Recent developments at in-flight facilities

Christoph Scheidenberger

GSI and JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

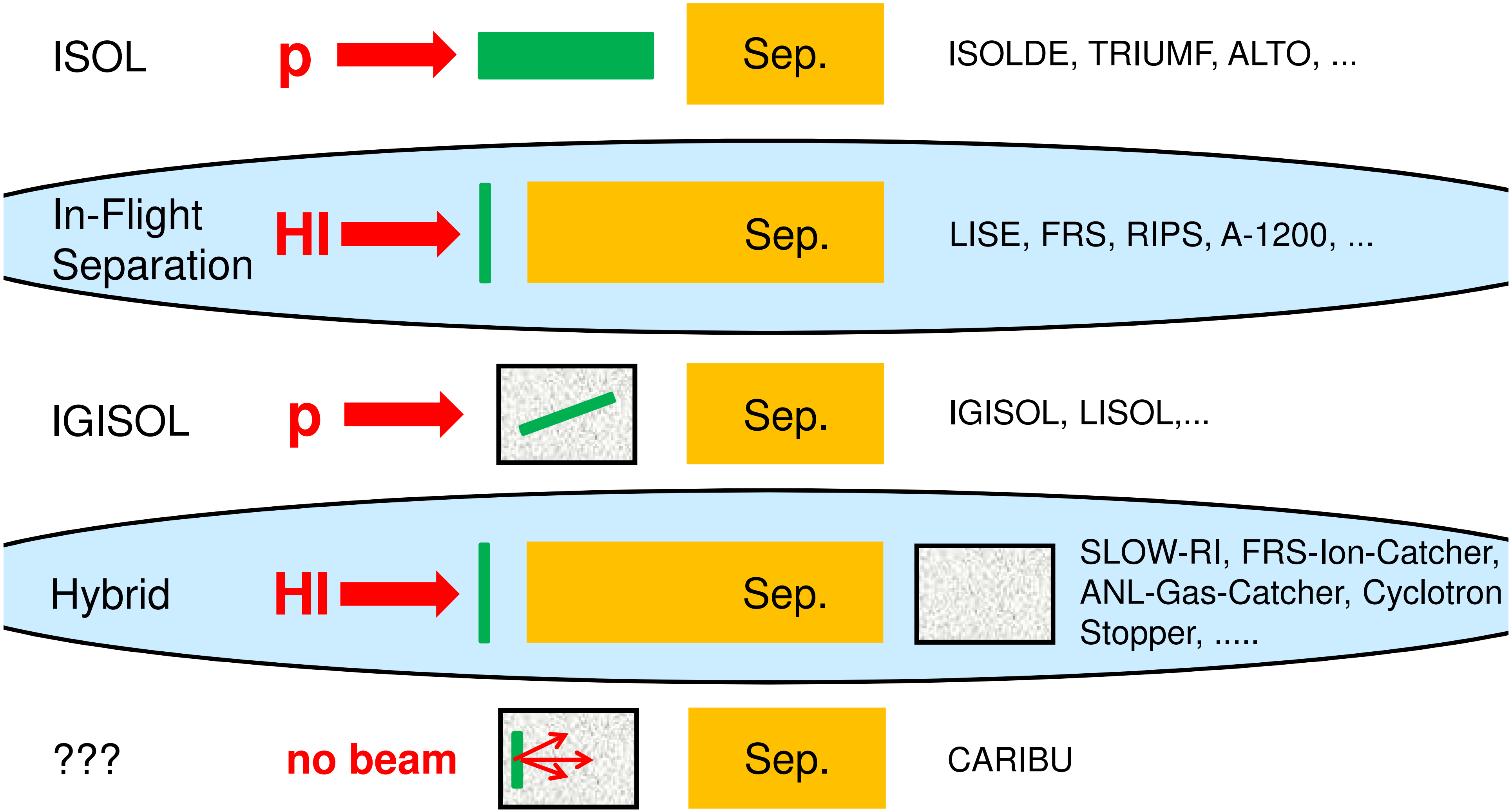
In-flight separators world-wide

Evolution towards **multiple-stage and high-resolution** systems

Storage rings, stopping cells, hybrid systems

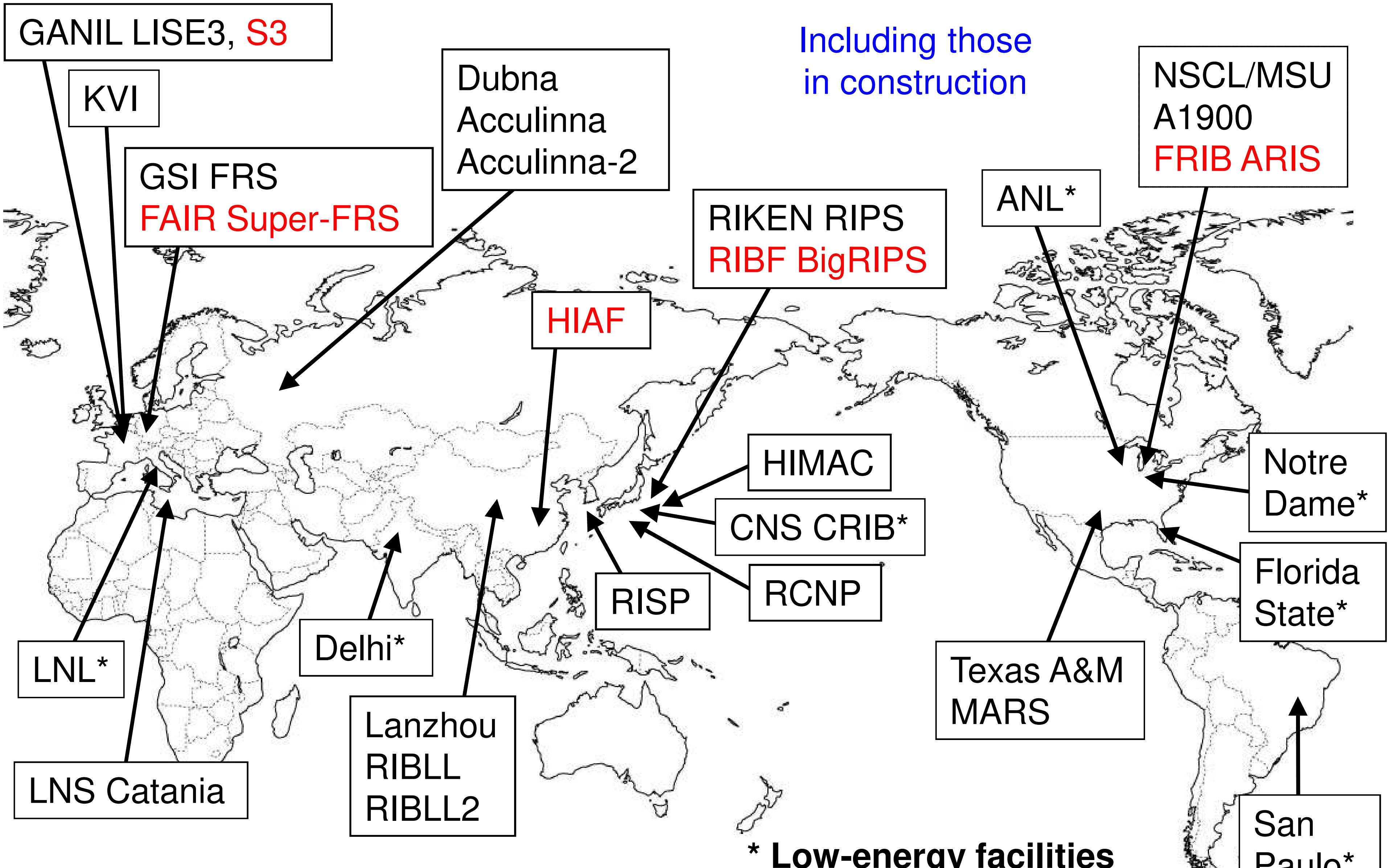
Future directions and new experiments

Exotic nuclei: ISOL, in-flight separation, and more...



Proceedings of ARIS-2014 conference
CSch, JPS Conf. Proc. 6, 010027 (2015)

World map of in-flight (radioactive) beam facilities

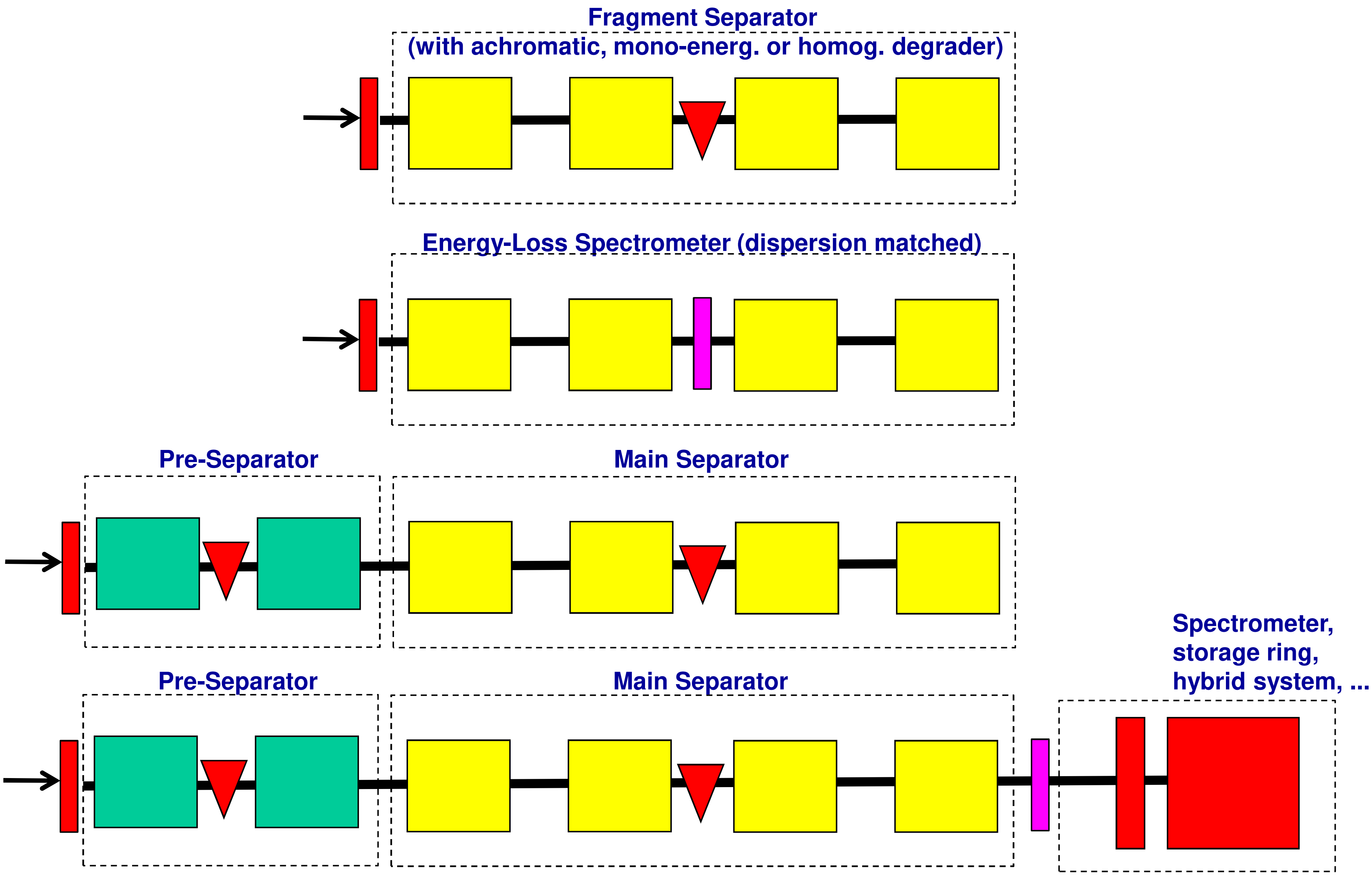


Adapted from: T. Kubo

*** Low-energy facilities**

Multiple-stage systems

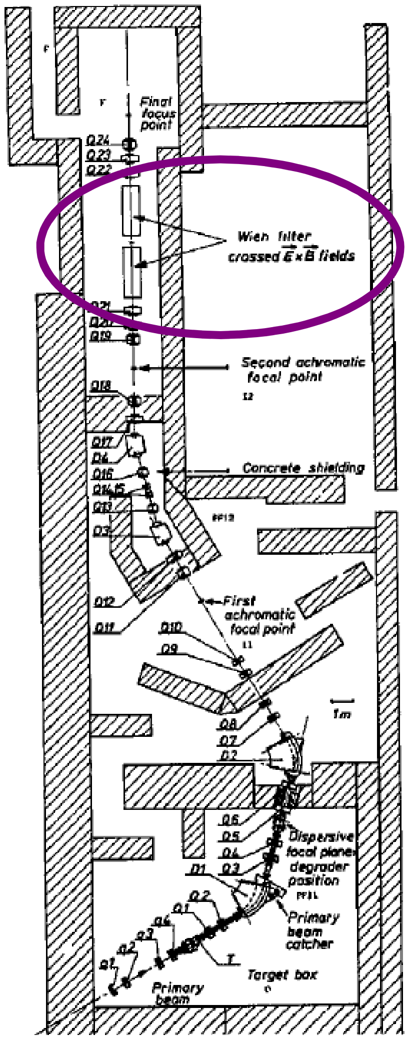
Outline of the talk



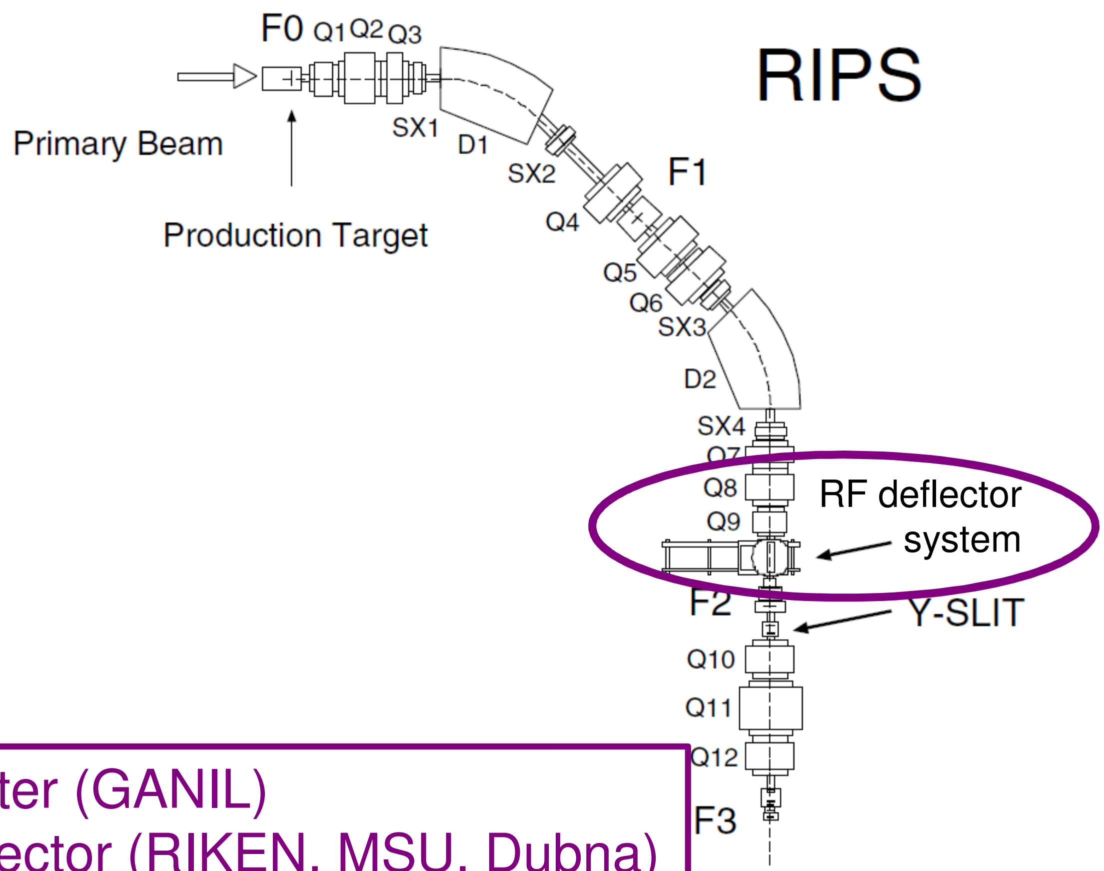
First-generation in-flight separators

Low-energy fragmentation facilities

Large relative velocity spread δv/v induced by fragmentation reaction
→ Bρ-ΔE-Bρ method not sufficient:
→ Isotopic separation needs additional velocity analysis/separation

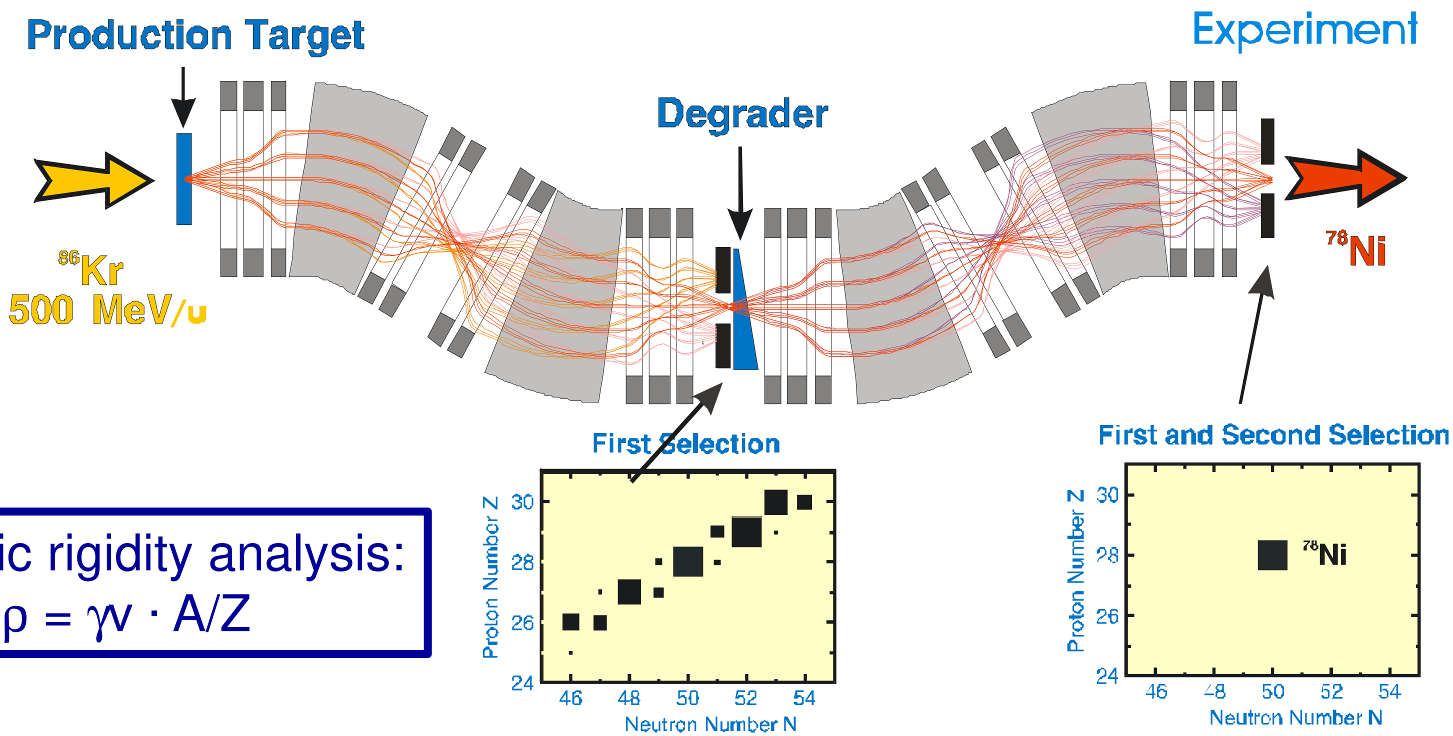


LISE3



→ Wien filter (GANIL)
→ RF deflector (RIKEN, MSU, Dubna)

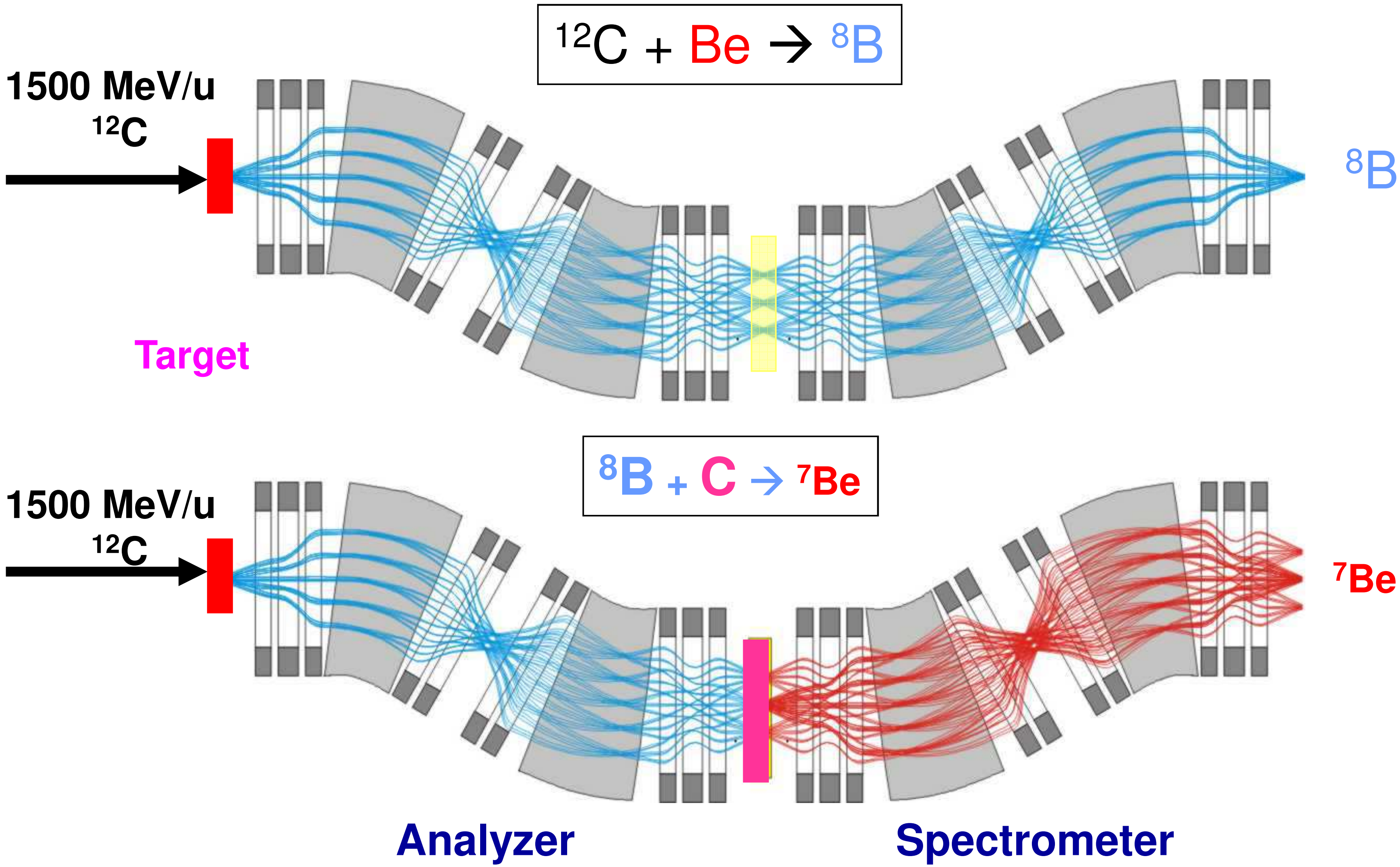
Separation principle: Bρ-ΔE-Bρ method



Magnetic rigidity analysis:
$B\rho = \gamma v \cdot A/Z$

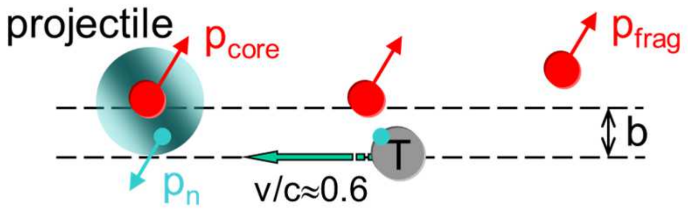
$V_{Fragment} \sim V_{Projectile}$ ⟶ $A/Z \sim$ const. ⟶ Magnetic-rigidity analysis of energy loss yields single isotope !

Important asset for precision measurements: dispersion matching

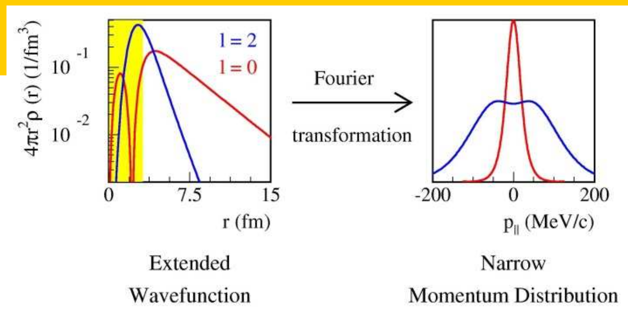


Other examples: **SPEG, Grand-RAIDEN, SHARAQ, S-800, ...**

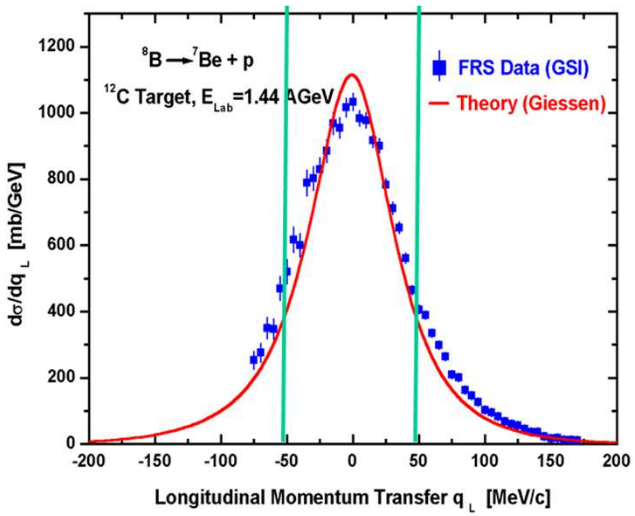
Spectroscopy by knock-out reactions



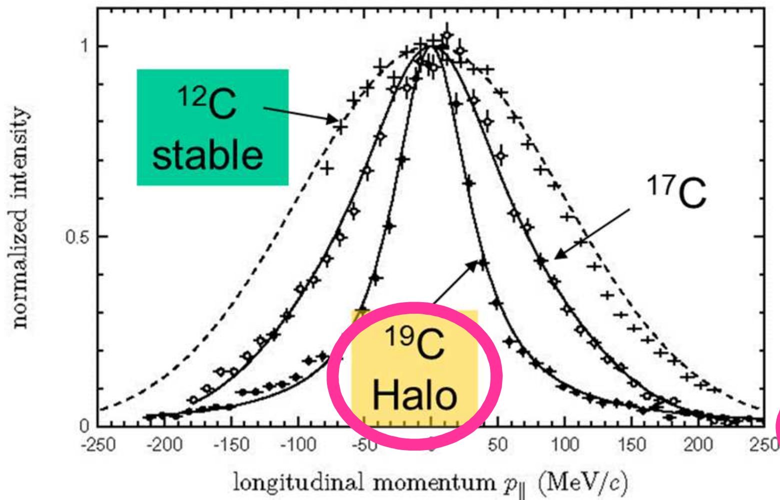
Sudden process
Reaction: $\Delta t \approx 10^{-22}$ s
Internal motion: $\approx 10^{-21}$ s

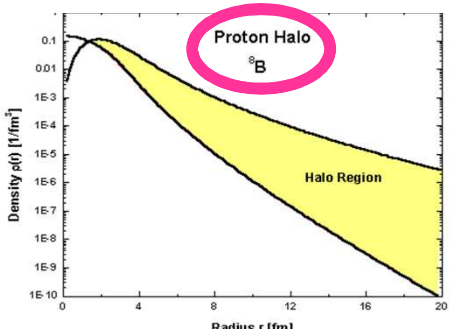


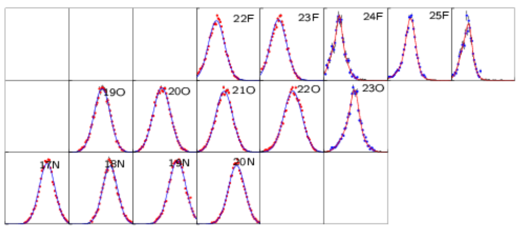
1.4 GeV/u $^{8}B \rightarrow C$



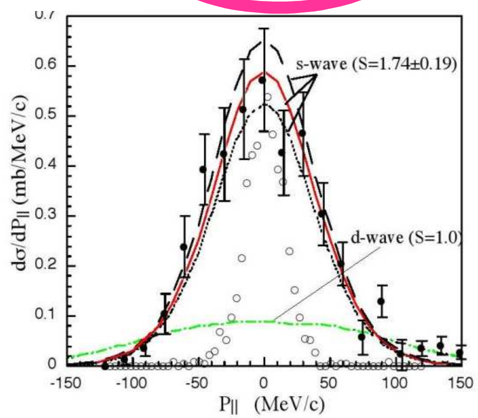
900 MeV/u $^{A}C + C \rightarrow {}^{A-1}C + x$







Shell closure in ^{24}O

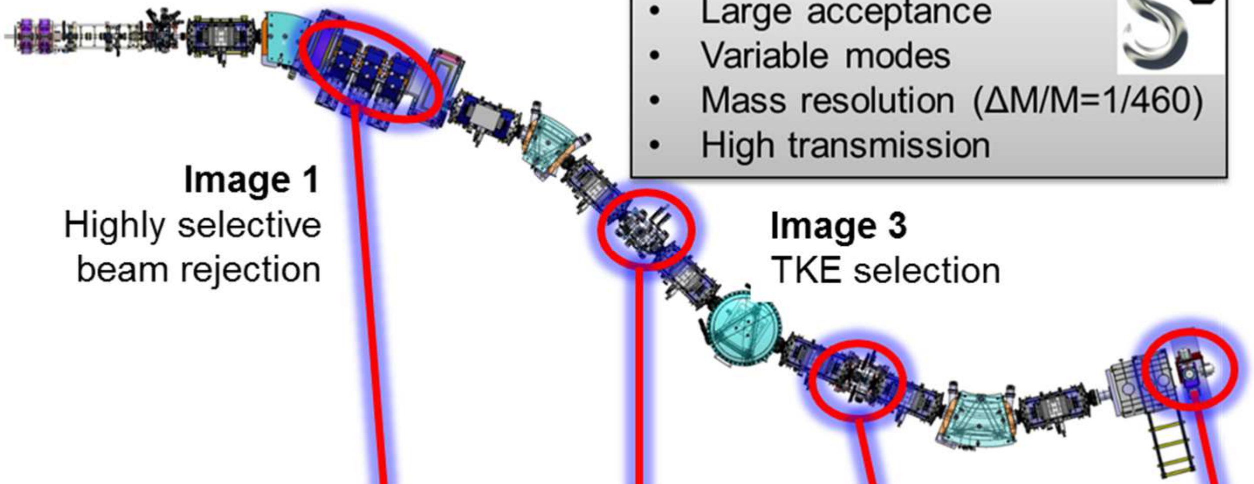


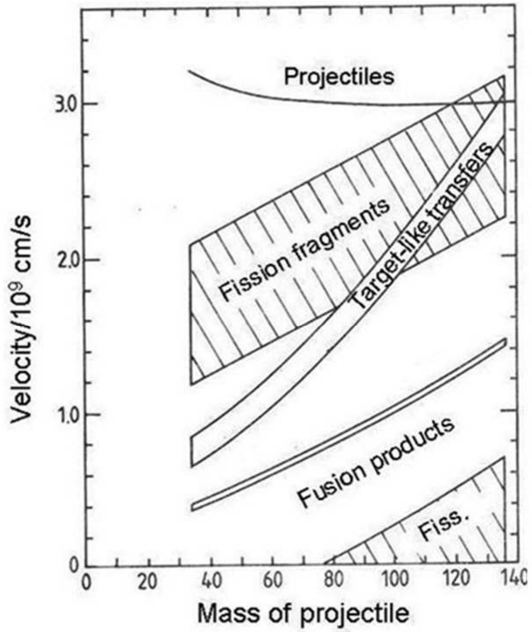
W. Schwab et al., Z. Phys. A350 (1995) 283

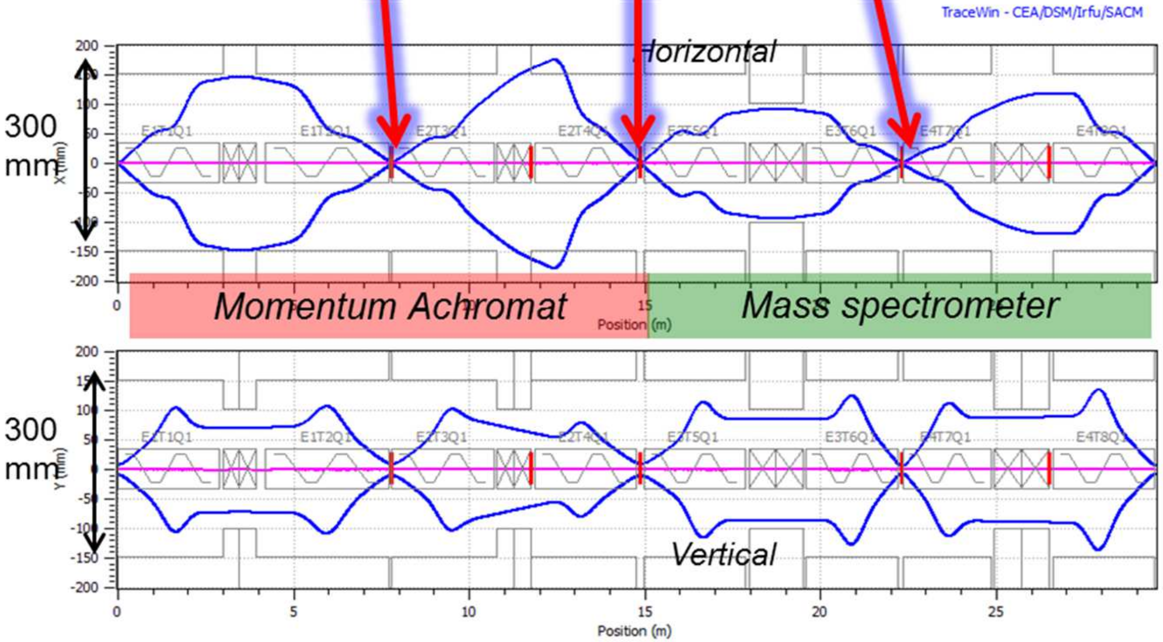
Next-generation in-flight separators

Multiple-stage mass separation for fusion products

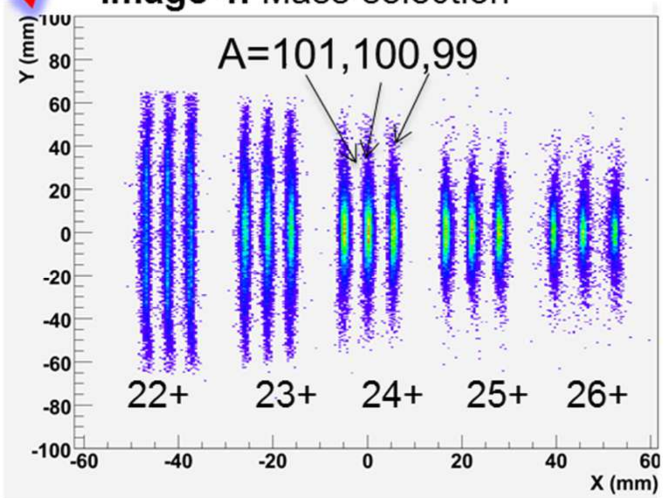
- **Multistep separation**
- Large acceptance
- Variable modes
- Mass resolution (ΔM/M=1/460)
- High transmission







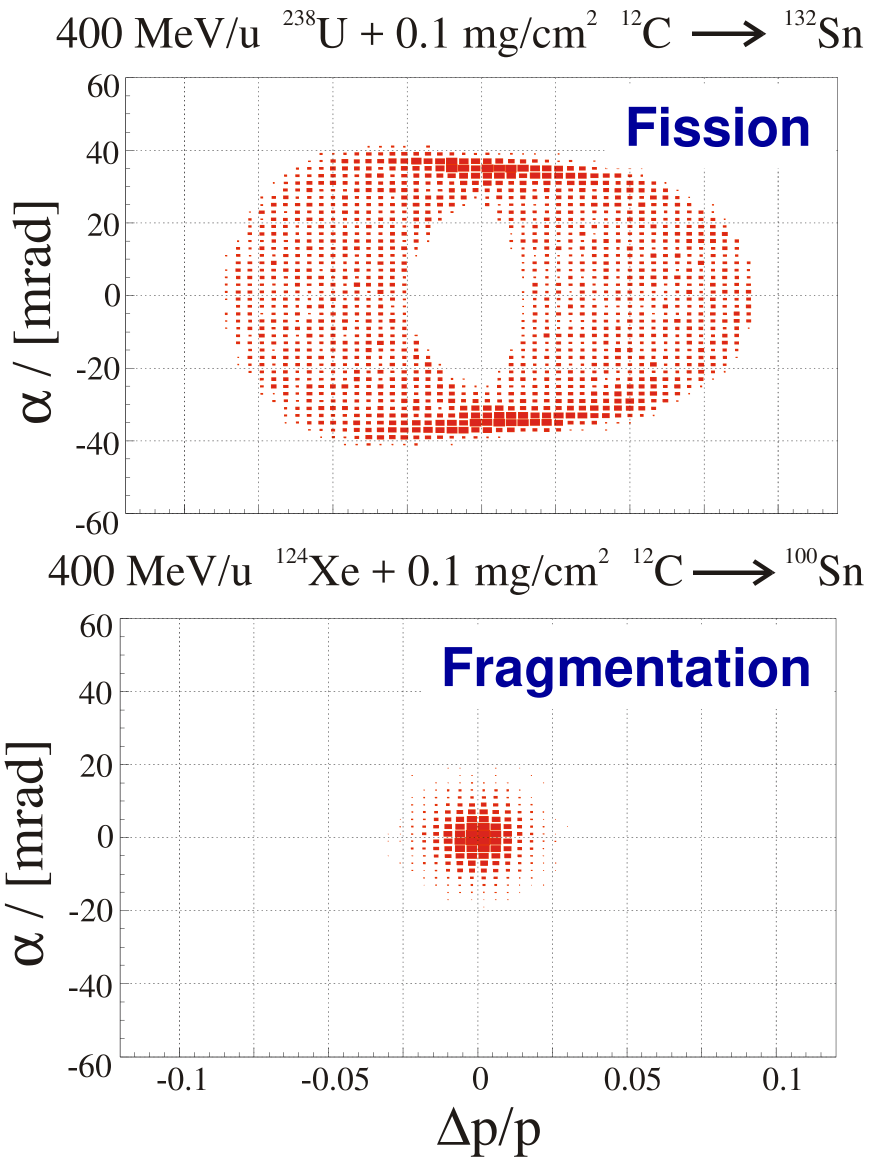
F. Dechery et al., Eur.Phys.J. A 51 (2015) 66



Courtesy: H. Savajols

→ talk yesterday by J.Piot

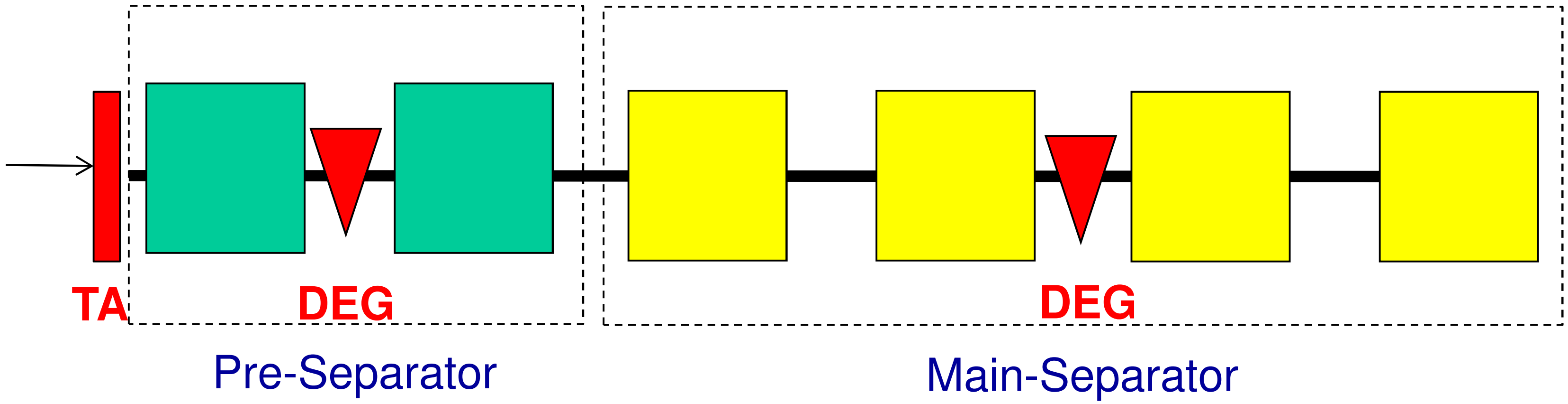
Kinematics of projectile fragmentation and fission



Courtesy: H. Geissel

The new generation of in-flight separators

Coupling of two achromatic systems

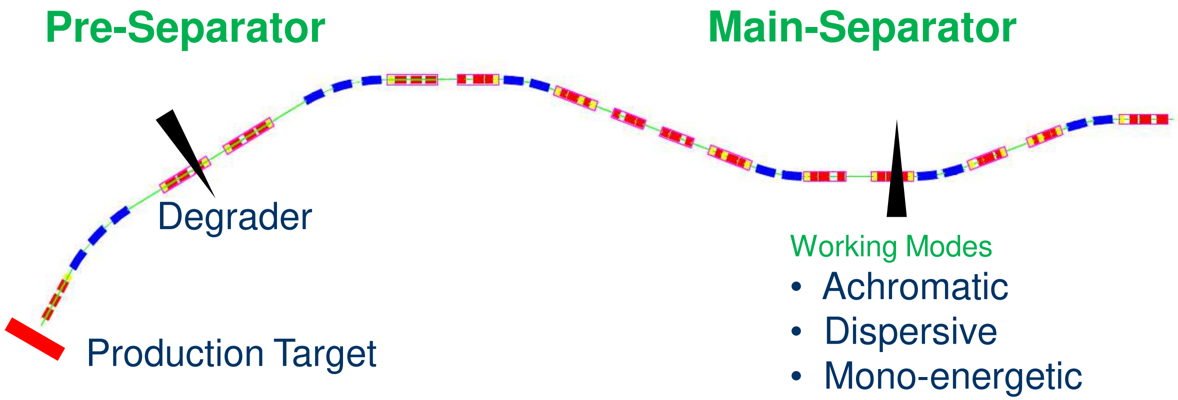


Examples:

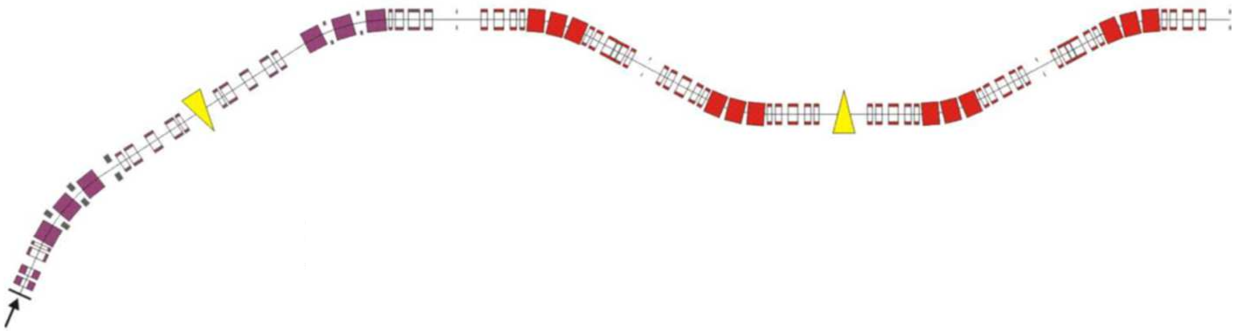
HIAF: **HFRS** (25Tm, 180m)
FAIR: **Super-FRS** (20Tm, 176m) H.Geissel et al.,NIM B204, (2003), 71
RIKEN: **BigRIPS** (9 Tm, 78m) T.Kubo et al.,NIM B204, (2003), 97
MSU: **ARIS** (8 Tm, ~80m) M.Hausmann et al.,NIM B317, (2013), 349

→ all major, next-generation in-flight facilities are based on a pre- plus main-separator

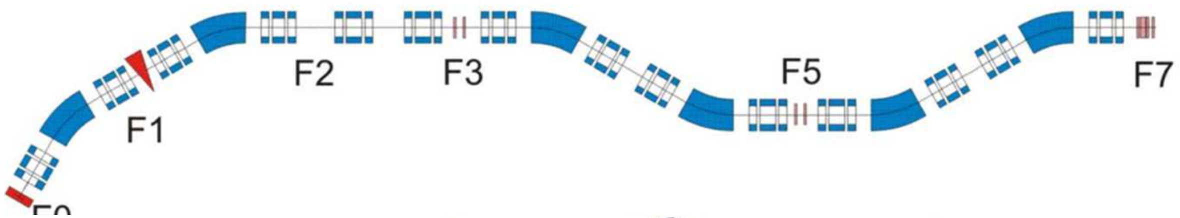
The new generation of fragment separators



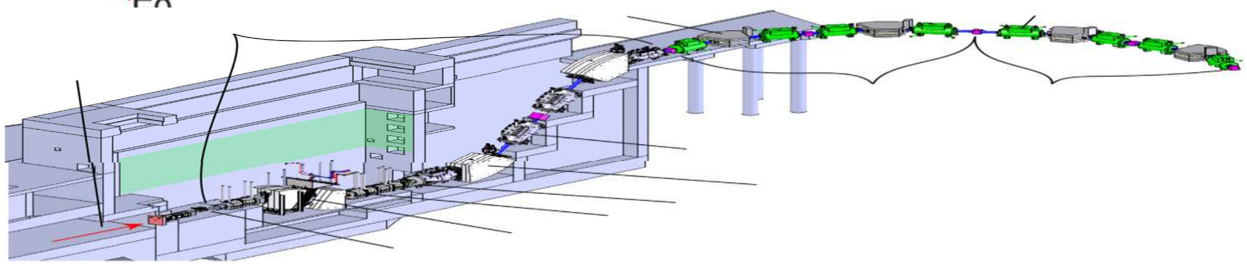
HIAF: HFRS
25Tm, 180m



FAIR: Super-FRS
20Tm, 176m
H.Geissel et al.,NIM B204 (2003), 71



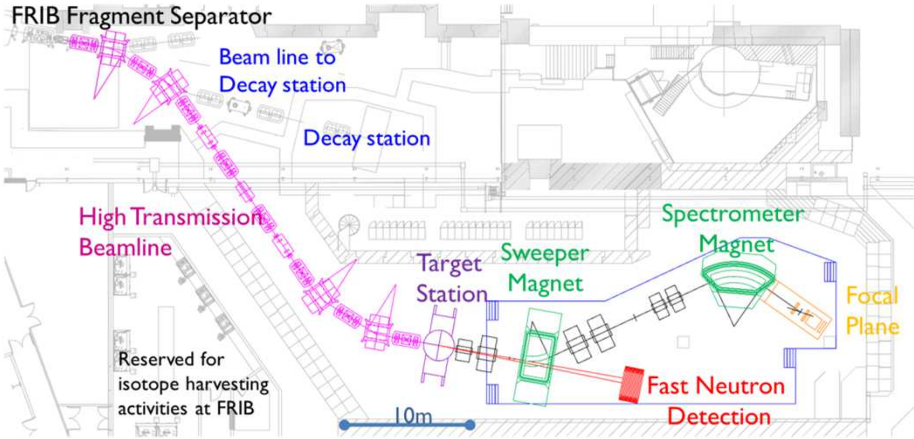
RIKEN: BigRIPS
9 Tm, 78m
T.Kubo et al.,NIM B204 (2003), 97



MSU: ARIS
8 Tm, ~80m
M.Hausmann et al.,NIM B317 (2013), 349

Reaction studies with relativistic radioactive beams

High Rigidity Spectrometer (HRS) at FRIB



- Kinematic focusing → high efficiency
- Thick targets → high luminosity
- "Simple" reaction mechanism (sudden approximation) → "easy" theory
- Particle tracking → complete kinematics

- Broad range of techniques, such as
  - in-beam gamma ray spectroscopy
  - direct reaction studies
  - heavy-ion collisions
  - invariant-mass spectroscopy
  - time-of-flight mass spectroscopy

Other facilities for RRR beams:

- RIKEN: Zero-Degree Spectrometer
- SHARAQ
- Super-FRS: LEB E-Buncher/Spectrometer
- R^3B+High-Resolution Spectrometer

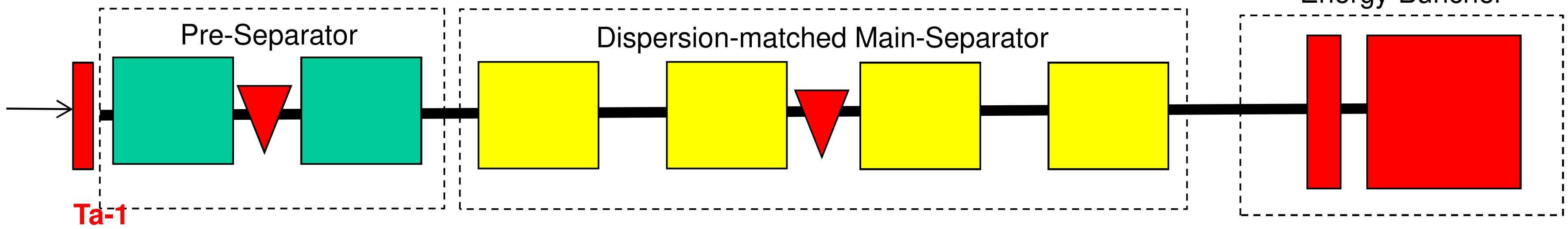
→ Few ions/sec.
→ Unbound systems
→ Studies beyond the driplines

- Nuclear structure
- Nuclear astrophysics,
- Applications (space, medicine, energy)

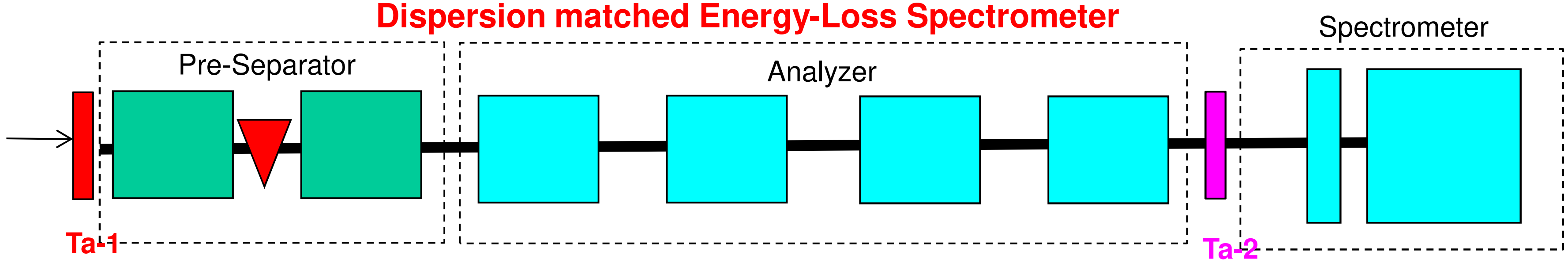
Courtesy: R. Zegers

High-resolution spectrometers coupled with in-flight separators

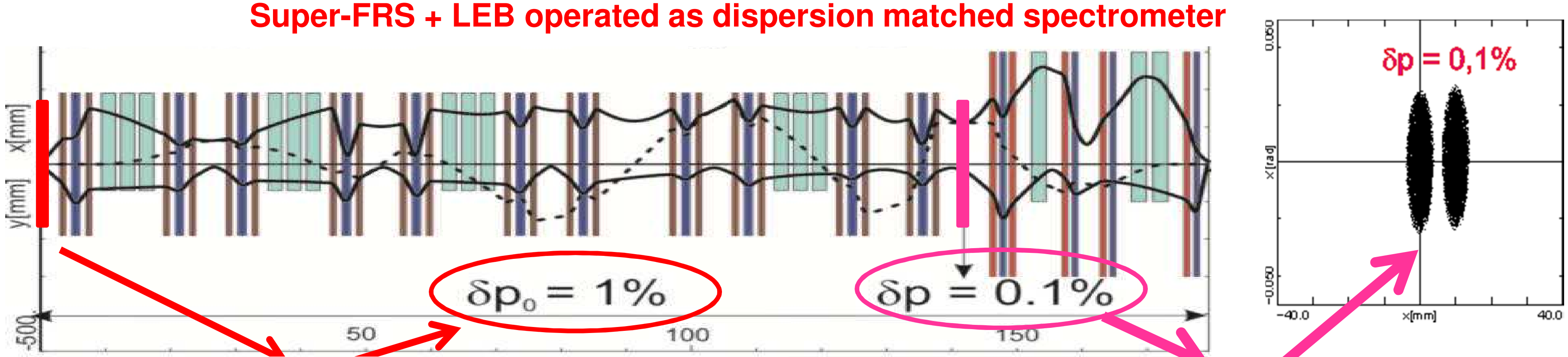
Standard operation mode of LEB



Dispersion matched Energy-Loss Spectrometer



Super-FRS + LEB operated as dispersion matched spectrometer



Nuclear reactions in TA-1 lead to a momentum spread e.g. $\delta p_0 = 1\%$

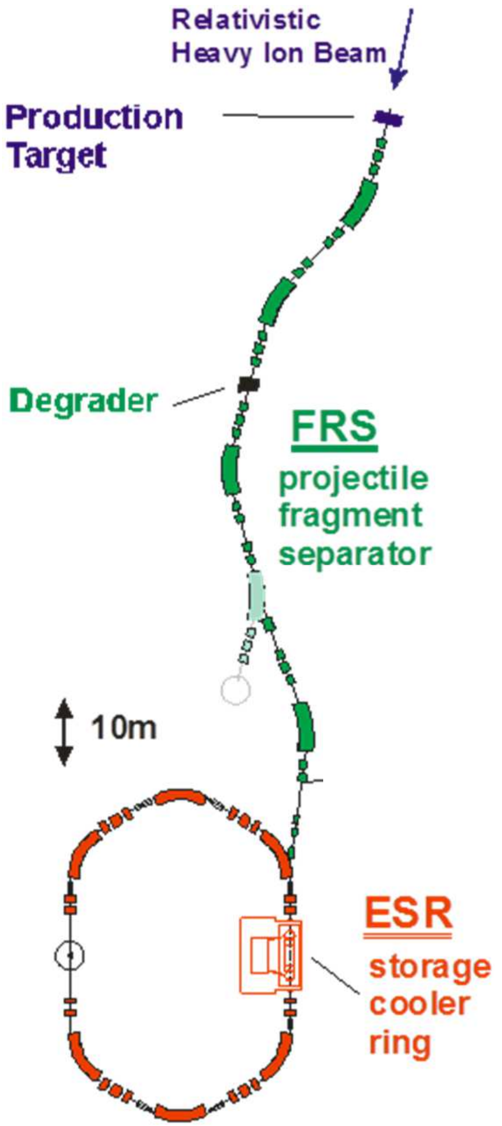
The tiny momentum change $\delta p = 0.1\%$, induced in TA-2, can be resolved!

Courtesy: H. Geissel

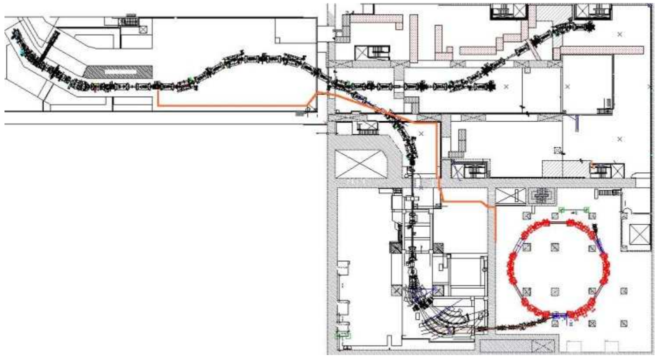
Storage and cooler rings

Storage and cooler rings coupled to in-flight separators

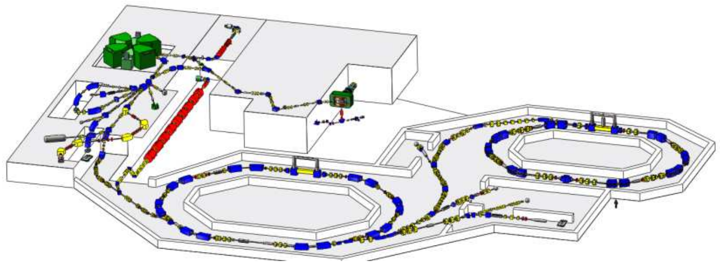
GSI: FRS+ESR



RIKEN: BigRIPS+RI-Ring



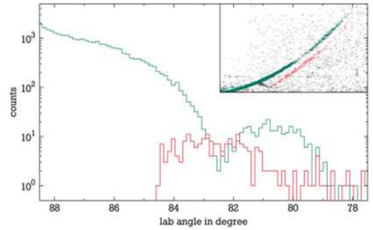
IMP-Lanzhou: RIBLL+CSRe



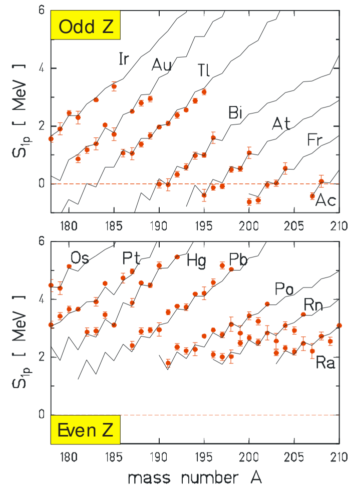
Discovery potential:

- Mass measurements
- New decay modes of HCI
- Nuclear reactions
- Astrophys. reaction rates

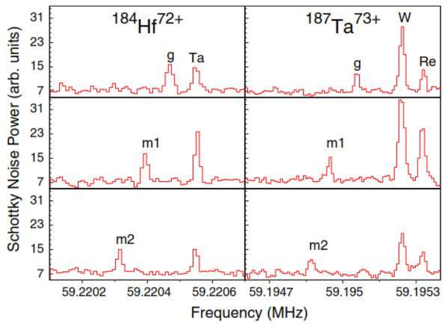
(In-)elastic scattering



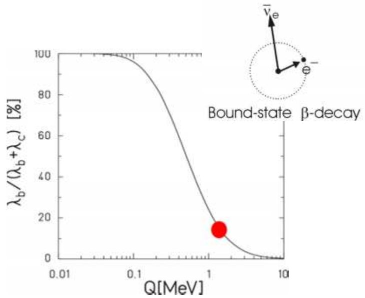
Dripline and shells



Isomer discoveries and studies



Bound beta decays



Hybrid systems

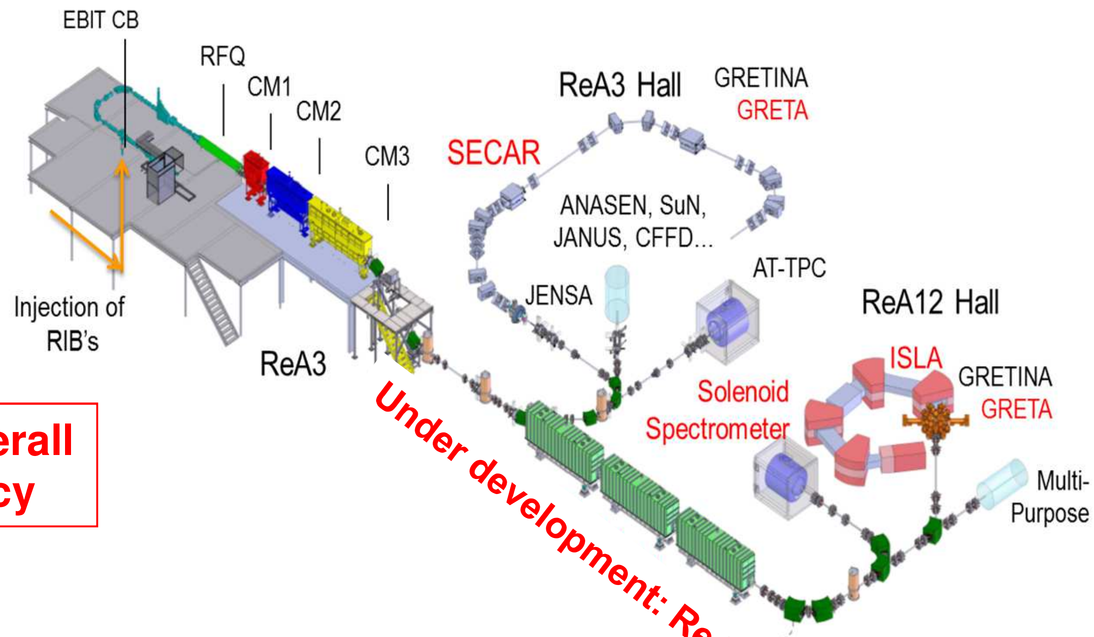
Hybrid systems (I): reaccelerated beams at MSU with ReA facility

ReA builds on various ion-stopping and manipulation techniques

- gas-filled ion catcher
- cyclotron stopper
- solid beam catchers

EBIT/S charge breeder and linac

Recent result with ReA3: 3 MeV/u

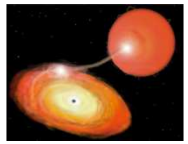


Equipment	Efficiency (%)
Gas cell	15
BCB - EBIT	12
RFQ-LINAC	70
Transport to experiment	90

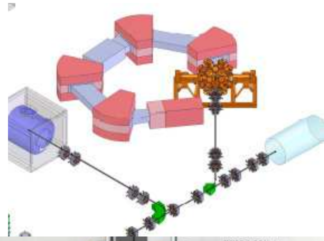
~1% overall efficiency

First successful rare isotope beam experiment with ReA3 in September 2015

AT-TPC: ^{46}Ar, ^{40}Ar (α,α'), ^{32}S, ^{38}S
JENSA: ^{34}Ar, $^{34m+g}$Cl, ^{40}Ar, ^{39}K, (α,α'), (α,p)
General Purpose Line:
^{46}K, ^{39}K Fusion-Fission
^{47}K, ANASEN
^{75}Ga, ^{85}Rb, NERO, (α,n)
^{47}K, ^{39}K, Fusion
^{77}Br, ^{82,84}Kr, ^{85}Rb, SuN (p,γ)



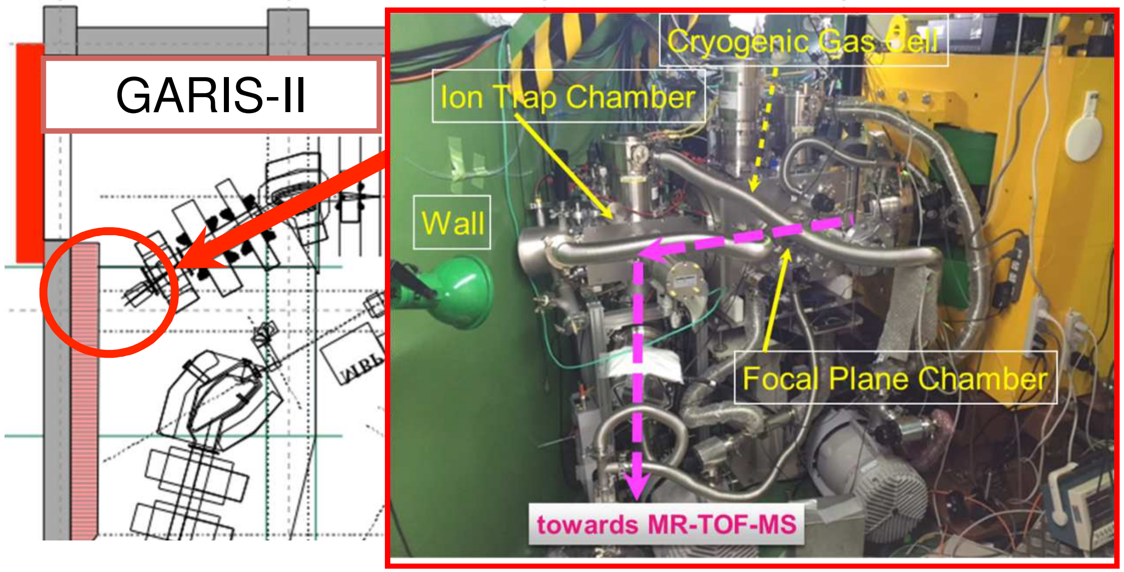
ISLA (ISochronous Large-Aperture spectrometer), based on former TOFI

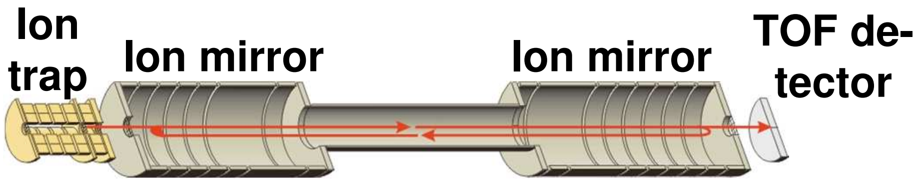


SECAR (SEparator for CApture Reactions)

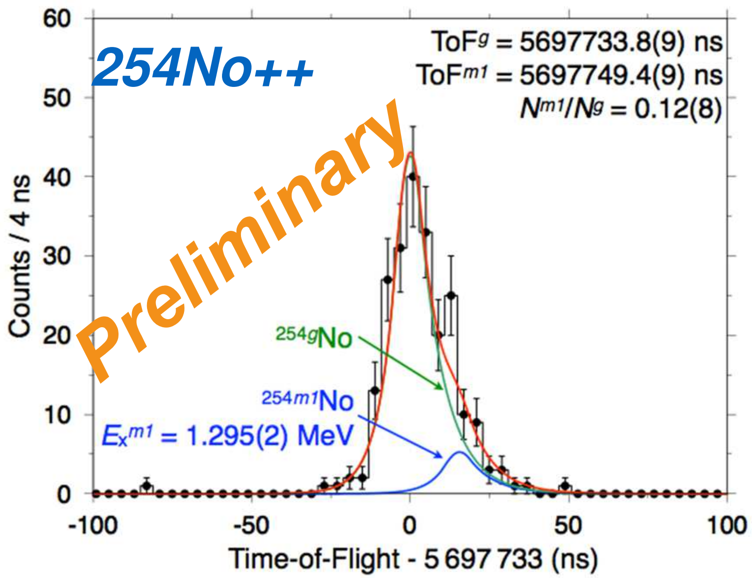
Courtesy: D. Morrissey

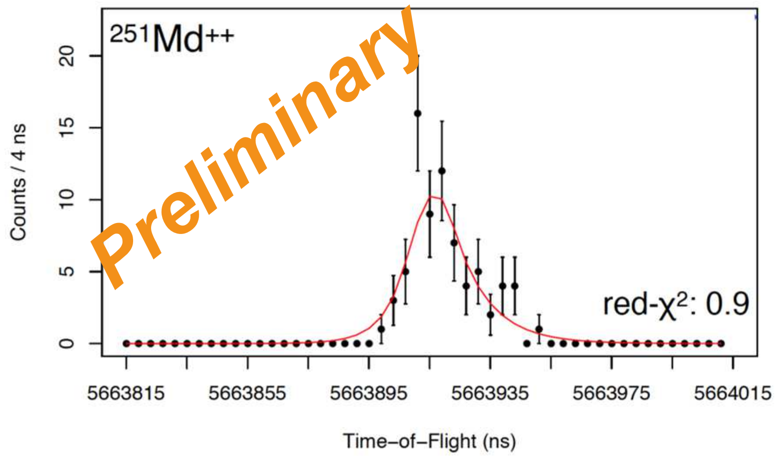
Hybrid systems (II): SHE identification and mass measurements with high-resolution MR-TOF-MS at GARIS-II





Y. Ito et al, submitted arXive: 1709.06468

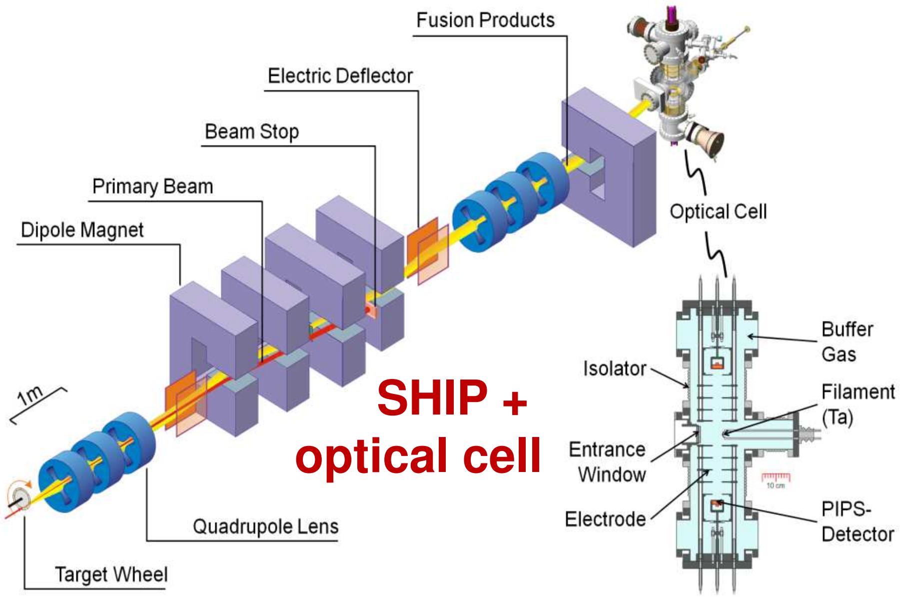


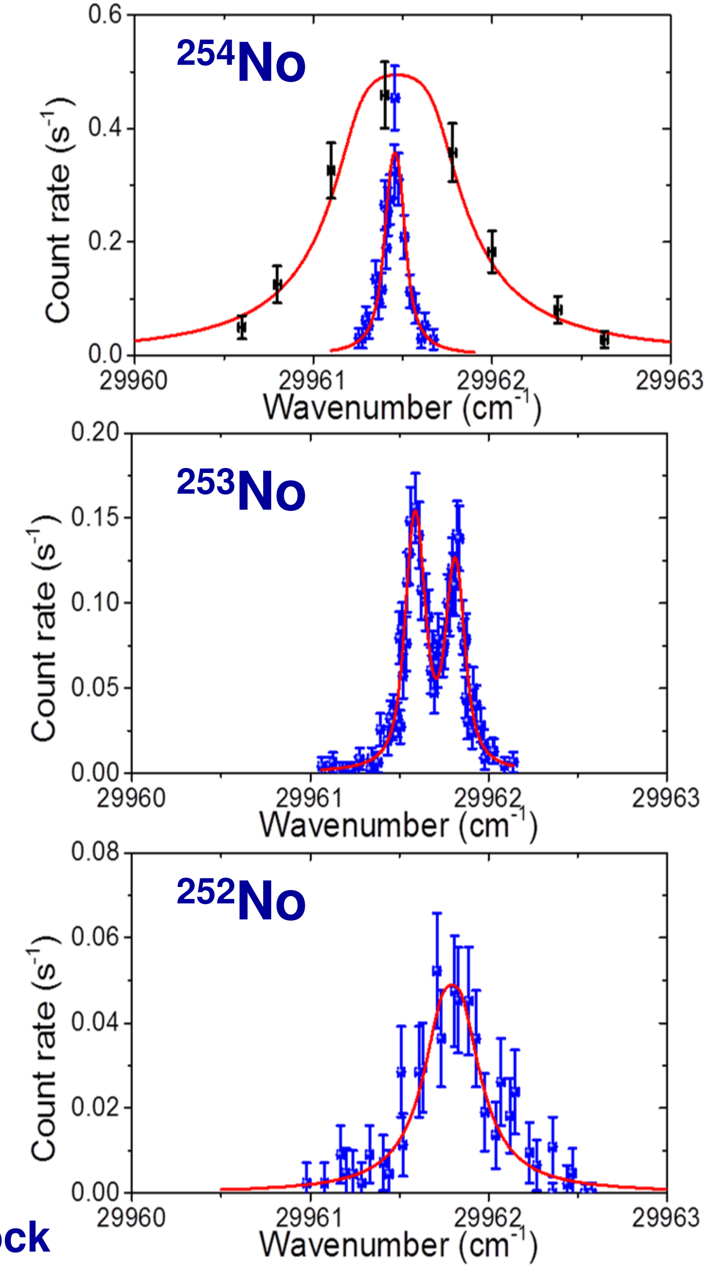


Courtesy: M. Wada

10 SHE masses measured
80 masses in 4 weeks
30 masses for first time
Shortest $T_{1/2} \approx 10$ ms
Precision $\delta m/m \approx 2 \cdot 10^{-7}$

Hybrid systems (III): laser spectroscopy of superheavy elements





Recent laser spectroscopy results:

- Study of Rydberg states
- Determination of first ionization potential (^{254}No)
- Hyperfine spectroscopy (^{253}No)
- Atomic structure
- Isotope shifts ($^{252...254}$No)
- Charge radii

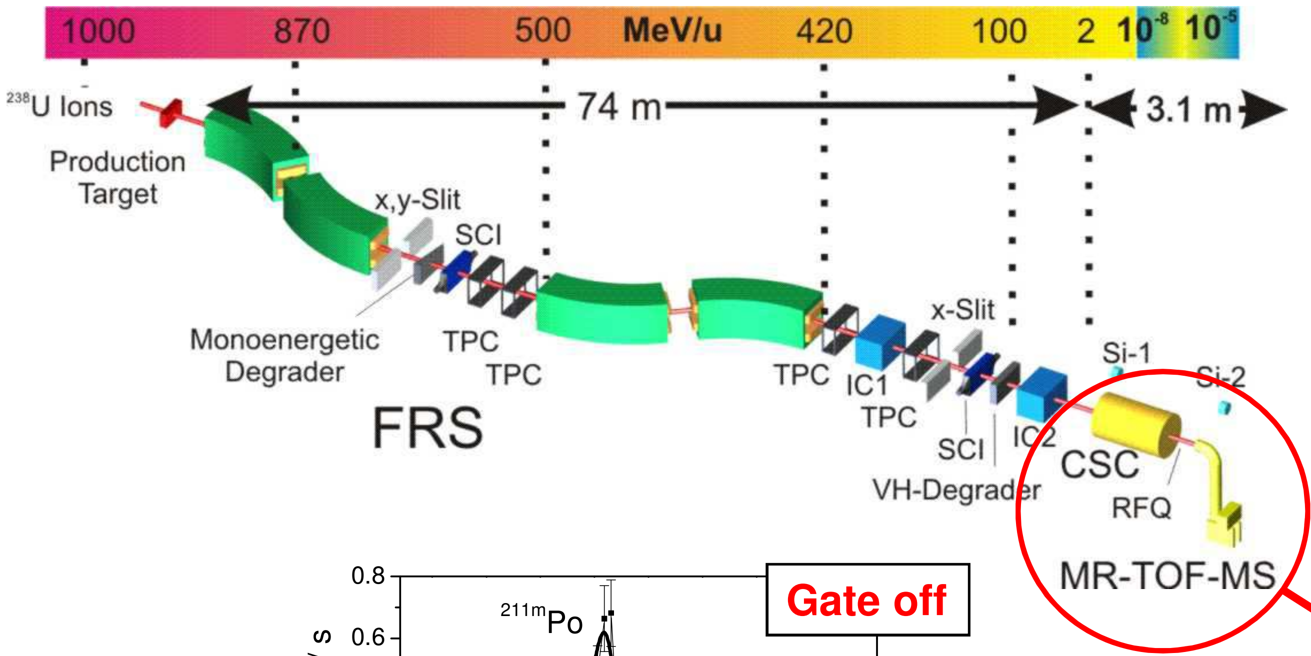
Isotope	N	$\delta\langle r^2\rangle$ (fm^2)
^{254}No	152	0
^{253}No	151	-0.057 $(1)_{stat}$
^{252}No	150	-0.089 $(4)_{stat}$

M. Laatiaoui et al., Nature 538 (2016) 495
M. Laatiaoui et al., Eur. Phys. J. D 68 (2014) 71
H. Backe et al., Eur. Phys. J. D 45, 99 (2007)

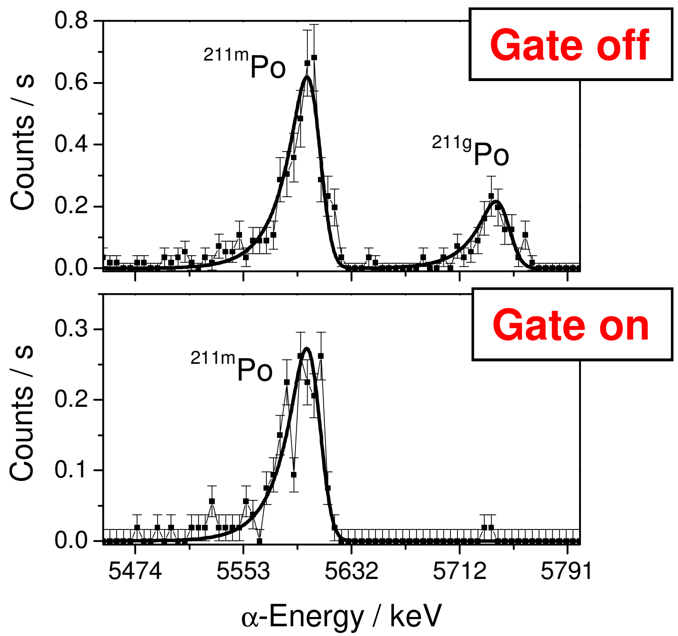
Courtesy: M. Block

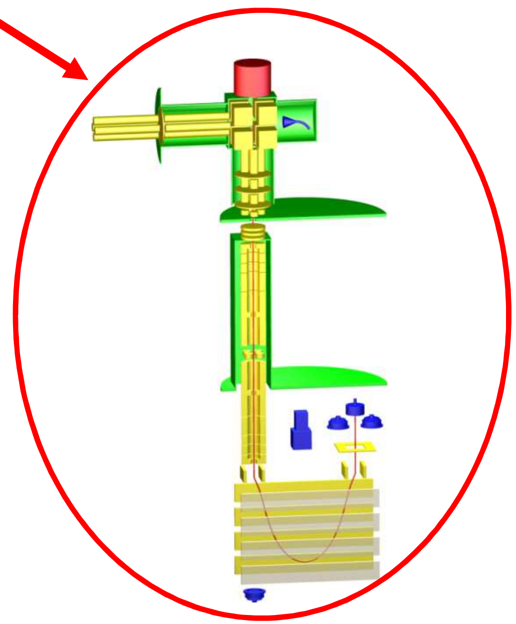
→ talk yesterday by M.Laathiaoui

Hybrid systems (IV): isomeric beams



- **-> Production**
- **-> Separation In-Flight**
- **-> Energy-Bunching**
- **-> Slowing-Down**
- **-> Buffer-Gas-Cooling**
- **-> High-Resolution Separation+Meas-urements**





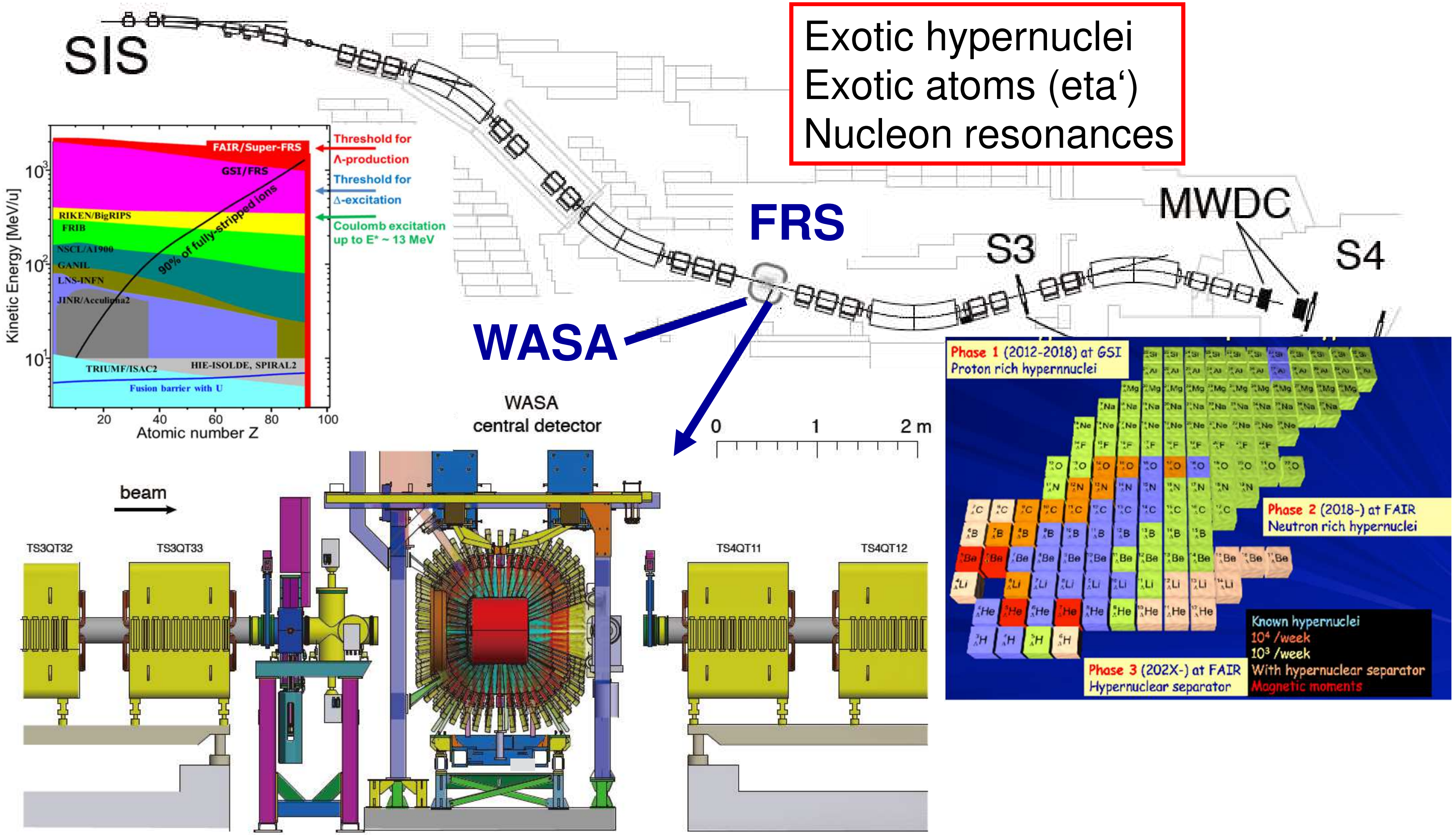
First spatial separation of ground state and isomeric state with an MR-TOF-MS

T. Dickel et al., Phys. Lett. B 744 (2015) 137

Complex focal-plane equipment

(Particle-)detector arrays coupled to high-res.spectrometer stages

Exotic hypernuclei
Exotic atoms (eta‘)
Nucleon resonances

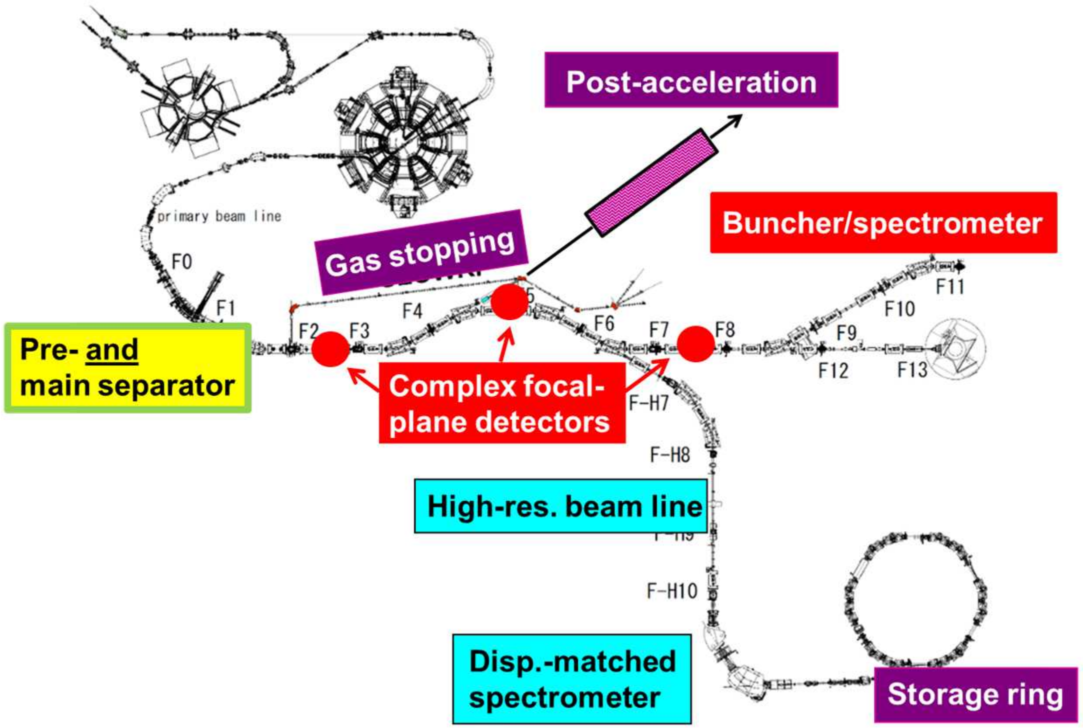


→ New opportunities at the boarder line of nuclear and hadron physics with (Super-)FRS

Summary

A) The elements of a modern in-flight facility

B) Solutions for precision measurements with RIBs with large emittance



1. Special ion optical systems
   (energy-loss spectrometer, isochronous systems)
2. Phase-sp. reduction by beam cooling
   (stochastic, electron or laser cooling in storage rings, buffer-gas cooling)
3. Multiple-stage separators
   (coupling of various sections for momentum and energy(-loss) analysis)
4. Coincidence measurements
   (in front and behind the reaction target, event-by-event tracking)