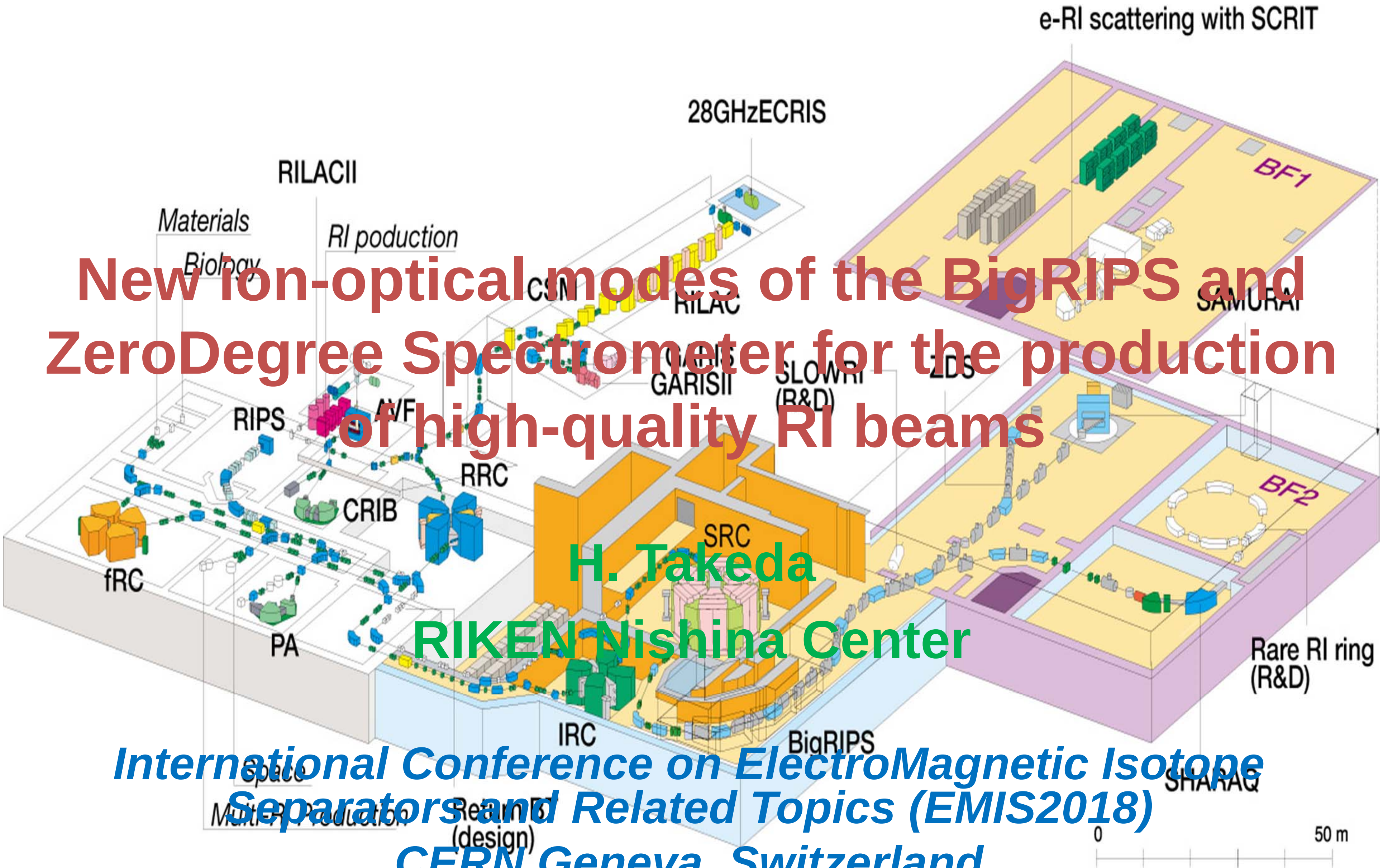
New ion-optical modes of the BigRIPS and ZeroDegree Spectrometer for the production of high-quality RI beams



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RIKEN Nishina Center

International Conference on ElectroMagnetic Isotope Separators and Related Topics (EMIS2018)

CERN Geneva, Switzerland

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Outline

- **Introduction**
  - **RIBF / BigRIPS / ZeroDegree**
  - **BigRIPS standard optics mode**
- **Development of new optics modes**
  - **Additive mode**

    (H. Takeda[1], T. Kubo[2], N. Fukuda[1], H. Suzuki[1], H. Geissel[3], E. Haettner[3] Y. Tanaka[3], Y. Shimizu[1], D. S. Ahn[1], T. Sumikama[1], N. Inabe[1])
  - **High resolution Ddouble mode**

    (H. Suzuki[1], T. Kubo[2], N. Fukuda[1], T. Sumikama[1], H. Takeda[1], Y. Shimizu[1], D. S. Ahn[1], N. Inabe[1])
  - **High resolving power in F0-F2 and F3-F7 for additive / subtractive modes**

    (E. Haettner[3], Y. Tanaka[3], H. Geissel[3], H. Takeda[1], H. Suzuki[1], T. Kubo[2], B. Franczak[3])
  - **Dispersion-matched ion-optical systems for BigRIPS-ZeroDegree**

    (Y. Tanaka[3], H. Geissel[3], T. Kubo[2], H. Takeda[1])
  - **Dispersion-matched ion-optical systems for SRC-F0-F5**

    (Y. Tanaka[3], T. Nishi[1], H. Geissel[3], T. Kubo[2], K. Itahashi[1], H. Takeda[1], H. Suzuki[1])
- **Summary**

[1]RIKEN Nishina Center, [2]FRIB/NSCL, MSU, [3]GSI

Features of RIBF/BigRIPS/ZeroDegree

<u>BigRIPS separator</u>

1) Large acceptances

Comparable with angular / momentum spreads of in-flight fission (100 mrad / 10%)

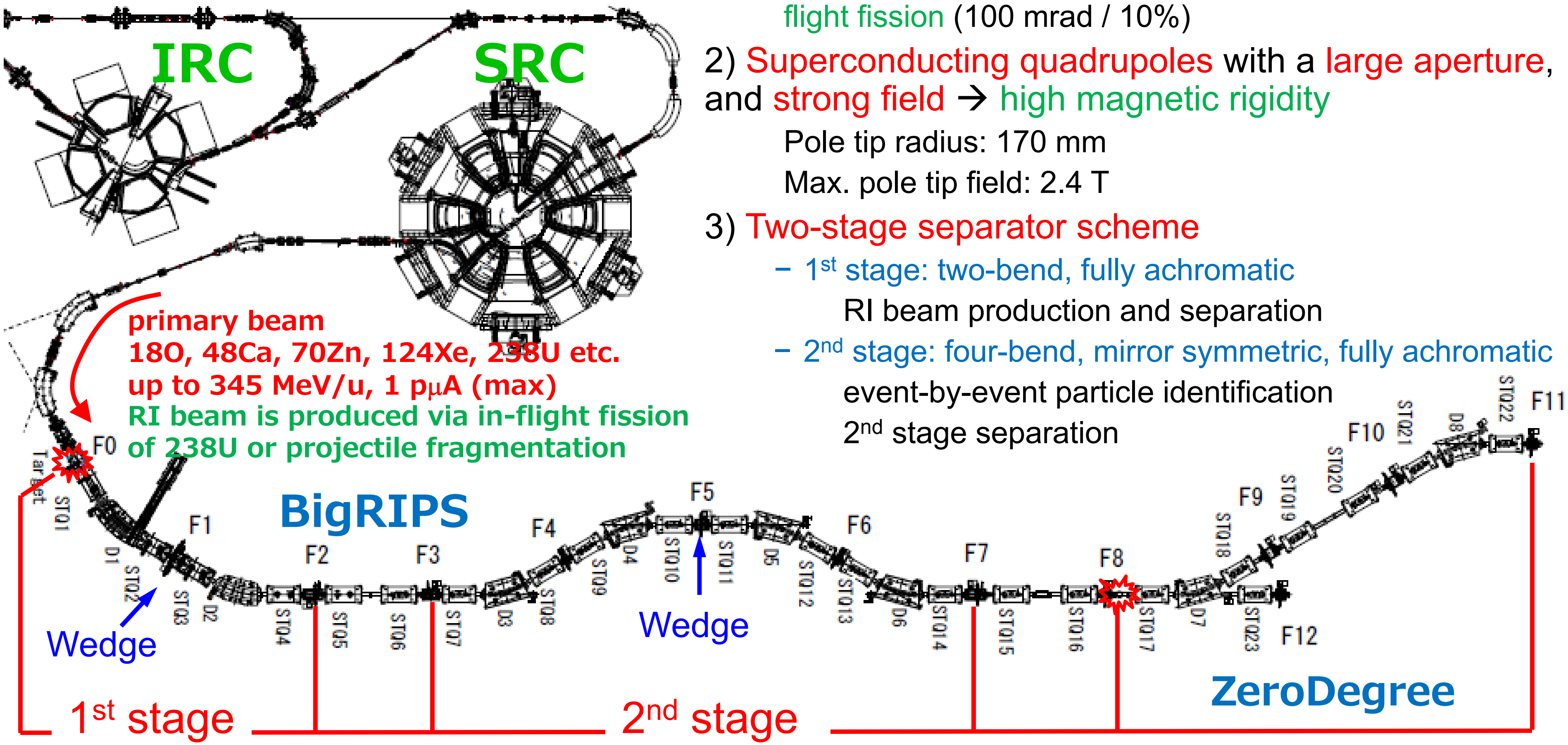
2) Superconducting quadrupoles with a large aperture, and strong field → high magnetic rigidity

Pole tip radius: 170 mm

Max. pole tip field: 2.4 T

3) Two-stage separator scheme

- 1st stage: two-bend, fully achromatic
  RI beam production and separation
- 2nd stage: four-bend, mirror symmetric, fully achromatic
  event-by-event particle identification
  2nd stage separation



Production & separation

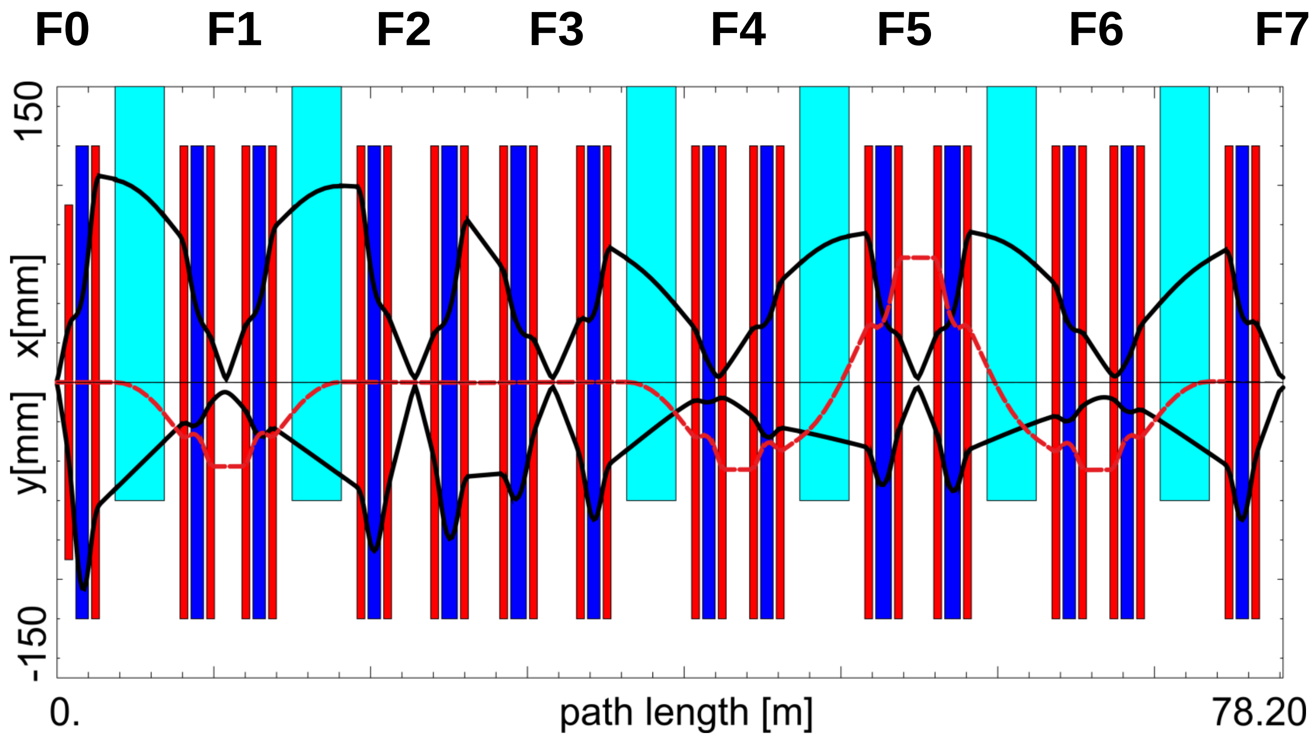
Matching section

Particle identification & 2nd-stage separation

Matching section

two-bend, anti-mirror sym.
flexibility to be operated in both achromatic and dispersive modes

BigRIPS standard optics mode



acceptance
θ=±40mrad
ϕ=±50mrad
δ=±3%
P/ΔP=
1260 (F0-F1)
3440 (F3-F5)
(Δx=1 mm)
max Bρ=
9.5Tm (F0-F2)
8.8Tm (F3-F7)
total length=78.2m

T. Kubo, Nucl. Instr. Meth. Phys. Res. B 204, 97 (2003)
T. Kubo et al., Prog. Theor. Exp. Phys. 2012, 03C003 (2012)

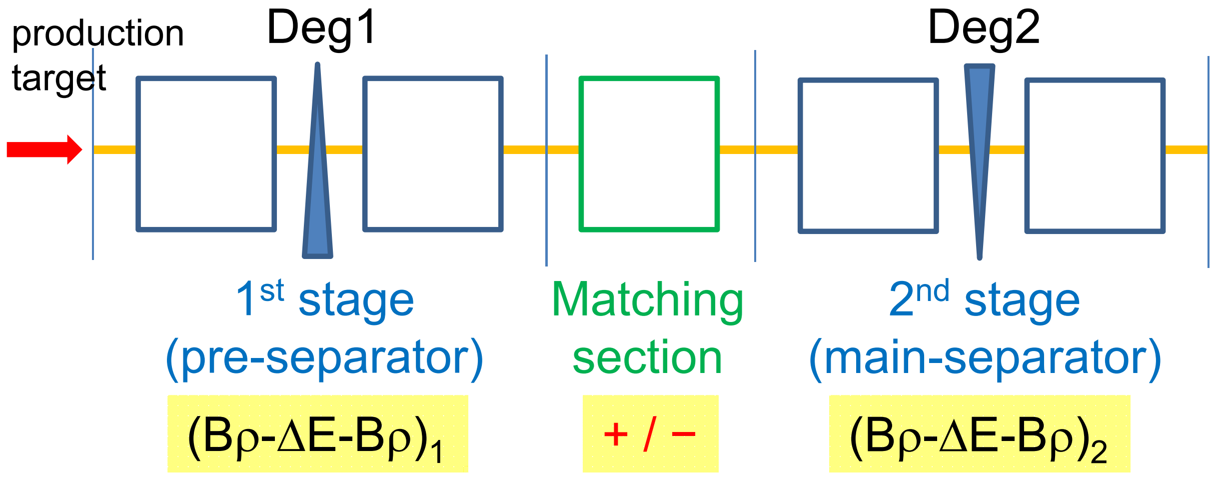
BigRIPS is a very powerful and versatile in-flight fragment separator.
Ion-optical mode combined with ZeroDegree and/or primary beam line can be flexibly modified from the standard one according to the experimental requirements.

→ Various new modes are developed and reported.

Development of new optics modes

Additive mode

Two-stage Bρ-ΔE-Bρ separation
- additive and subtractive modes -



Total mass dispersion

$$(x|m)_{07} = \underline{(x|x)_{23}(x|x)_{37}}(x|m)_{02} + (x|m)_{37}$$

$$\begin{cases} \text{Additive :} & (x|m)_{07} = +(x|m)_{02} + (x|m)_{37} \\ \text{Subtractive :} & (x|m)_{07} = -(x|m)_{02} + (x|m)_{37} \end{cases}$$

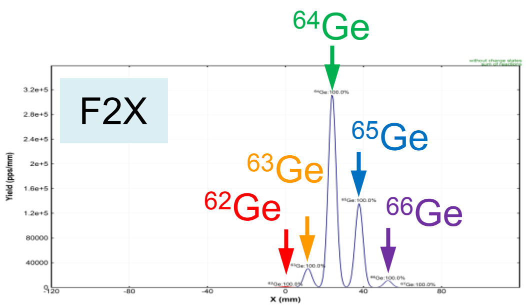
BigRIPS standard mode: $(x|x)_{23} = -1$, $(x|x)_{37} = +1$ → subtractive

Two stages act independently and the isotopic separation power of the two stages can be added or subtracted by changing the sign of the magnification of the matching section depending on the experimental requirements.

(T. Kubo et al., Prog. Theor. Exp. Phys. 2012, 03C003 (2012))

Action of additive & subtractive modes

Setting:
^{78}Kr 345 MeV/u + Be 10 mm
^{62}Ge center
$B\rho_{01}$=4.7381 Tm
F1 deg. Al 4 mm (d/R = 0.353)
F5 deg. Al 0 ~ 4 mm (d/R = 0 ~ 0.560)



LISE++ simulation

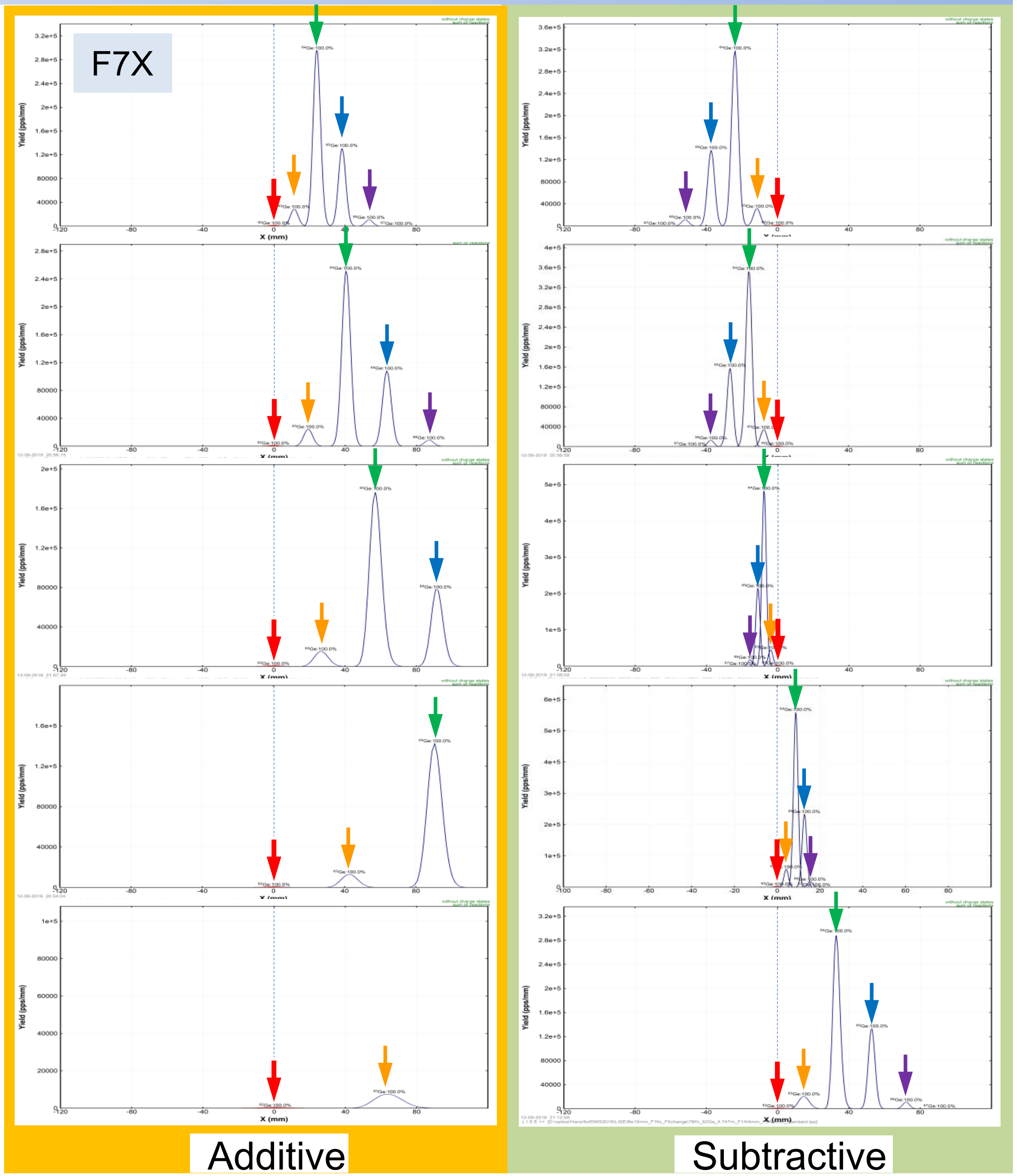
F5 deg. none

F5 deg. Al 1 mm

F5 deg. Al 2 mm

F5 deg. Al 3 mm

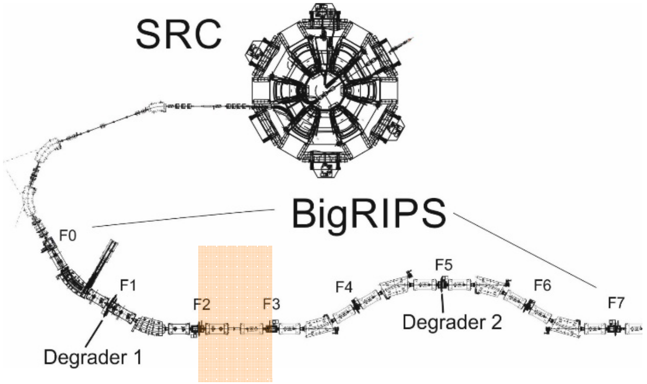
F5 deg. Al 4 mm

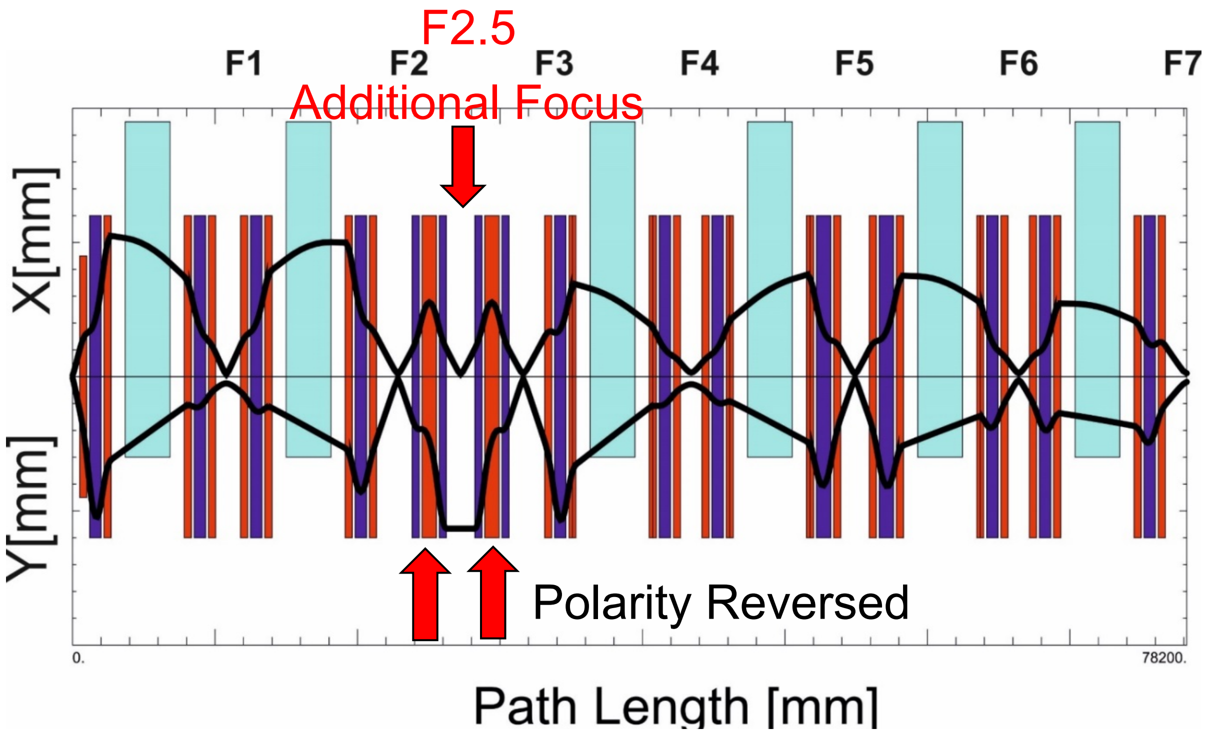


Development of the additive mode

The additive mode can be realized by changing sign of $(x|x)_{23}$

- For this purpose, we added one focus in X direction in between F2 and F3.
  - Optics of F0F2 and F3F7 are the same as the standard mode.
- We needed to change polarities of STQs in F2F3 section to reduce excitation currents.

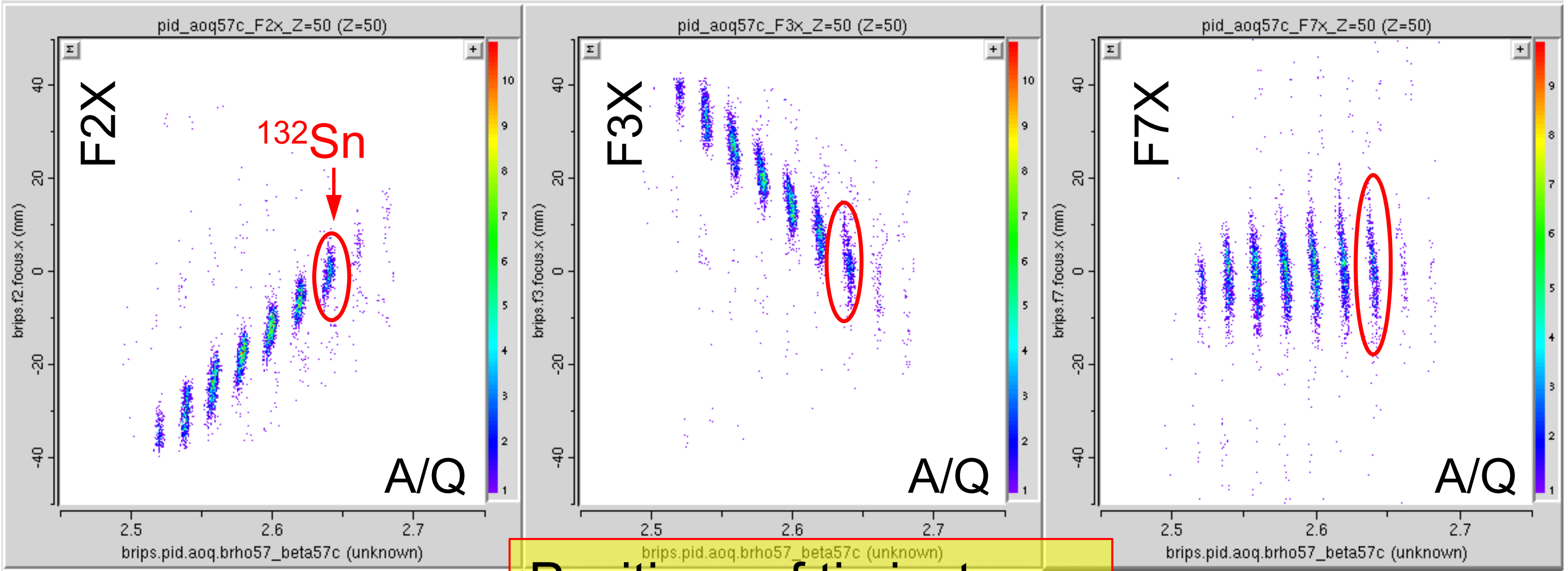




^{132}Sn test experiment

^{238}U 345 MeV/u + Be 5 mm, $B\rho_{01}$=7.1 Tm, ^{132}Sn center
F1 deg. Al 5 mm (d/R=0.38), F5 deg. Al 3 mm (d/R=0.37)

Subtractive mode

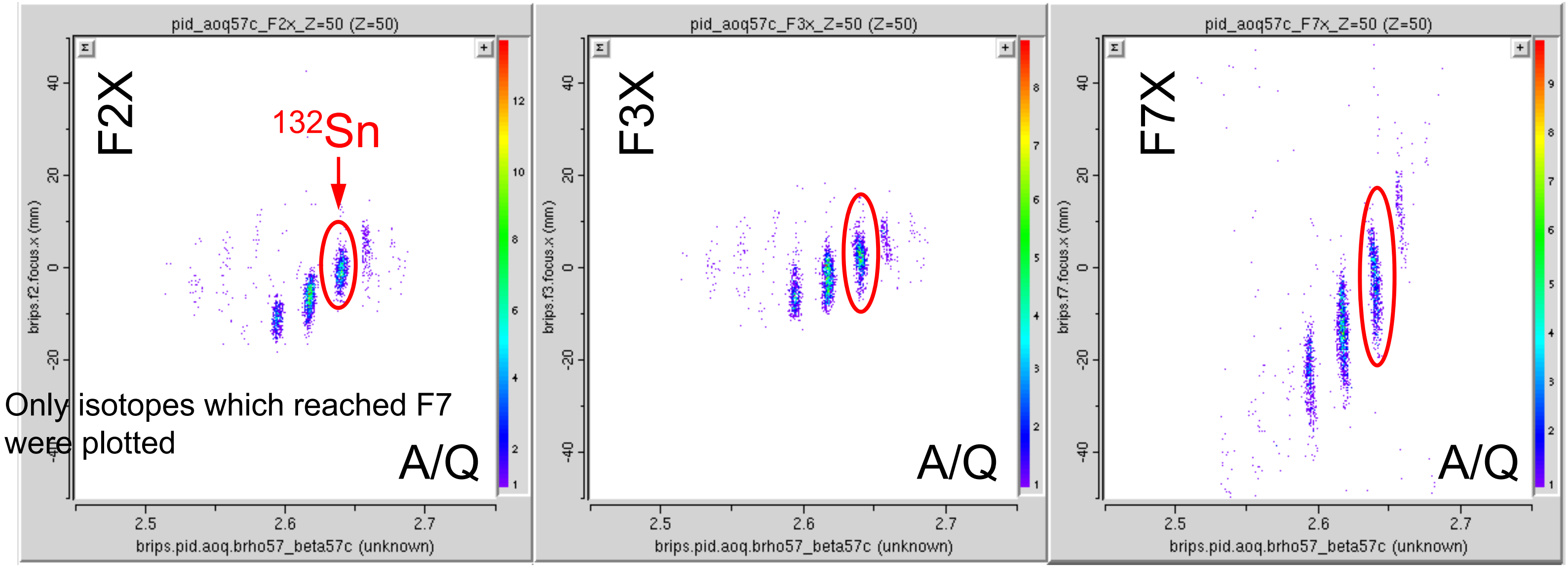


Mass dispersion
[mm / ΔA]
EXP. (LISE)
F2: 5.82 (6.05)
F3: -6.33 (-6.41)
F7: 0.23 (-0.71)

A/Q res. 0.05%
(1st order only)

Positions of tin isotopes

Additive mode



Only isotopes which reached F7 were plotted

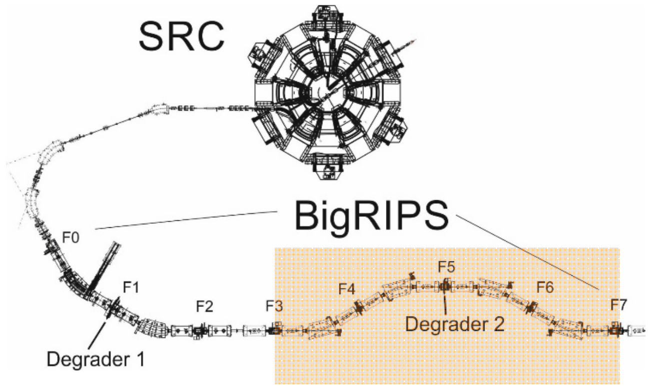
Mass dispersion
[mm / ΔA]
EXP. (LISE)
F2: 5.54 (6.05)
F3: 4.72 (6.11)
F7: 12.1 (18.5)

A/Q res. 0.06%
(1st order only)

High-resolution modes

High resolution Ddouble mode

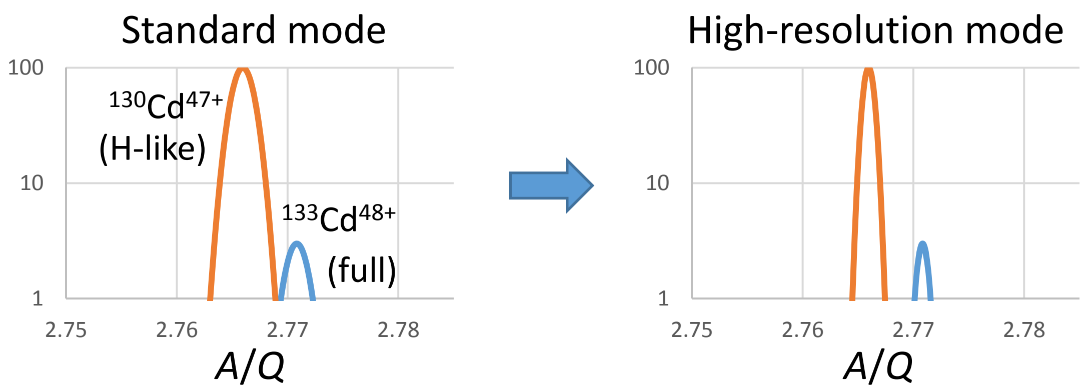
- Purpose: To improve the momentum resolution at the 2^{nd} stage
  - High-*Z* region (*Z* ~ 70,80,…)
    - Many charge state (full, H-like, He-like, Li-like, …) are produced.
  - Separation of mid-heavy very-neutron-rich nuclei
    - *A*/*Q* values of fully-stripped $^{A}Z^{Z+}$ nuclide and hydrogen-like $^{A-3}Z^{(Z-1)+}$ contaminants are close, where *A*/*Z* value is close to 3.



Resolution: $R \propto \dfrac{D}{M \cdot \Delta x}$ (D: dispersion, M: magnification)

→In the high-resolution mode, the D value is doubled (D-double mode)
($P/\Delta P$ = 3420 → 6840, Δx_{F3}=1 mm is assumed)

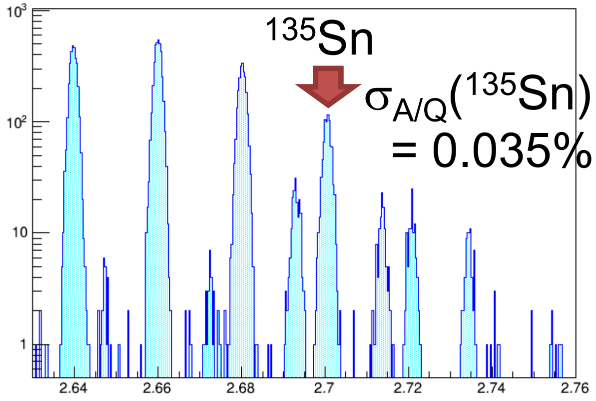
Ex) Separation of $^{A}Z^{Z+}$ and $^{A-3}Z^{(Z-1)+}$



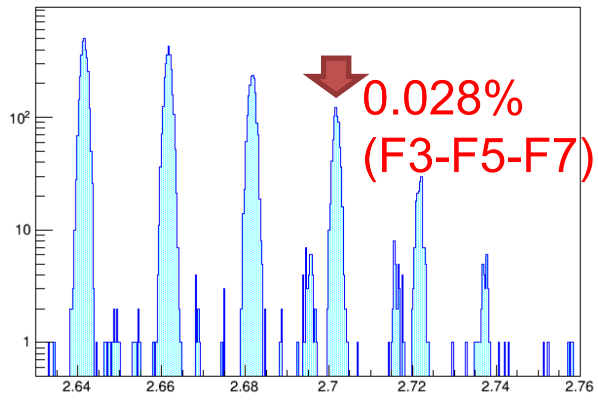
^{136}Sn test experiment

A/Q resolution

Standard



D-double

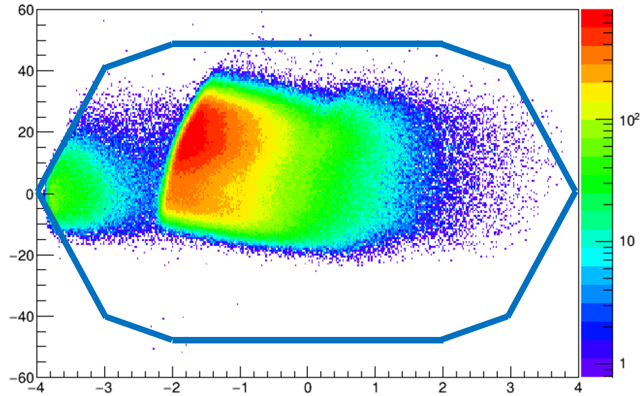


Resolution was not halved due to TOF resolution.
It was improved up to 0.020% by using ZeroDegree in addition.
(TOF resolution is doubled)

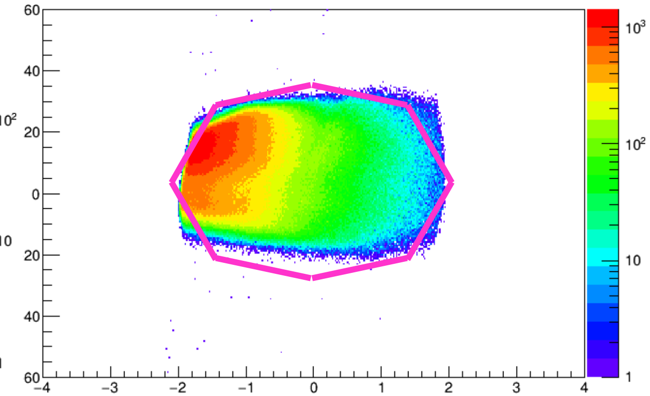
Momentum and angular acceptance

- Beam spreads are cut by the acceptances of each mode (*Z* = 48-54 nuclei)

F0A [mrad]* Standard



D-double



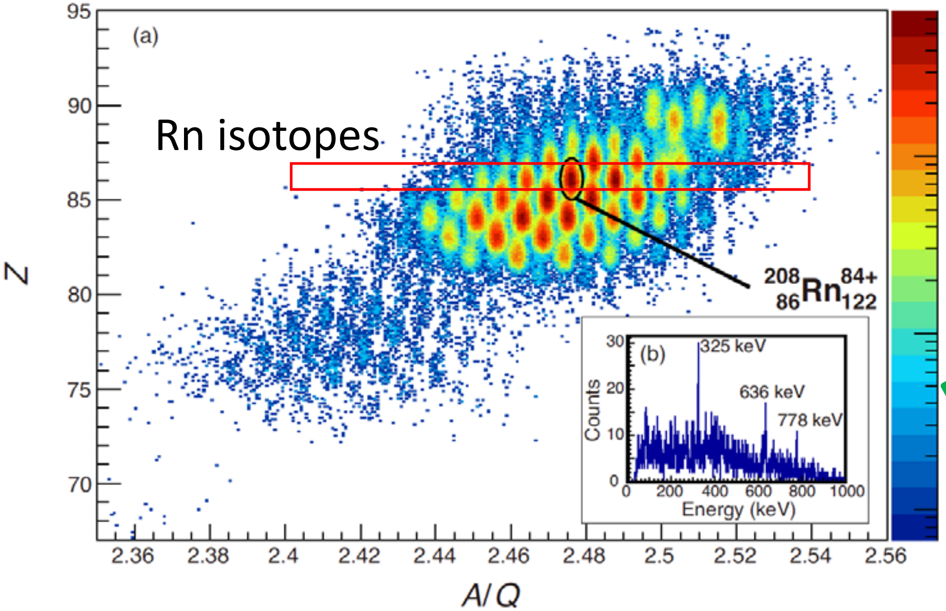
Momentum [%]

* F0A = F3A / 0.465

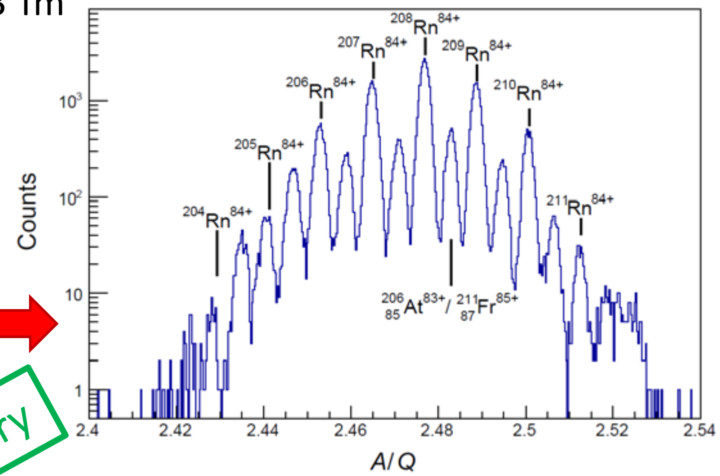
High-Z test experiment

→ T. Sumikama's poster in this conference.

- Settings
  - Center particle: $^{208}_{86}Rn^{84+,86+,84+,84+}$
  - Target: 3 mm, F1deg: 2 mm, F5deg: 1 mm
  - Bρ01: 6.475 Tm, Bρ12: 5.571 Tm, Bρ35: 5.634 Tm, Bρ57: 5.083 Tm
  - F1: +/-0.70%, F2: +/-10 mm, F5: +/-0.63%, F7: +/-30 mm

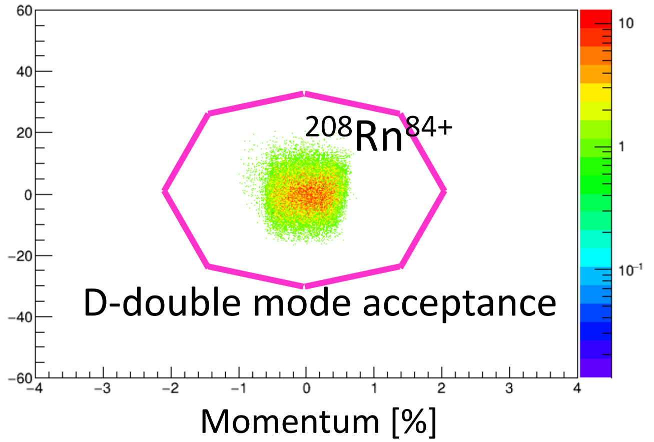


Rn isotope



Preliminary

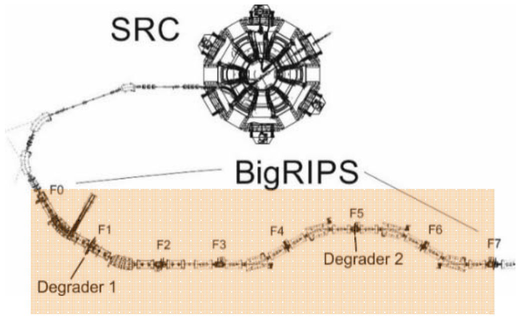
F0A [mrad] (F3A/0.465)



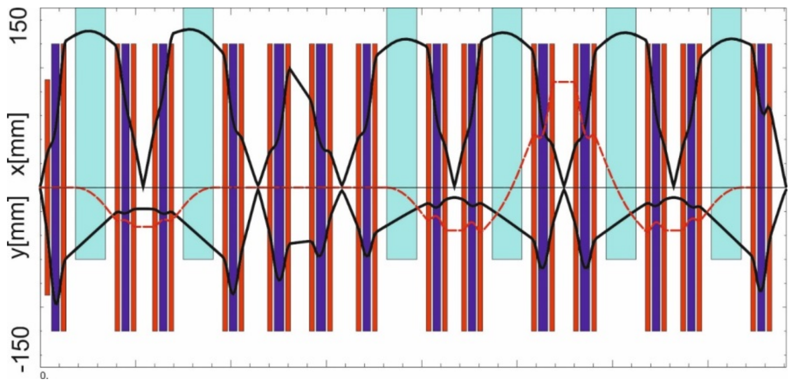
- Many charge states are observed. The D-double mode helps the separation of nuclei.

High resolving power modes

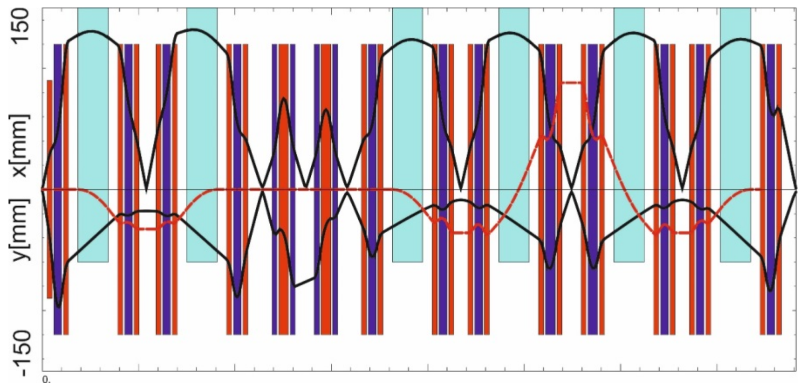
Resolving power of the first stage is also increased with the goals of lower background and better PID



for subtractive mode



for additive mode



Resolving Powers for both modes at : F1= 1690, F5=3272, x0=1 mm

or comparison Standard F1= 1260, F5=1677

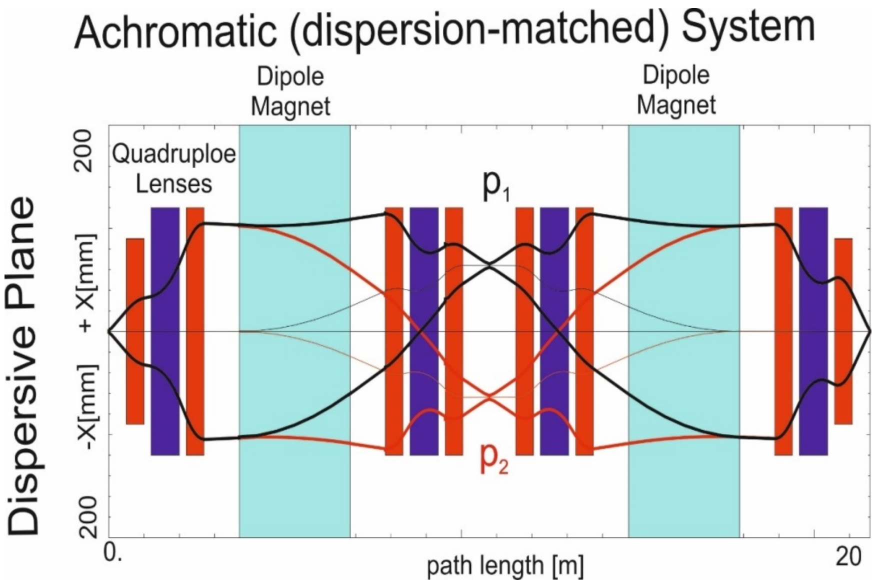
First simulations demonstrate that for fully ionized fragments the contaminants can be reduced by more than a factor of 3 for the additive mode with the increased resolving powers.

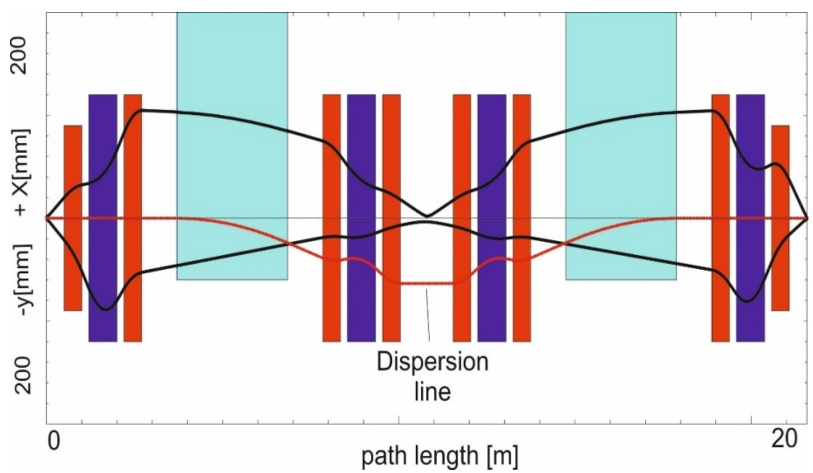
The work is in progress and will be applied to higher elements whereby the charge-state population causes additional difficulties for identification and background.

Dispersion-matched ion optical systems

Principle of dispersion-matched ion-optical systems

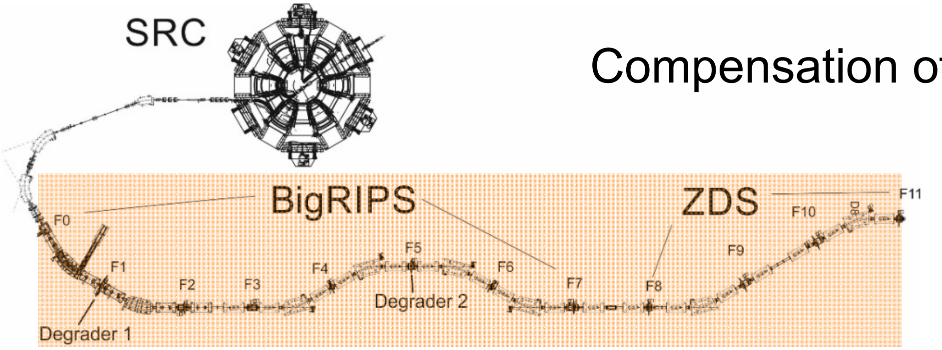
- **Precision spectrometer experiments can be limited by the relative large phase space (momentum spread) of the accelerator beam or by the inevitable large emittance of rare isotope beams.**
- **Solutions are operating modes with achromatic systems, where the incident emittance is canceled in the momentum measurement at the final focal plane (position measurement)**
- **Resolution can be up to limit of the resolving power of the spectrometer despite of the momentum spread of the beam.**

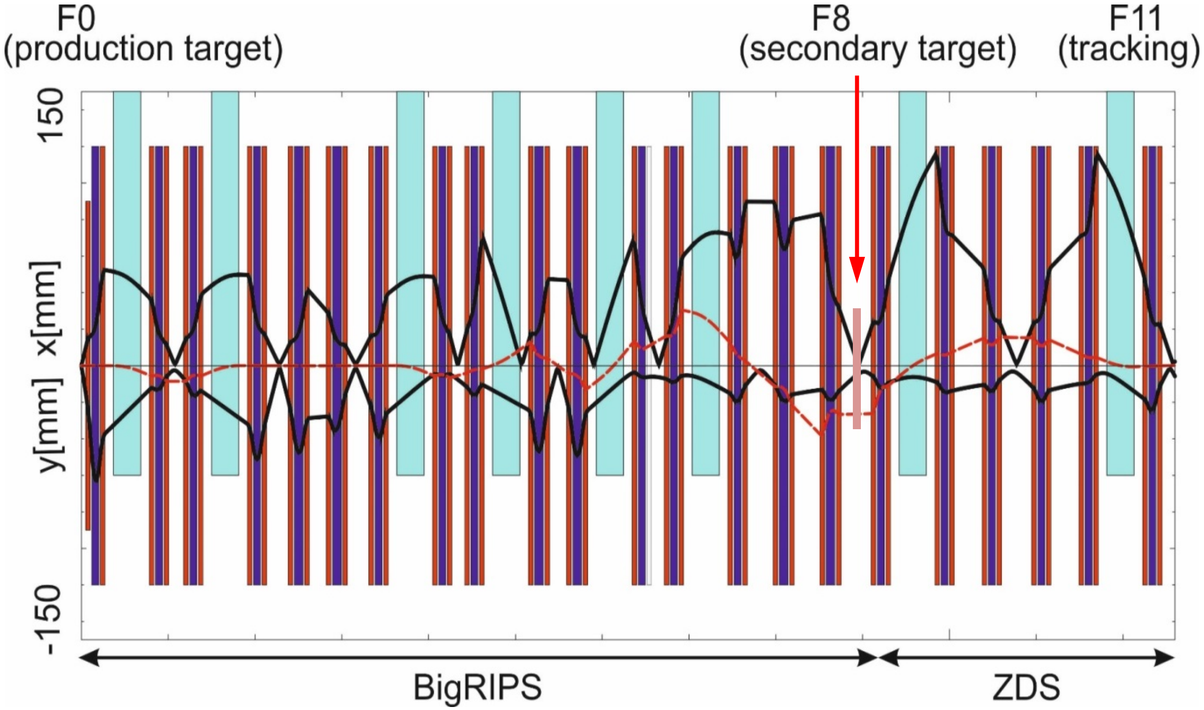




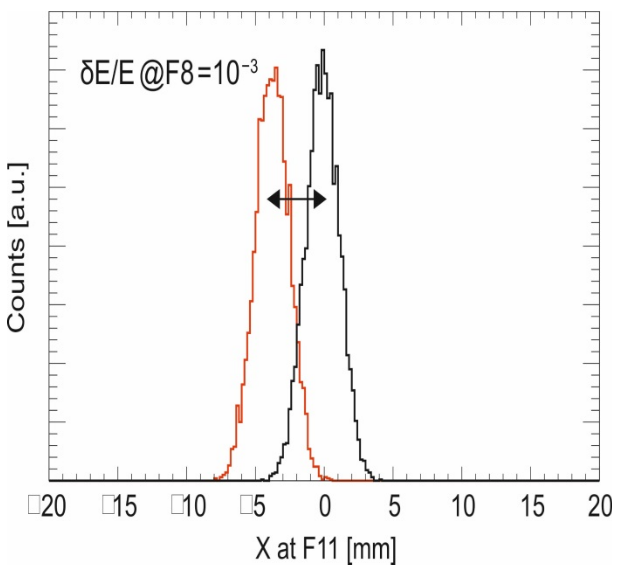
Dispersion-matched BigRIPS-ZeroDegree

Compensation of the momentum spread of RI beams



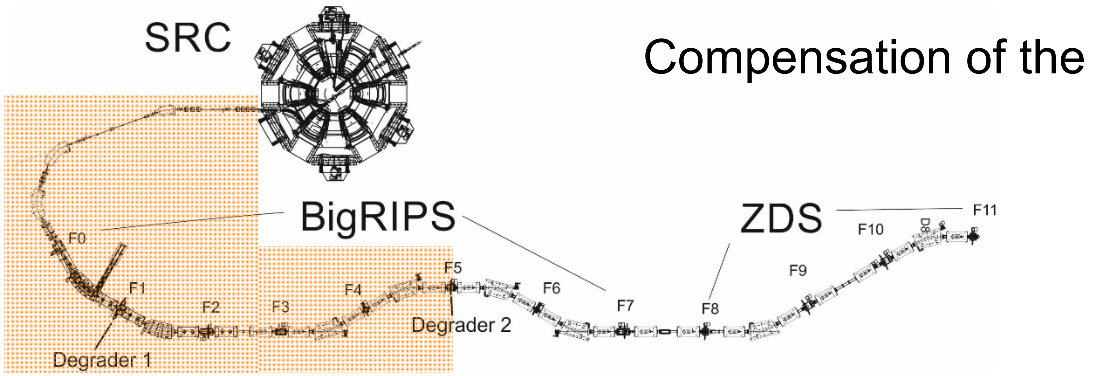


simulation

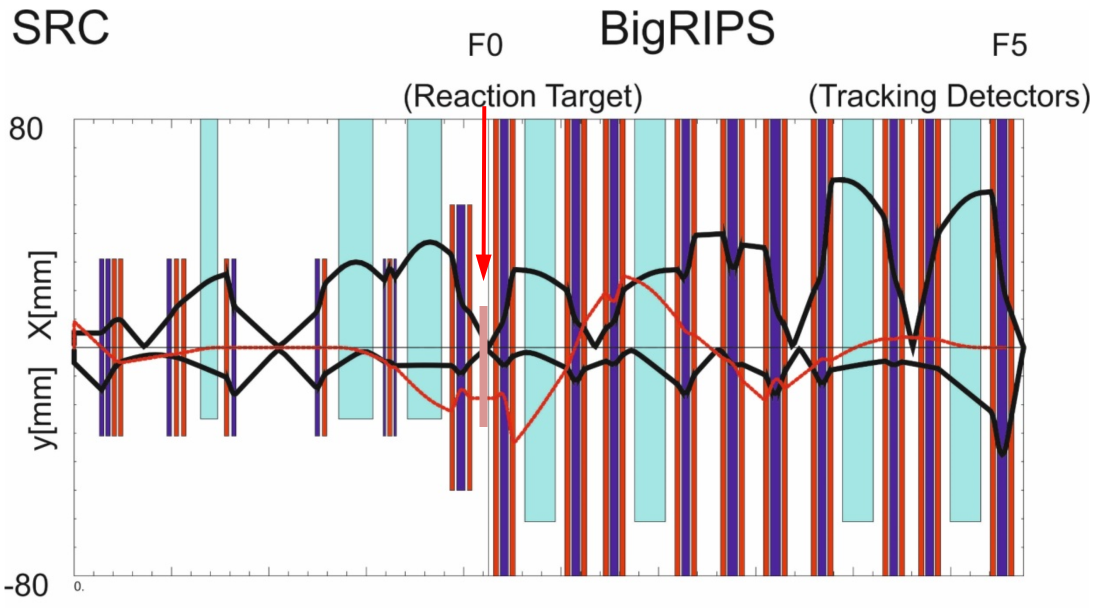


Despite of an incident RI beam momentum spread of a few x10^{-2}, the system can resolve 1*10^{-3}

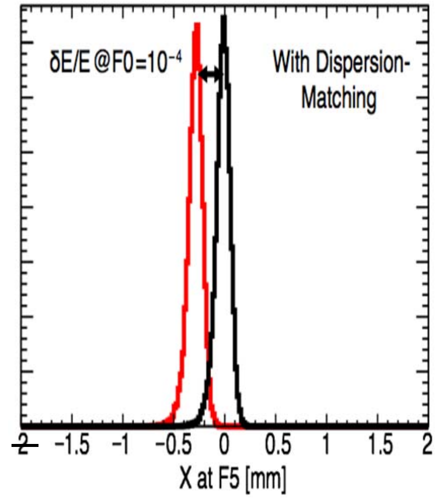
Dispersion-matched SRC-BigRIPS (F0-F5)

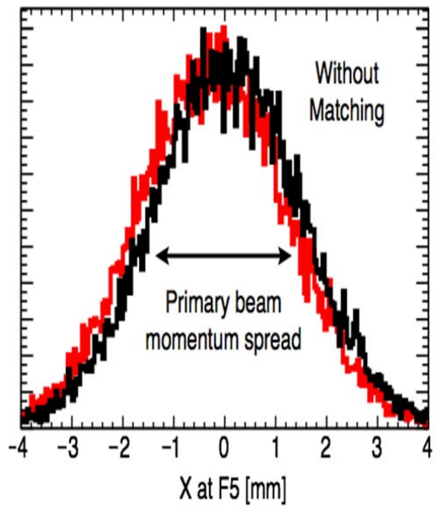


Compensation of the SRC momentum spread



simulation





- Momentum resolving power is several x 10^4
- Despite of a primary beam momentum spread of 10^{-3}, the system can resolve $\delta E/E=1*10^{-4}$ in the target at F0

Summary

- **The powerful in-flight separator BigRIPS represents also a high-resolution spectrometer.**
- **BigRIPS is a very versatile fragment separator to be tuned flexibly depending on the experimental requirements. Various new modes are developed and reported.**
  - ✓ Additive mode was developed and tested. Mass dispersion was well reproduced, showing the uniqueness of the BigRIPS which can switch the additive and subtractive modes of the two-stage separation.
  - ✓ High resolution Ddouble mode was developed and tested. A/Q resolution was improved up to the limitation of TOF resolution. It was successfully applied to the High-Z machine study.
  - ✓ First simulations show the reduced background obtained with the High-resolving power modes compared to standard resolving powers.
  - ✓ High-resolution experiment are possible with dispersion-matched SRC-BigRIPS and BigRIPS-ZDS facilities despite of the incident relative large phase space.

Thank you for your attention!