary

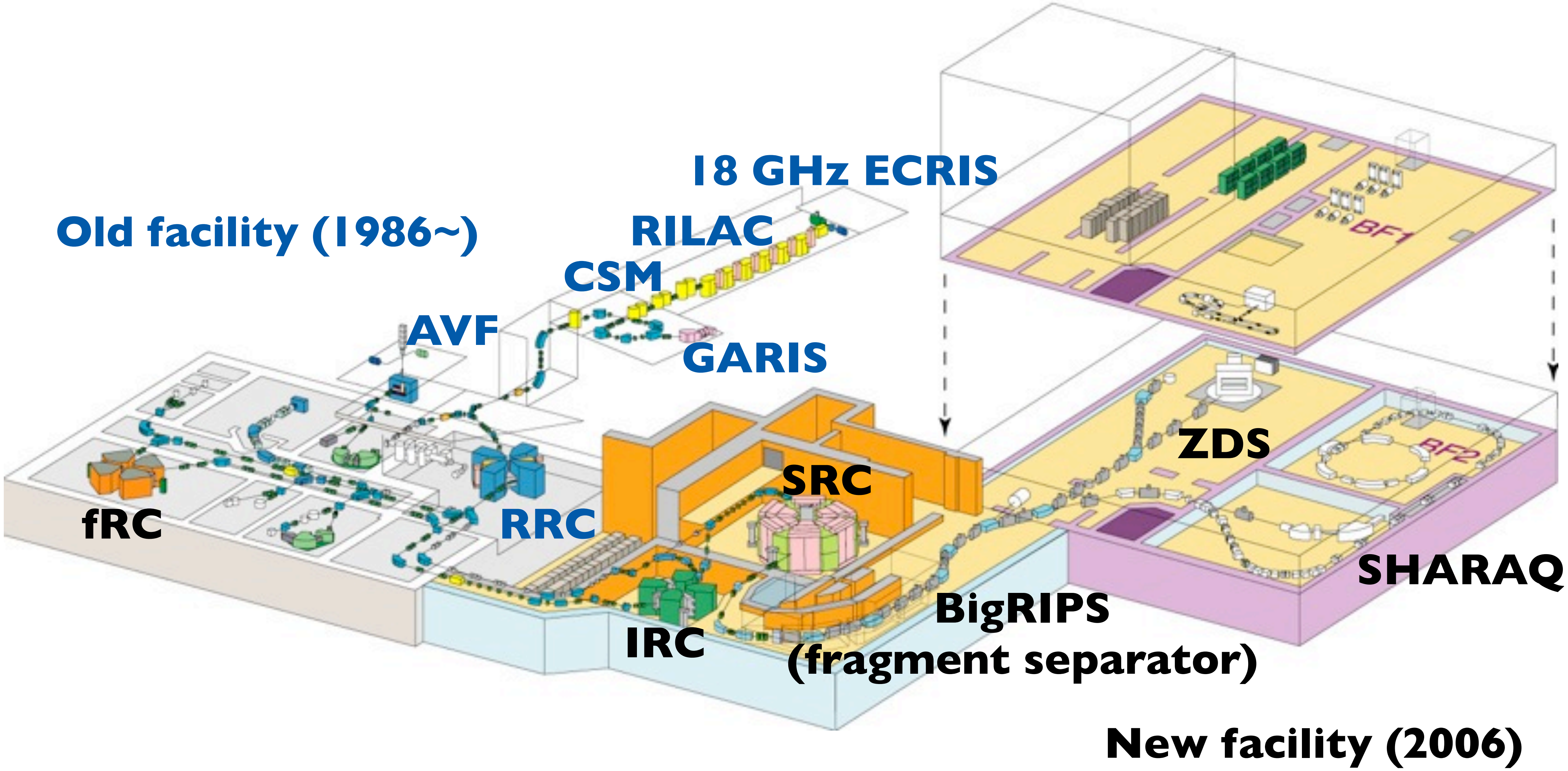
| | ISOL | In-flight |
|---|---|---|
| **Driver ion** | light ions (p, d) | heavy ion |
| **Origin of RI** | target ion | projectile ion |
| **Target** | thick target | thin target |
| **In-target yield** | high | low |
| **RI separation** | sensitive to chemical properties | physical |
| **Time scale** | > 50 ms | > 1 μs |
| **Instrumentation** | post accelerator | fragment separator |
| **Beam quality** | good | poor |
| **Experiments** | spectroscopy | reaction scheme |

# First-generation RI beam facilities



# RIKEN RI Beam Factory

*The first of the second-generation in-flight facilities*



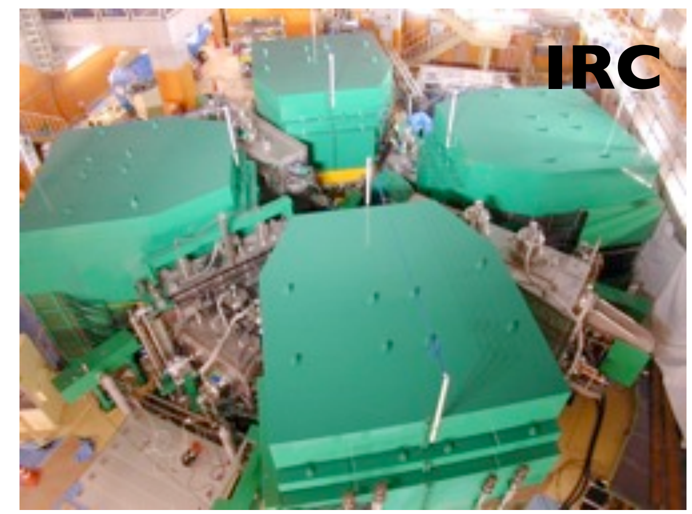

RILAC = RIKEN Heavy-ion linac (1980~)
CSM = Charge-State Multiplier (2001~)
RRC = Riken Ring Cyclotron (1986~)
fRC = fixed-frequency Ring Cyclotron (2006~)
IRC = Intermediate-stage Ring Cyclotron (2006~)
SRC = Superconducting Ring Cyclotron (2006~)

# Specifications of RIBF ring cyclotrons

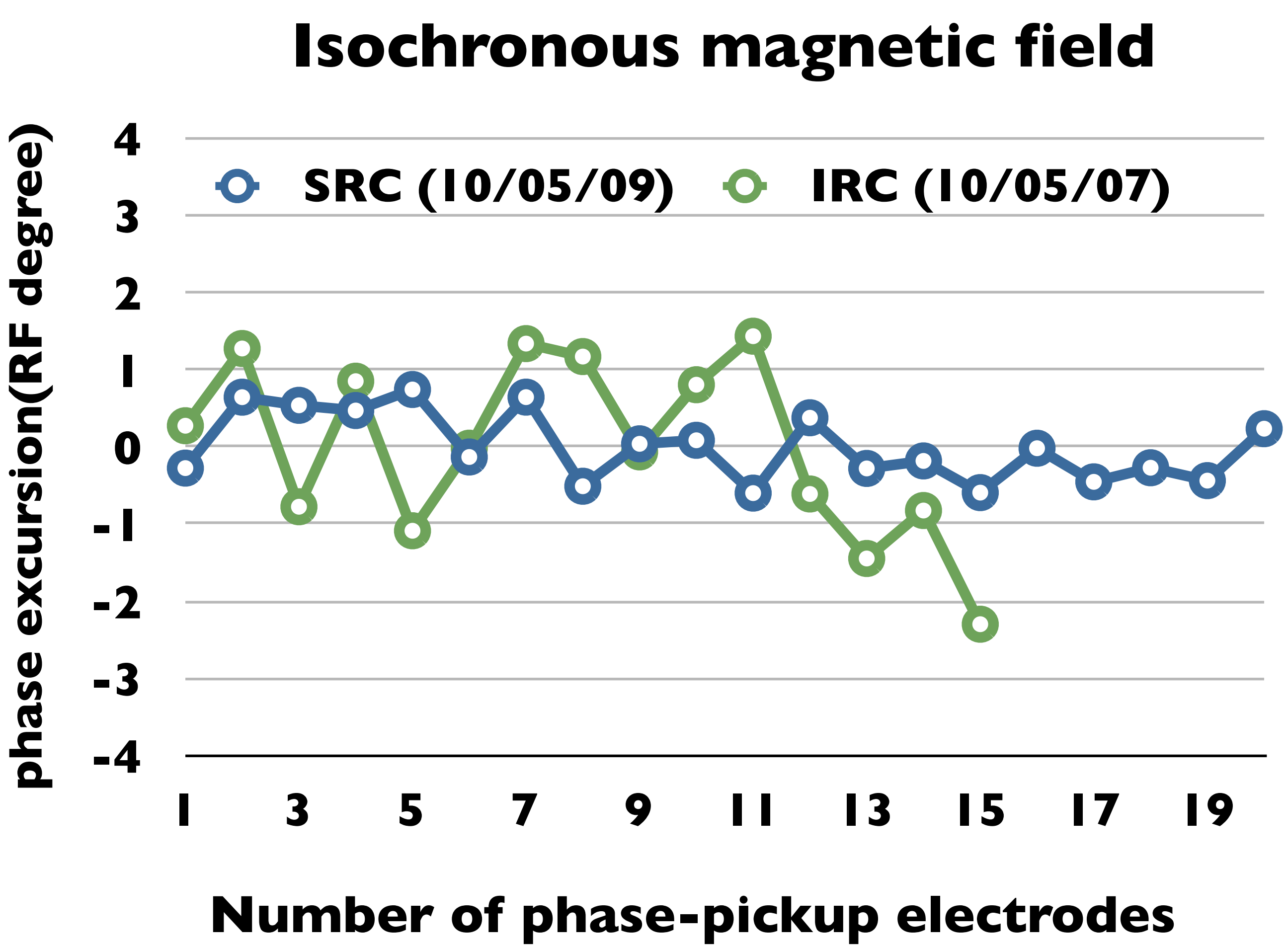
| | fRC | IRC | SRC | RRC |
|---|---|---|---|---|
| **K-number (MeV)*** | 570 | 980 | 2600 | 540 |
| **Number of sector magnets** | 4 | 4 | 6 | 4 |
| **Velocity gain** | 2.1 | 1.5 | 1.5 | 4.0 |
| **Number of trim coils ( / sector magnet)** | 10 | 20 | 4(SC) 22(NC) | 26 |
| **RF resonators** | 2+FT | 2+FT | 4+FT | 2 |
| **Frequency range (MHz)** | 54.75 | 18～38 | 18～38 | 18～38 |

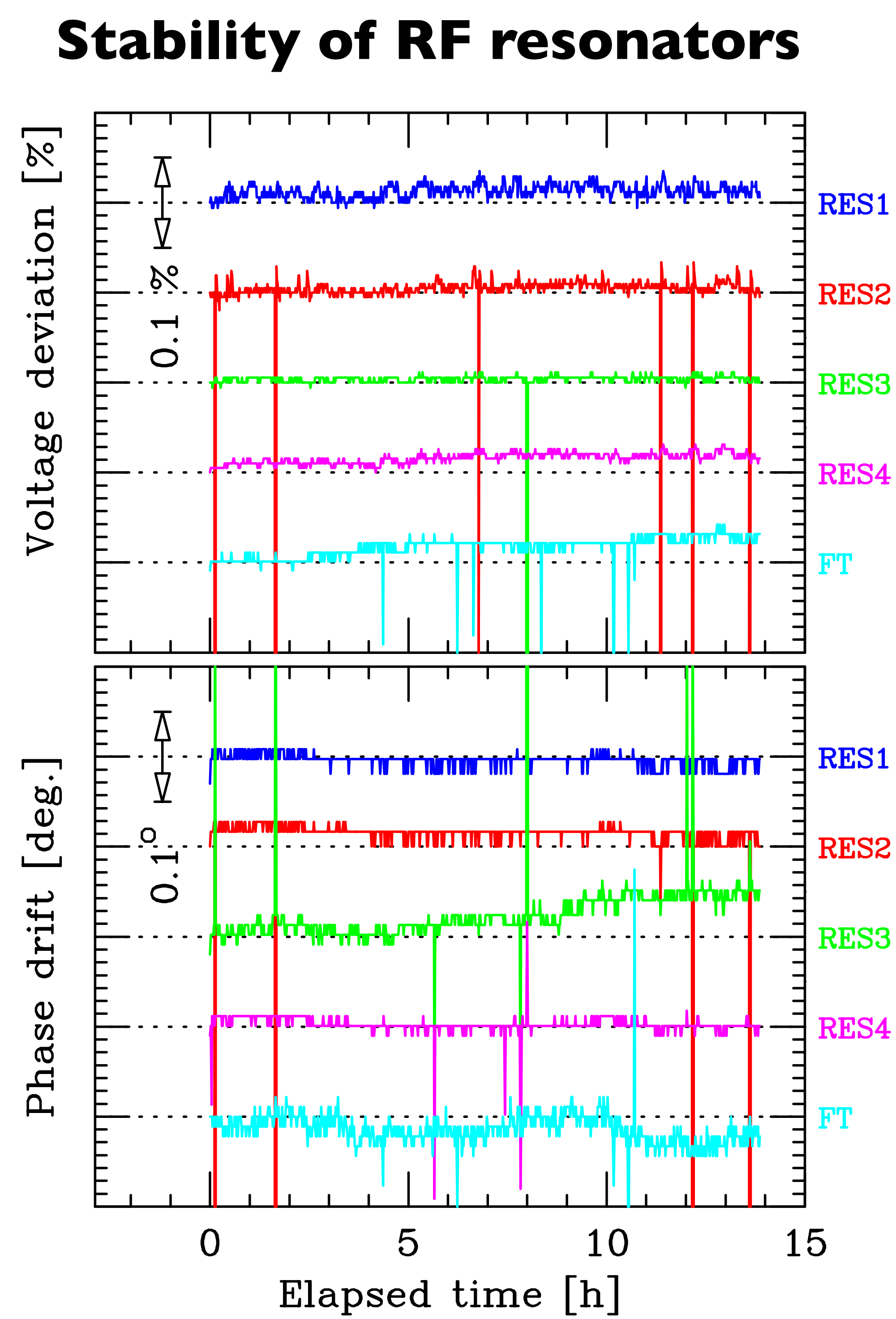
SC = superconducting
NC = normal conducting
FT = flattop resonator

*$K=(M/q)^2 \times E_{max}$ (MeV/nucleon)


# SRC works as a good isochronous cyclotron

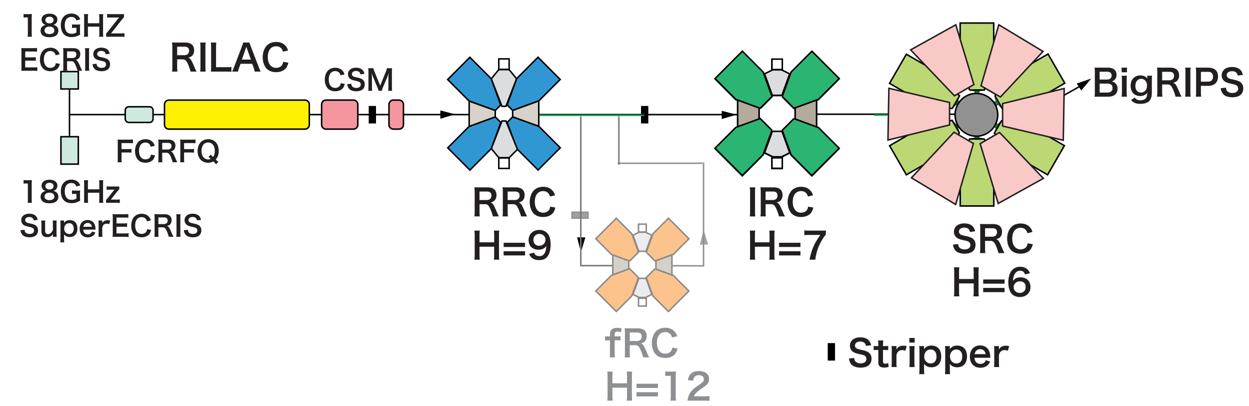


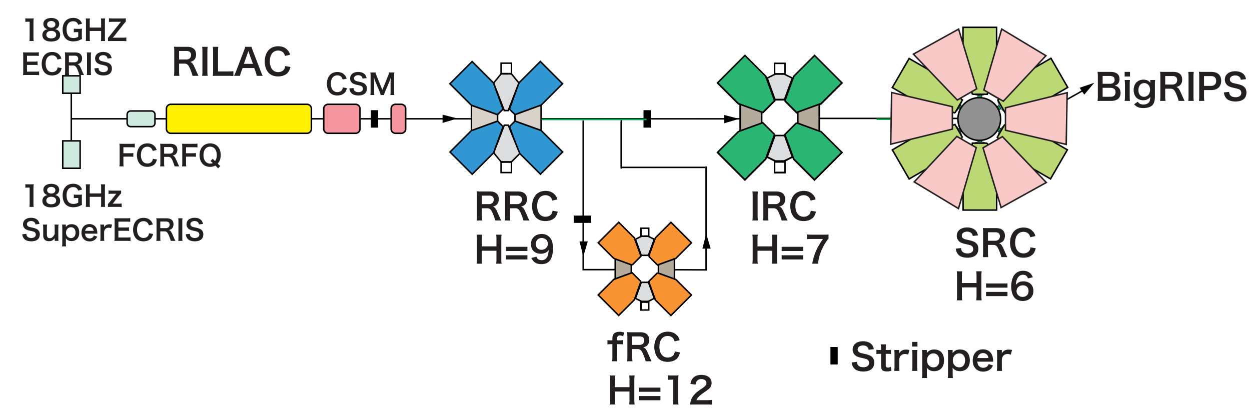

**ΔV/V∼0.01% Δψ∼±0.1° RF**

# Acceleration modes in RIBF

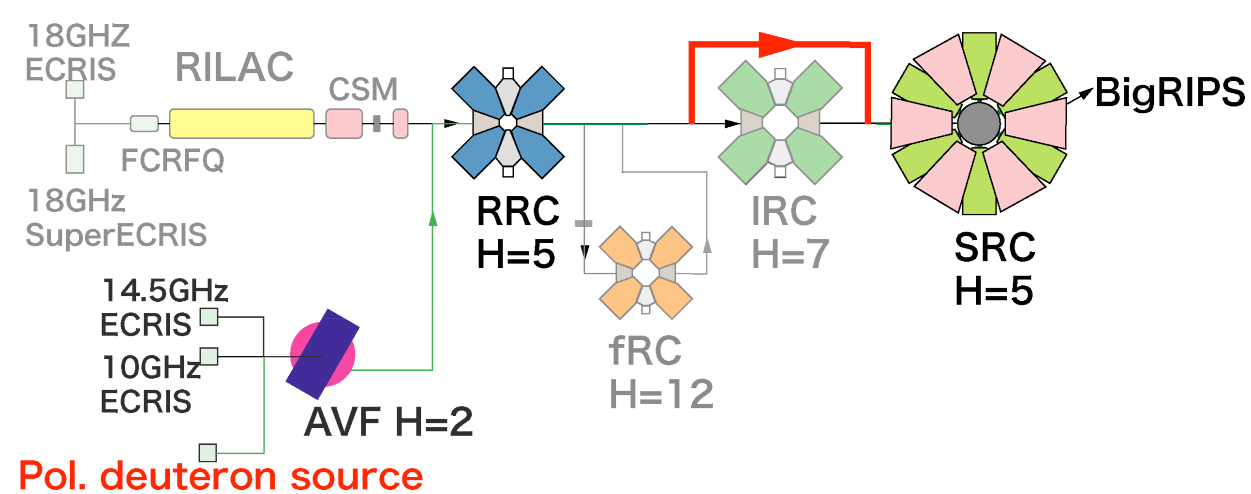
**(1) Variable-energy mode**
**$^{27}$Al, $^{48}$Ca, $^{86}$Kr**
**~400 MeV/u @ SRC**




**(2)Fixed-energy mode**
**$^{238}$U 345 MeV/u @ SRC**




**(3) AVF-injection mode**
**Polarized deuteron, $^{14}$N**
**250 ~ 440 MeV/u @ SRC**



# Operation statistics / Stability

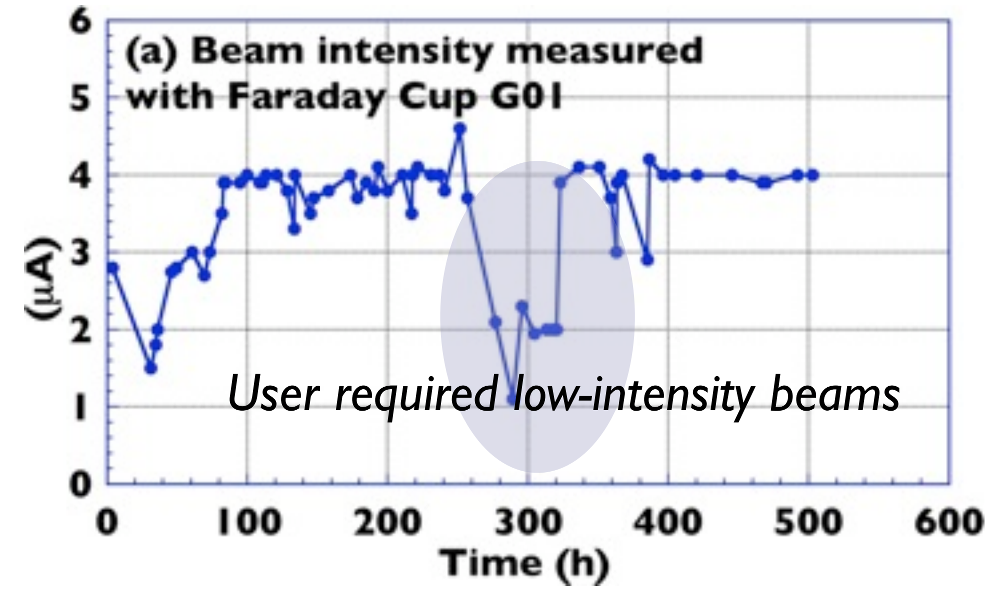
| Year | Beam service to users (h) | All RIBF operation (h) | Reliability |
|---|---|---|---|
| **2007** | 414 | 1845 | / |
| **2008** | 496 | 2051 | 0.68 |
| **2009** | 1129 | 3036 | 0.68 |
| **2010*** | 907 | 1820 | 0.86 |

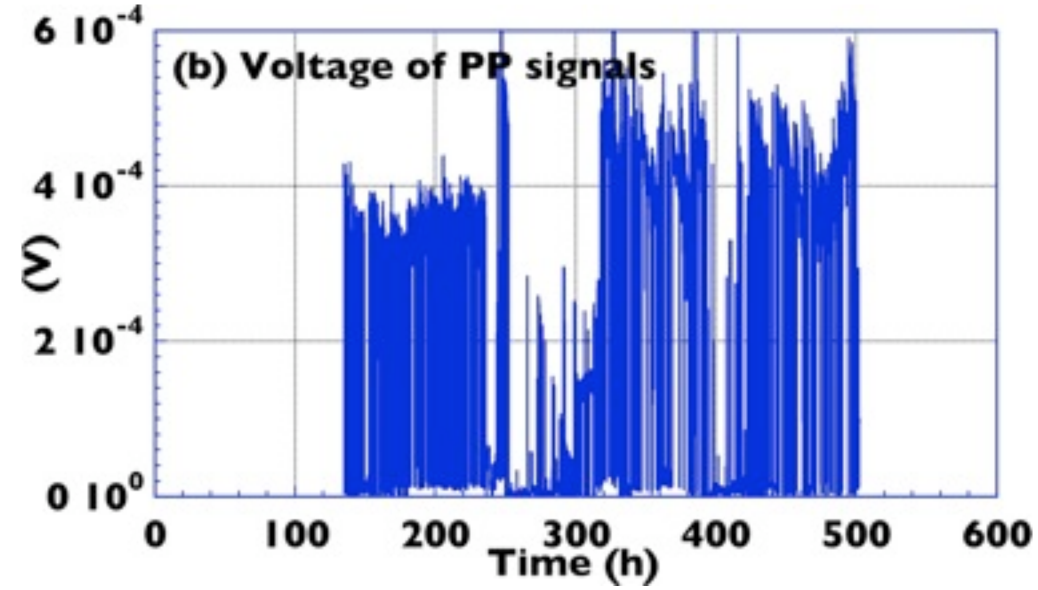
$$\textbf{Reliability} = \frac{\textbf{actual beam service time}}{\textbf{scheduled beam service time}}$$

“All RIBF operation” include beam tuning, beam commissioning etc in addition to beam service to users.

*First half of 2010

***2010/5/21 ~ 6/11***
***$^{48}$Ca 345 MeV/nucleon***




Beam bunch signals measured by a phase-pickup electromode

# RIBF performance

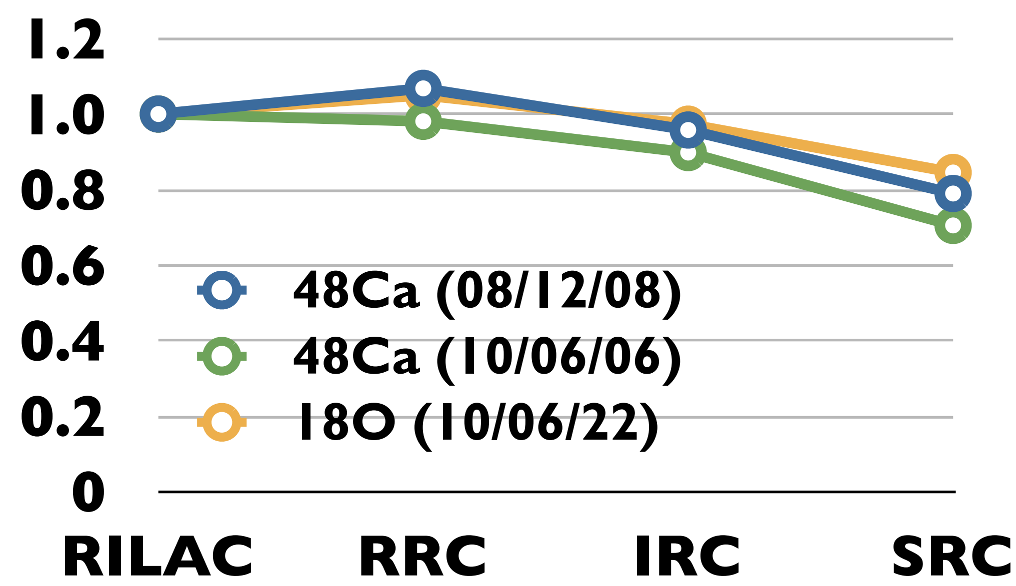
## Beam intensity

| ion (date) | (pnA) |
|---|---|
| $^{238}U^{86+}$ (07/07/03) | 0.05 |
| $^{86}Kr^{34+}$ (07/11/04) | 33 |
| $^{238}U^{86+}$ (08/11/16) | 0.4 |
| $^{48}Ca^{20+}$ (08/12/21) | 175 |
| $^{4}He^{2+}$ (09/10/31) | 1000 |
| $^{238}U^{86+}$ (09/12/19) | 0.8 |
| $^{48}Ca^{20+}$ (10/5/31) | 230 |
| $^{18}O^{8+}$ (10/6/17) | 1000 |

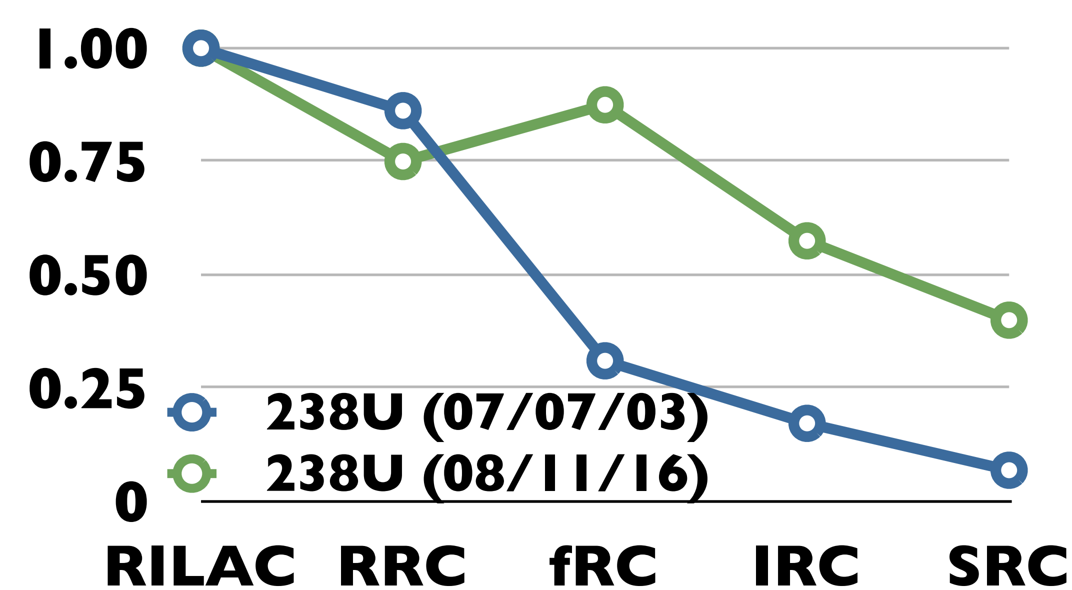
*Charge stripping efficiencies are excluded

## Transmission efficiency*

### Variable-energy mode




### Fixed-energy mode



# RILAC2

*Intensity upgrade of uranium beams*

*Y. Higurashi et al.;*
*Proc. IPAC10,THPEC060*

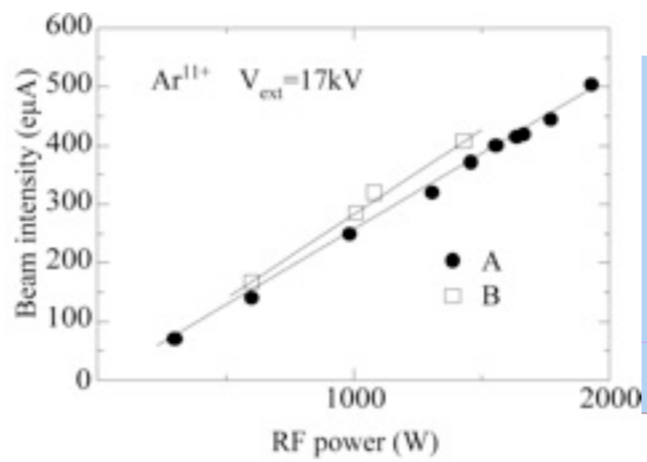
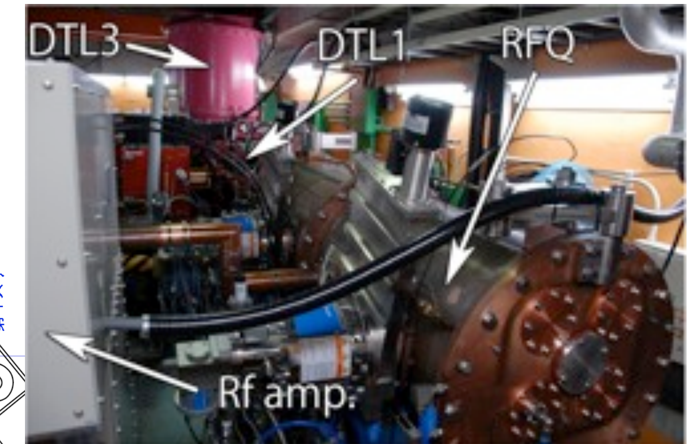
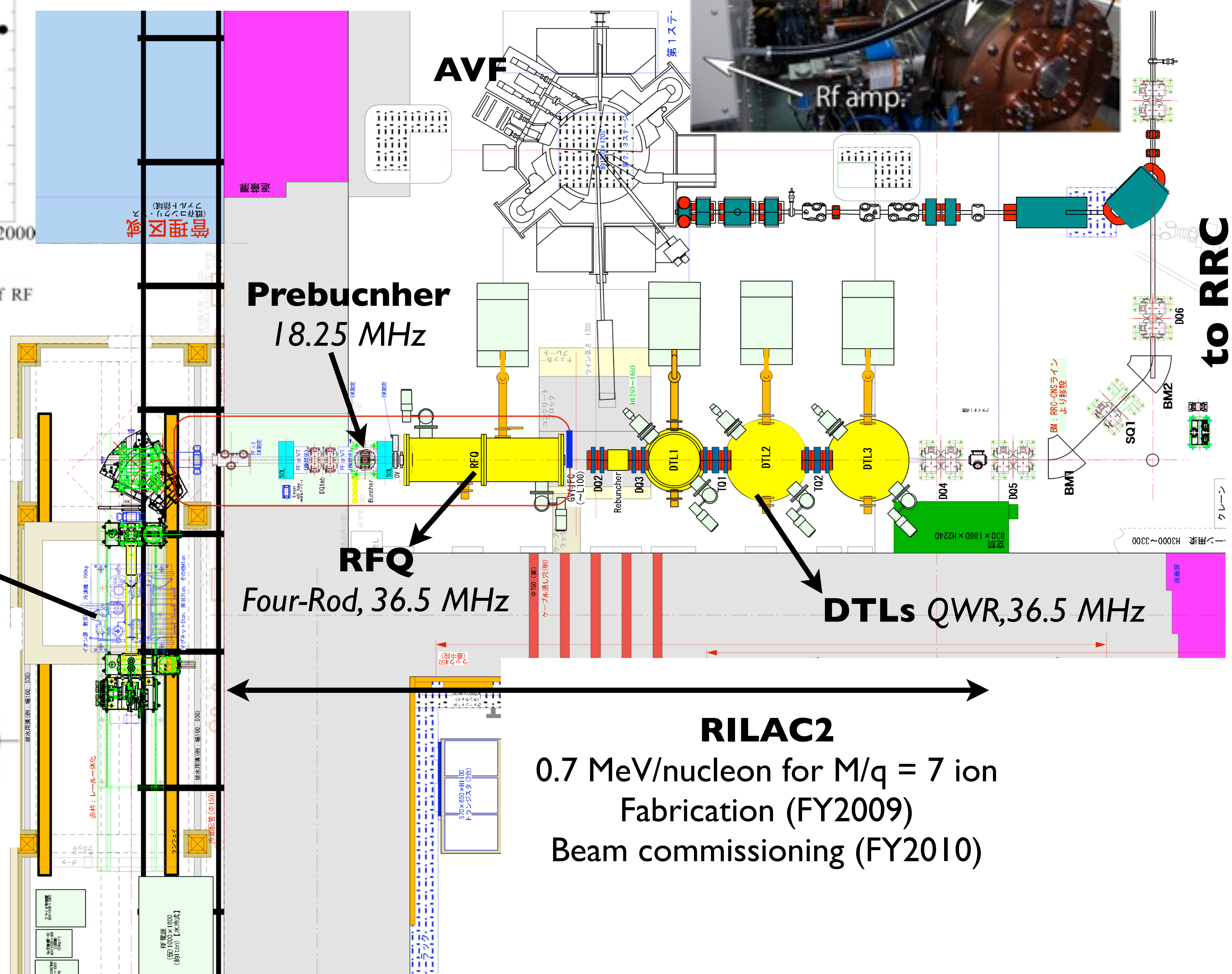
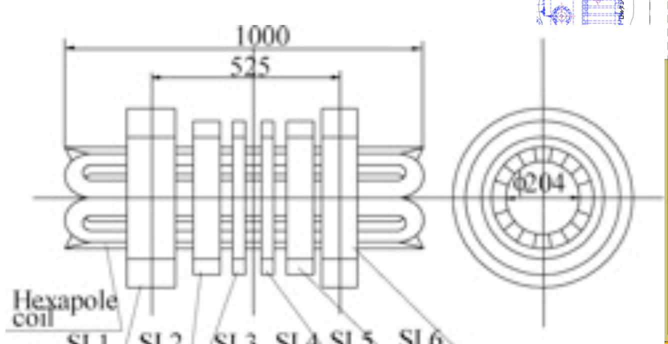



Figure 7: Beam intensity of Ar$^{11+}$ as a function of RF power at two conditions (A and B).




**28-GHz SC-ECRIS**
*T. Nakagawa et al.*
Tests @ RILAC (2009)
Installation (2010)




**RILAC2**
0.7 MeV/nucleon for M/q = 7 ion
Fabrication (FY2009)
Beam commissioning (FY2010)

# New RI beam facilities worldwide

## ISOL facilities

| | Location | Driver | Power (kW) | Post accel. | Fission rate | RI yield |
|---|---|---|---|---|---|---|
| **Spiral2 (2012)** | France | d, sc-linac | 200 | K265 cyclo. | $10^{14}$ (pps) | $10^{10}$ (pps) |
| **SPES (2013)** | Italy | p, cyclotron | 8 | sc-linac | $10^{13}$ (pps) | $10^{9}$ (pps) |
| **HIE-ISOLDE (2015)** | Swiss | p, synchrotron | 10 | sc-linac | $10^{13}$ (pps) | $10^{9}$ (pps) |
| **ARIEL (2015)** | Canada | p, cyclotron e-linac | 100 / 100 | sc-linac | $\sim 10^{14}$ (pps) | |
| **EURISOL (> 2020)** | EU | p, sc-linac | 5000 | sc-linac | $10^{16}$ (pps) | $10^{12}$ (pps) |

## In-flight facilities

| | Location | Driver | Energy (MeV/A) | Intensity (uranium) | Fragment separator |
|---|---|---|---|---|---|
| **FAIR (2016)** | Germany | synchrotron | 1500 | $2\times10^{11}$ pps | Super-FRS |
| **FRIB (2017)** | USA | sc-linac | 200 | $5\times10^{13}$ pps | 3-stage separation |

# Next (intermediate) generation ISOL facilities

**SC-linacs**

- higher energy post-accelerator
  - PIAVE-ALPI, SPES
  - REX upgrade, HIE-ISOLDE
  - ISAC upgrade, ARIEL
- high intensity driver
  - 200-kW driver (SPIRAL2)
  - 5-MW driver (EURISOL)
  - 100-kW electron driver (ARIEL/ISAC)

**Target technology**

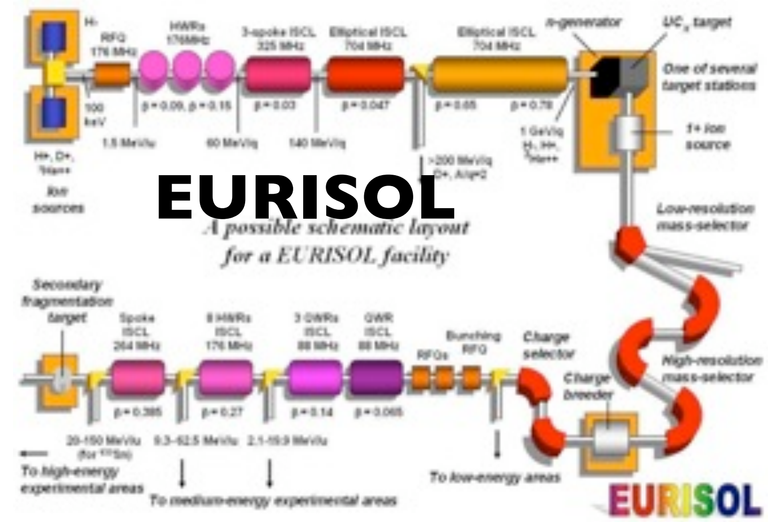
- neutron converter
  - carbon, SPIRAL2
  - Hg, EURISOL
- UCx target with a fast release time
  - SPES, SPIRAL2, EURISOL

**Multi-user capability**

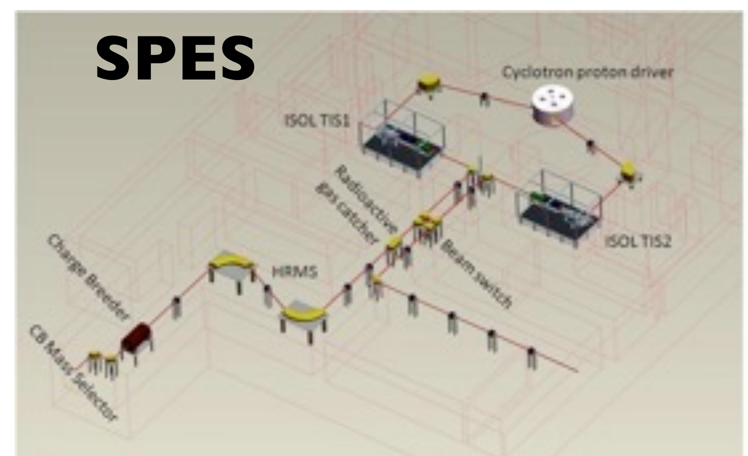
5 experimental ports (GANIL/SPIRAL/SPIRAL2)
Two new target stations (ARIEL)
6 UCx targets (EURISOL)

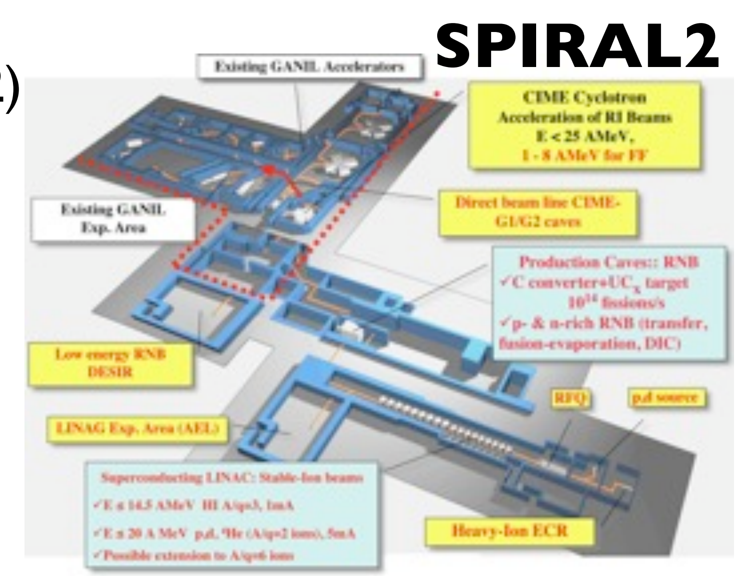
**RI beam intensity**

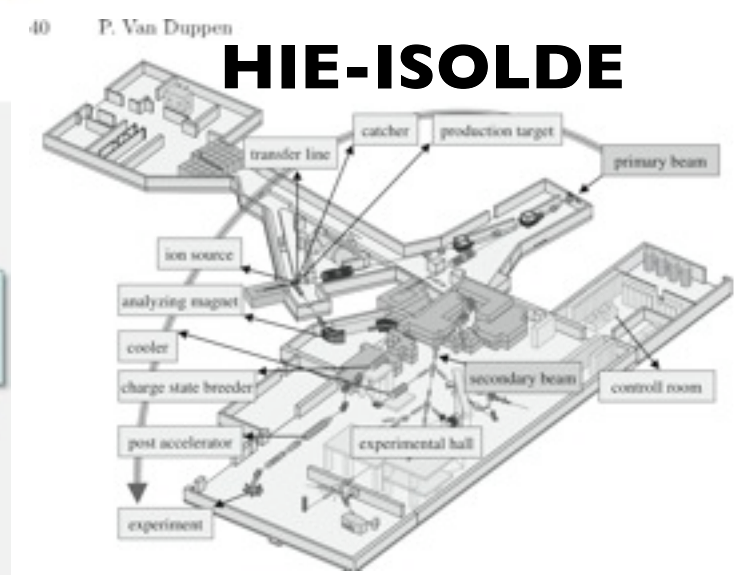
$10^{9}$ pps (SPES, HIE-ISOLDE)
$10^{10}$ pps (ARIEL, SPIRAL2)
$10^{12}$ pps (EURISOL)







# Asian activities in RI beam science

## HIRFL-CSR
## IMP Lanzhou, China

*Beam commissioning of cooler storage rings*

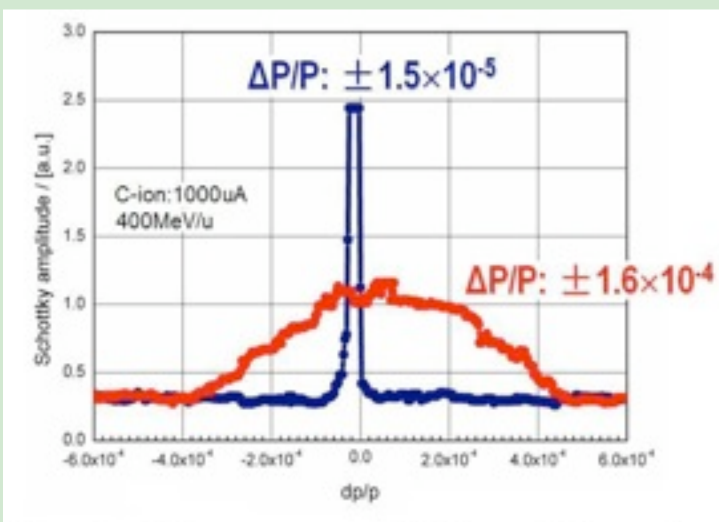



Figure 8-a): Momentum spread before and after cooling.

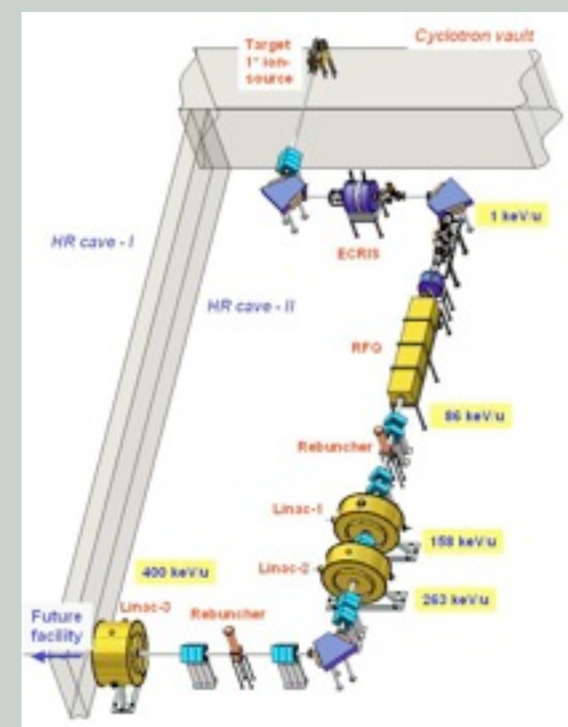
*J. W. Xia et al.; Proc. of IPAC'10,THYMH01*

## South Korea
## Heavy-ion Accelerator for RIB (KoRIA)

- *Multi-purpose*
- *Both ISOL and In-flight*
- *In-fight fragmentation after ISOL*

- *SC linac*
*10-pμA 200-MeV/nucleon U beam*
- *K = 100 MeV high-intensity cyclotron*
- *Budget = 0.4 B US$, Schedule = 2016 construction complete*

## VEC-RIB Facility
## VECC Kolkata, India




*Four RF systems have been successfully commissioned*

*RFQ*

*Pre-buncher*

*IH-linac*

*H. K. Pandey et al.; Proc. of IPAC'10,THPEA002*

# FAIR

***(Facility for Antiproton and Ion Research)***

*The next generation in-flight facility in Europe*

- **Synchrotron-based multipurpose facility**
  APPA (Atomic and Plasma Physics, and Applied Science)
  CBM (Hadron and quarks in compressed nuclear matter)
  NuSTAR (Nuclear and Nuclear Astrophysics)
  PANDA (Antiproton)

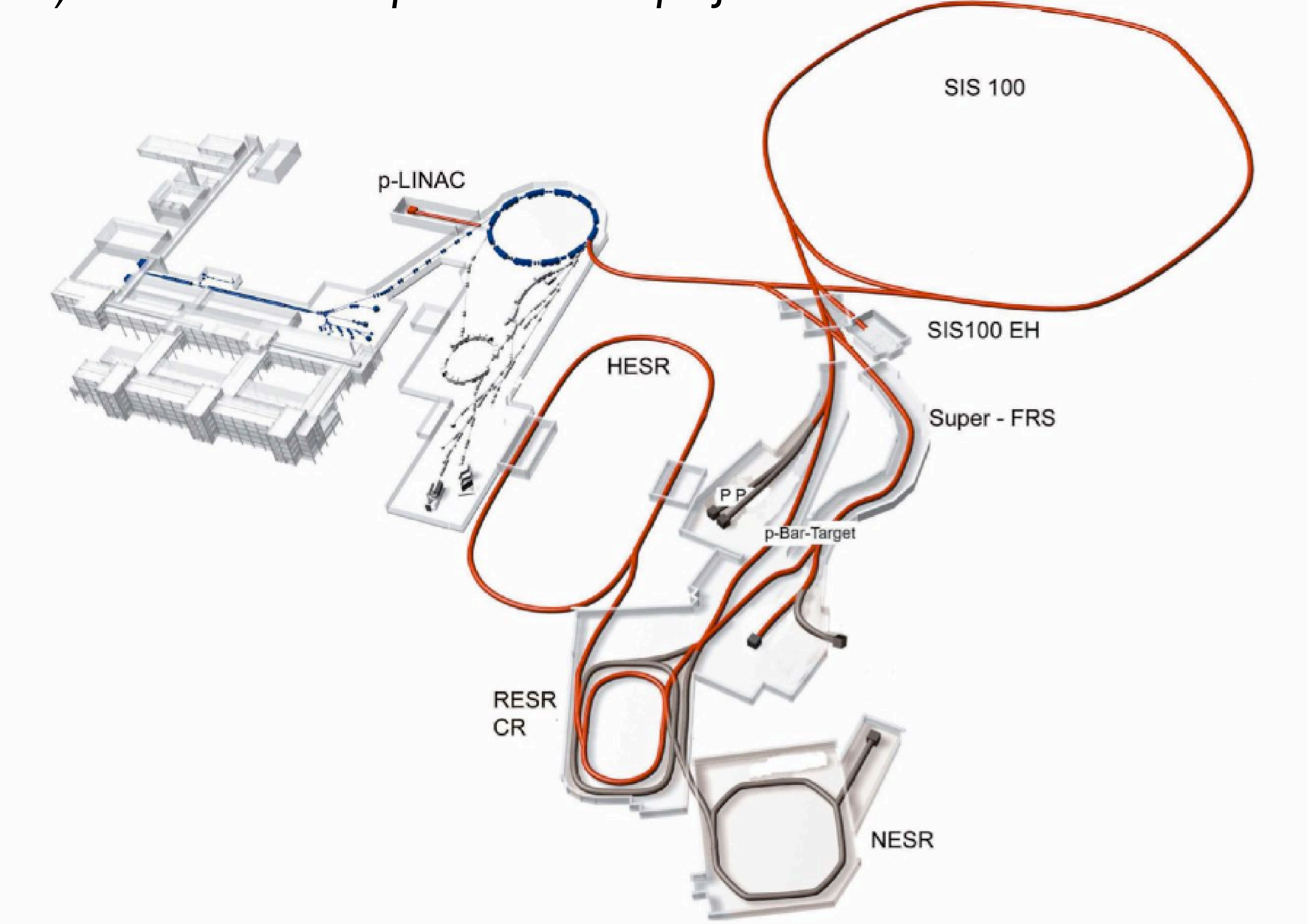
- **Main Accelerator SIS100**
  Ultra-high vacuum under the control with dynamic pressure rise
  Rapid cycling superconducting magnets (4 T/s)
  High RF voltage

- **Advanced Ring technologies**
  CR - fast stochastic cooling and isochronous mass measurements
  NESR - precise mass measurements, e-RI scattering, internal -target experiments

- **Stripper-problem free facility**

- **Construction will be completed in 2015 - 2016**

*GSI (Germany and State Hesse ) and 15 partner countries promote FAIR project.*




*O. Boine-Frankenheim et al.; Proc. of IPAC10, WEYRA01*

*FIAR Baseline Technical Report (March 2006)*
*Green Paper "The Modularized Start Version" (Nov. 2009)*

# FRIB

## *(Facility for Rare Isotope Beams)*

*The power-front in-flight facility*

**Front-end ( < 0.3 MeV/nucleon)**

High-intensity ECR ion source (33+ & 34+, 6 pμA each)

**Driver Linac (Sc-linac)**

Segment 1 ( < 17.5 MeV/nucleon for uranium)

2 types (β = 0.041 & 0.085) of QWRs at 80.5 MHz

14 cryomodule

Charge stripping at 17.5 MeV/nucleon for uranium

Segment 2

2 types (β = 0.285 & 0.53) of HWRs at 322 MHz

31 cryomodule

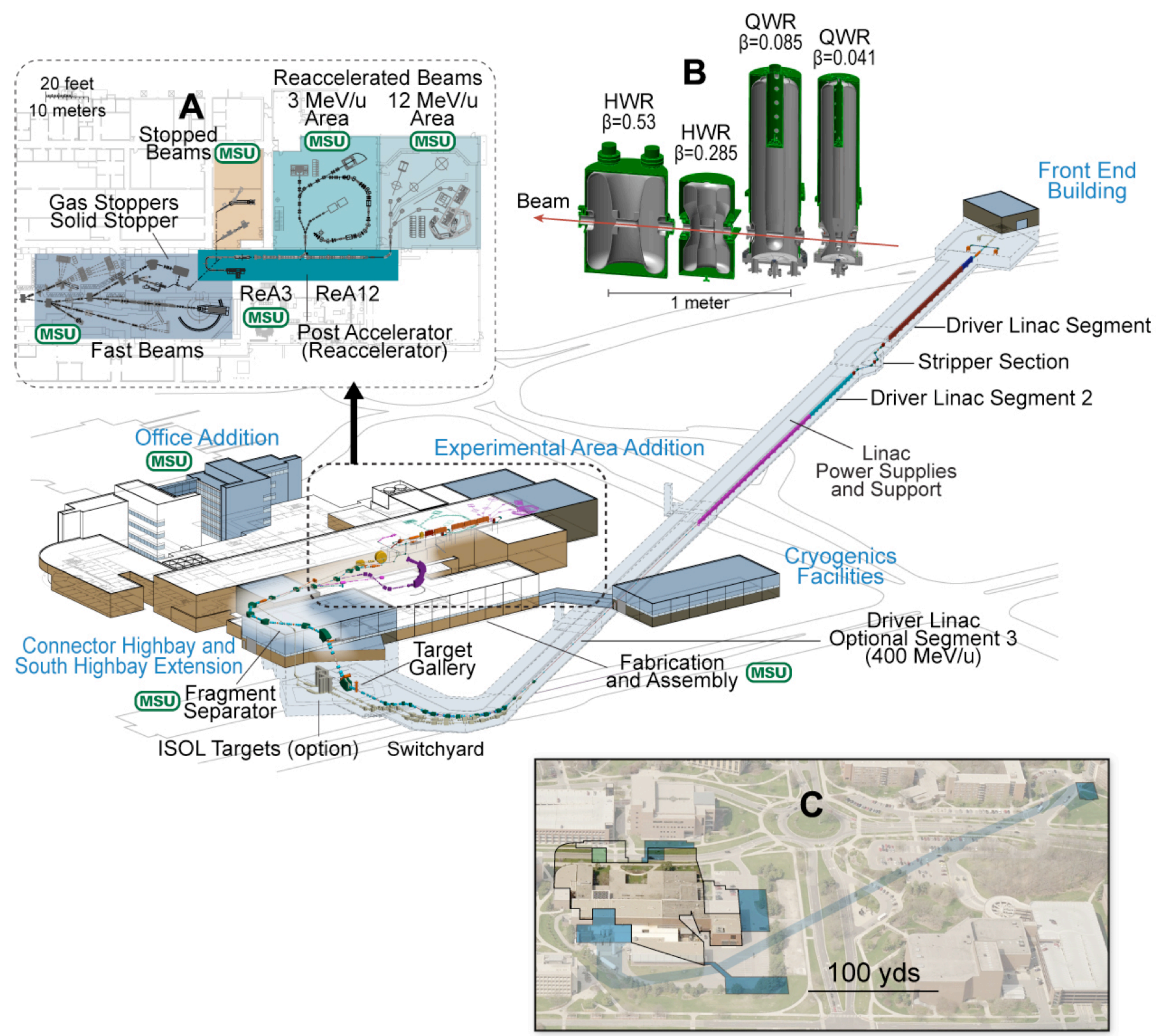
400 kW beam power for all ions

200 MeV/nucleon for uranium → 8 pμA

610 MeV for protons

- High-acceptance & high-resolution 3-stage fragment separator
- MSU contribution

- First beam ~ 2017
- Future upgrade - 400 MeV/nucleon uranium




*R. C. Yoke et al.; Proc. of SRF2009, FR0AAU02*

# RIBF, FRIB, FAIR

| | RIBF | FRIB | FAIR |
|---|---|---|---|
| Energy (MeV/A) | 345 | 200 (400) | 1500 |
| Driver beam intensity (pps) | $1.5\times10^{12}$<br>($6\times10^{12}$, goal) | $5\times10^{13}$ | $2\times10^{11}$ |
| RI beam intensity for very exotic RIs* | 0.11<br>(0.47) | 1<br>(~10, after upgrade) | 0.62 |
| Driver | Cyclotron | SC-linac | Synchrotron |
| Charge stripper | 11 MeV/A<br>50 MeV/A | 17.5 MeV/A | 1.4 MeV/A<br>gas stripper OK |
| pro | •Simple<br>•Compact<br>•Few RF resonators<br>•cost effective CW machine | •Large acceptance<br>•Multi-charge-state acceleration possible<br>•High energy upgrade is straight forward | •High energy<br>•Free from stripper problem<br>•Cooler & storage ring experiments |
| con | •No design universality for large scale cyclotron<br>•Small longitudinal acceptance<br>•Beam loss at extraction is critical | •Not compact<br>•Large cryogenic facility | •Not compact<br>•High vacuum required<br>•Low beam intensity |

*$E^{2.5}$ dependence is assumed, E (MeV/A) - under discussion

# Uranium Beam Intensity

*FRIB vs RIBF*

**RIBF**

two-step charge-stripping scheme is adopted.

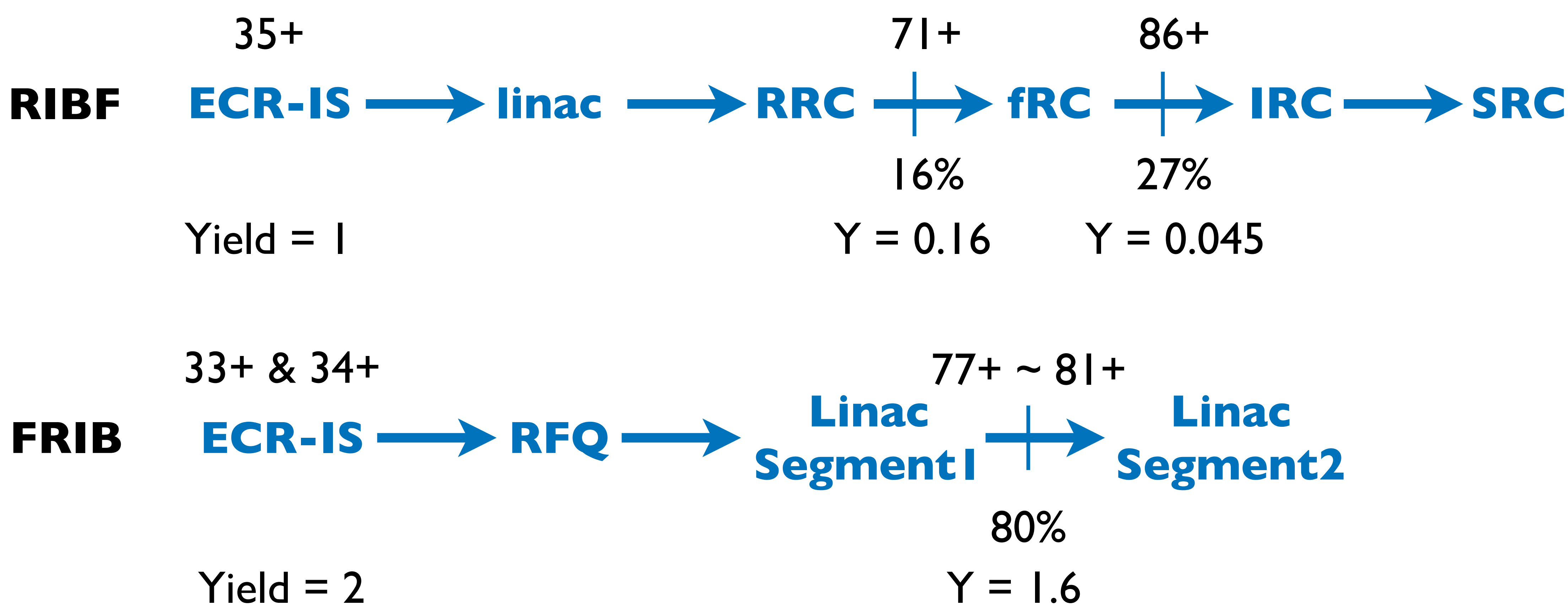
0.27 pμA uranium beam is expected after RILAC2 upgrade.

- 10 pμA $^{238}U^{35+}$ ion at ECR-IS
- 60% transmission efficiency in total (does not include charge stripping efficiency)

**FRIB**

A innovative multi-charge-state acceleration is proposed.

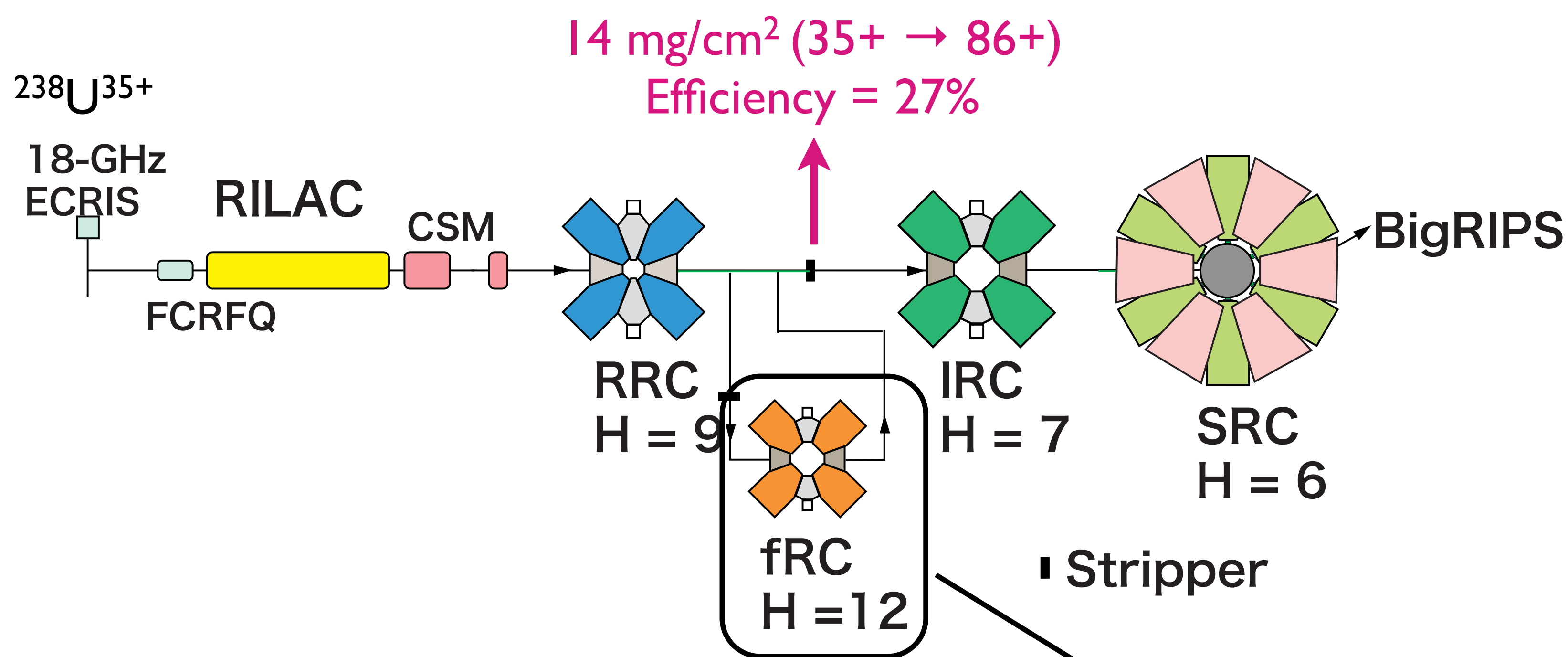
8 pμA uranium beam is expected with 6 pμA each for $^{238}U^{33+}$ and $^{238}U^{34+}$




*From R. C. Yoke et al.; Proc. of SRF2009, FR0AAU02*

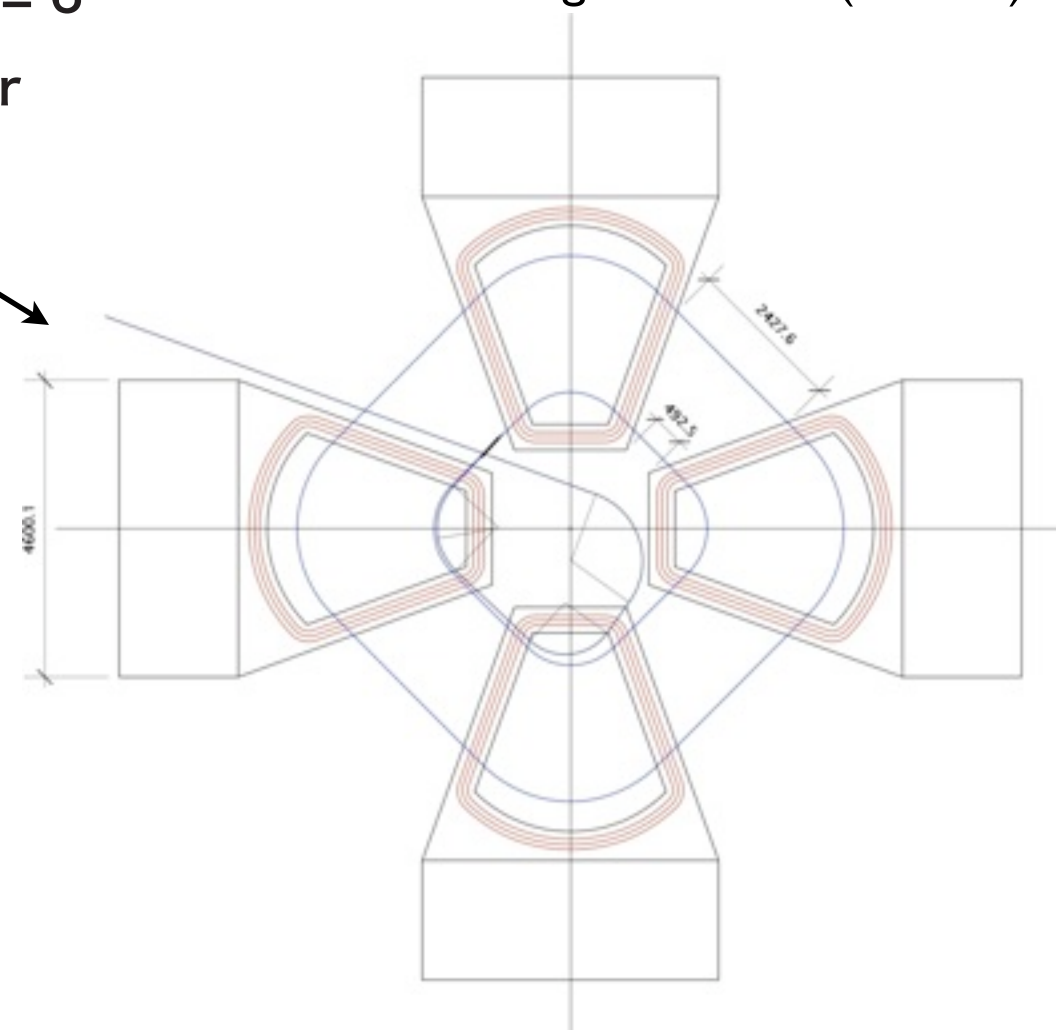
# Intensity upgrade strategy in RIBF

*Introduction of K=2300 MeV superconducting fixed-frequency cyclotron in stead of fRC*




***H=10 conceptual design***

Sector Magnet ~ 3.5 T ( ~ SRC)



**K=2300 MeV Superconducting fRC**

Harmonic number = 10 (challenging)
12 (modest)
Rinj = 2 m / 2.4 m
Rext = 4.05 m / 4.9 m
K = 2300 MeV
Weight = 3300 tons / 5700 tons

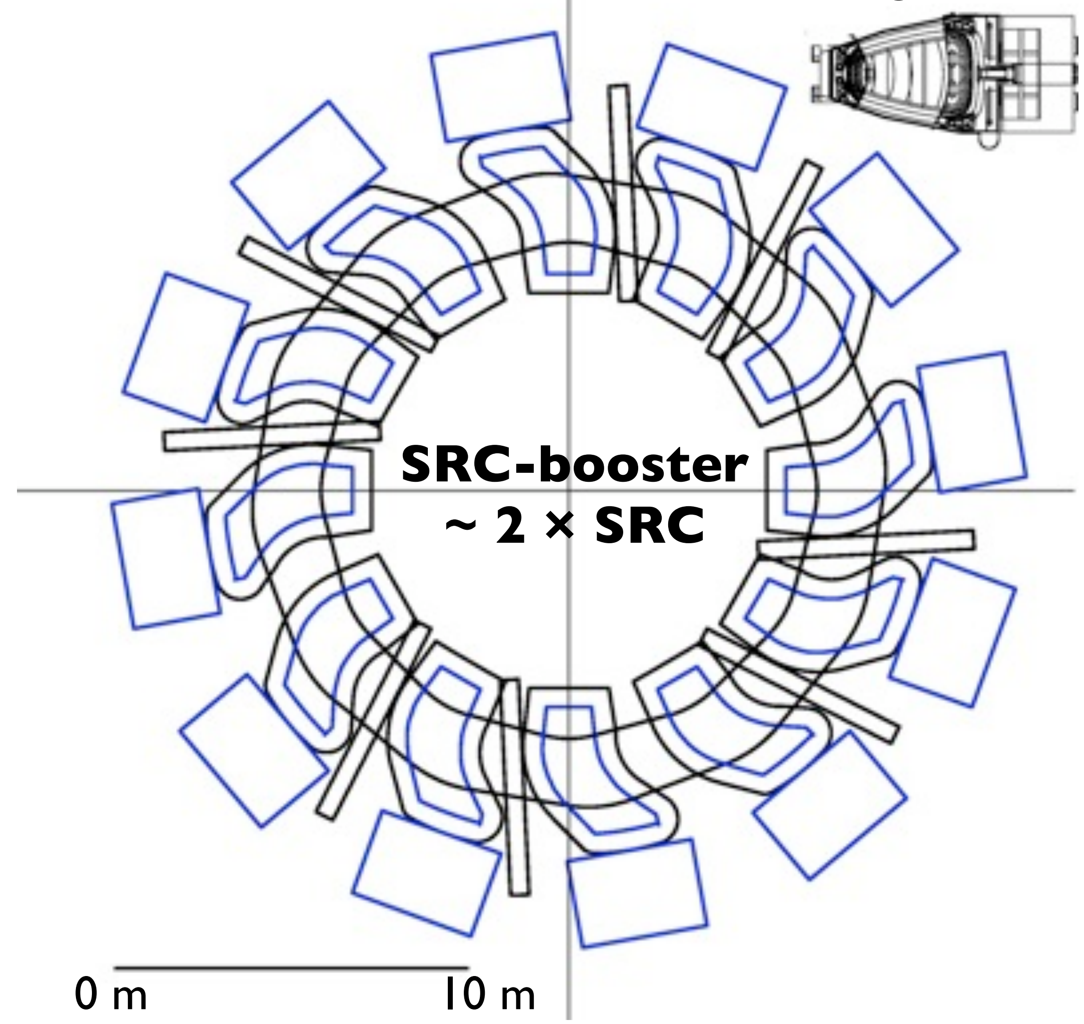
Design of the injection system is very challenging with a small injection radius of 2 m.

# Energy upgrade toward 1 A GeV ?

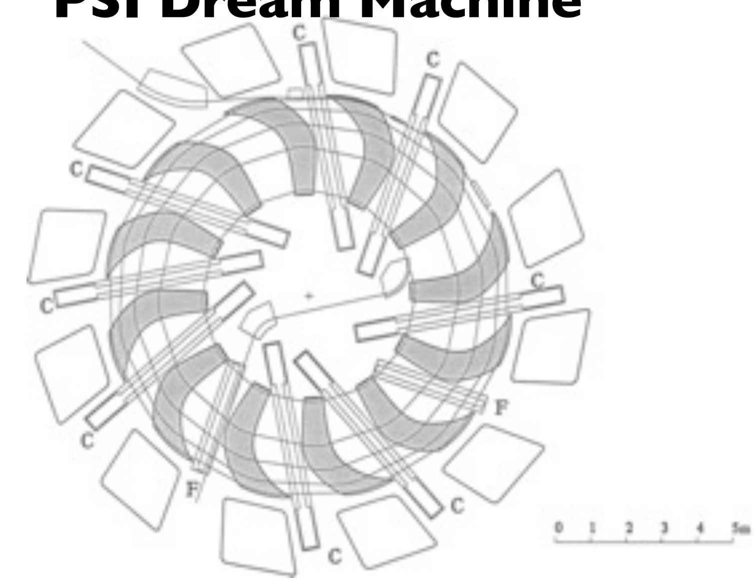
*A geometrical consideration indicates that RIBF Dream Machine is not crazy.*

| | SRC | PSI-DM | SRC-booster |
|---|---|---|---|
| **Eext** | 0.35 A GeV | 1 GeV | 0.9 A GeV |
| **Einj** | 0.12 A GeV | 0.12 GeV | 0.35 A GeV |
| **Magnets** | 6 (3.8 T) | 12 (2.1 T) | 12 (4 T) |
| **Cavity** | 4 (0.6 MV) | 8 (1 MV) | 7 (1 MV) |
| **Rinj** | 3.56 m | 2.9 m | 7.15 m |
| **Rext** | 5.36 m | 5.7 m | 9.0 m |
| **Velocity gain** | 1.5 | 2.0 | 1.26 |
| **Energy gain (extraction)** | 0.8 A MeV | 6.3 MeV | 2.9 A MeV |
| **DR/dn (centering)** | 2.5 mm | 5.6 mm | 4.3 mm |
| **K value** | 2.6 GeV | 1 GeV | 6.9 GeV |
| **Total Acc. Voltage** | 0.64 GeV | 0.88 GeV | 1.54 GeV |

Sector magnet of SRC




**PSI Dream Machine**



Th. Stammbach et al., AIP conf. Proc. 346 (1994) 229.

# Summary

## Radioactive Isotope beam facilities worldwide

- *RI beam intensities obtained by the first-generation RI beam facilities are not sufficient to access nuclei far from the stability of the nuclear chart.*
- *Many next-generation RIB facilities are under construction and planned including both ISOL and in-flight facilities.*
- *SC-linacs will be widely used for these new facilities.*
- *Activities of Asian countries in this research field has been increasing.*

## RIBF

- *Design goal intensity was established for light ions (He and O)*
- *$^{48}$Ca - 23% of design goal*
- *Uranium beam intensities should be increased.*
  *A new injector RILAC2 will be commissioned in 2010.*
  *Very-short life time of charge stripper is another important issue.*
- *Reliability has been improved.*

## Next generation in-flight facilities (FRIB and FAIR)

- *RI beam intensities expected in FRIB and FAIR are higher than RIBF.*

*Intensity-upgrade and/or energy-upgrade of RIBF is necessary.*