Recent developments at in-flight facilities

Christoph Scheidenberger

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...

ISOL

\[ p \rightarrow \text{Sep.} \]

ISOLDE, TRIUMF, ALTO, ...

In-Flight Separation

\[ HI \rightarrow \text{Sep.} \]

LISE, FRS, RIPS, A-1200, ...

IGISOL

\[ p \rightarrow \text{Sep.} \]

IGISOL, LISOL,...

Hybrid

\[ HI \rightarrow \text{Sep.} \]

SLOW-RI, FRS-Ion-Catcher, ANL-Gas-Catcher, Cyclotron Stopper, .....
World map of in-flight (radioactive) beam facilities

Including those in construction

GANIL LISE3, S3
KVI
GSI FRS
FAIR Super-FRS
Dubna Acculinna
Acculinna-2
NIKFI
RIKEN RIPS
RIBF BigRIPS
HIAF
RISP
HIMAC
CNS CRIB*
RCNP
LNS Catania
Delhi*
Lanzhou RIBLL
RIBLL2
ANL*
NSCL/MSU A1900
FRIB ARIS
Notre Dame*
Florida State*
San Paulo*
Texas A&M MARS
* Low-energy facilities
* Multiple-stage systems

Adapted from: T. Kubo

CdG-2017, Amboise (France), October 16-20, 2017
Christoph Scheidenberger - GSI
Outline of the talk

Energy-Loss Spectrometer (dispersion matched)

Pre-Separator

Main Separator

Pre-Separator

Main Separator

Fragment Separator
(with achromatic, mono-energ. or homog. degrader)

Spectrometer, storage ring, hybrid system, ...
First-generation in-flight separators
Low-energy fragmentation facilities

Large relative velocity spread $\delta v/v$ induced by fragmentation reaction

$\rightarrow$ B$p$-$\Delta E$-B$p$ method not sufficient:
$\rightarrow$ Isotopic separation needs additional velocity analysis/separation

$\rightarrow$ Wien filter (GANIL)
$\rightarrow$ RF deflector (RIKEN, MSU, Dubna)
Separation principle: $B\rho - \Delta E - B\rho$ method

Magnetic rigidity analysis:

$B\rho = \gamma v \cdot A/Z$

$V_{\text{Fragment}} \sim V_{\text{Projectile}} \quad A/Z \sim \text{const.} \quad \text{Magnetic-rigidity analysis of energy loss yields single isotope!}$
Important asset for precision measurements: dispersion matching

1500 MeV/u $^{12}$C + Be $\rightarrow$ $^{8}$B

Other examples: SPEG, Grand-RAIDEN, SHARAQ, S-800, ...
Spectroscopy by knock-out reactions

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

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

$^9\text{B} \rightarrow \text{Be} + p$
$^{12}\text{C}$ Target, $E_{lab}=1.44 \text{ GeV}$
FRS Data (GSI), Theory (Giessen)

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

$^{12}\text{C}$ stable
$^{17}\text{C}$
$^{19}\text{C}$ Halo
Shell closure in $^{24}\text{O}$

Next-generation in-flight separators
Multiple-stage mass separation for fusion products

- Multistep separation
- Large acceptance
- Variable modes
- Mass resolution ($\Delta M/M = 1/460$)
- High transmission

Image 1
Highly selective beam rejection

Image 3
TKE selection

Image 4: Mass selection
A = 101, 100, 99


Courtesy: H. Savajols

→ talk yesterday by J. Piot
Kinematics of projectile fragmentation and fission

\[ 400 \text{ MeV/u} \ ^{238}\text{U} + 0.1 \text{ mg/cm}^2 \ ^{12}\text{C} \rightarrow ^{152}\text{Sn} \]

\[ 400 \text{ MeV/u} \ ^{124}\text{Xe} + 0.1 \text{ mg/cm}^2 \ ^{12}\text{C} \rightarrow ^{100}\text{Sn} \]

\[ \Delta p/p \]

\[ \alpha/\text{[mrad]} \]

\[ \text{Fission} \]

\[ \text{Fragmentation} \]

 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

**Production Target**

**Degrader**

**Pre-Separator**

**Main-Separator**

**Working Modes**
- Achromatic
- Dispersive
- Mono-energetic

**HIAF: HFRS**
25Tm, 180m

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

**RIKEN: BigRIPS**
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T. Kubo et al., NIM B204 (2003), 97

**MSU: ARIS**
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M. Hausmann et al., NIM B317 (2013), 349
Reaction studies with relativistic radioactive beams

- 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

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

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

Other facilities for RRR beams:
- RIKEN: Zero-Degree Spectrometer
  - SHARAQ
- Super-FRS: LEB E-Buncher/Spectrometer
- R³B+High-Resolution Spectrometer

Courtesy: R. Zegers
High-resolution spectrometers coupled with in-flight separators

Standard operation mode of LEB

Pre-Separator

Dispersion-matched Main-Separator

Energy-Buncher

Dispersion matched Energy-Loss Spectrometer

Pre-Separator

Analyzer

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**
- Relativistic Heavy Ion Beam
- Production Target
- Degrader
- FRS projectile fragment separator
- ESR storage cooler ring

**RIKEN: BigRIPS+RI-Ring**

**IMP-Lanzhou: RIBLL+CSRe**

**Discovery potential:**
- Mass measurements
- New decay modes of HCI
- Nuclear reactions
- Astrophys. reaction rates

**Isomer discoveries and studies**

**Bound beta decays**

**Dripline and shells**

**(In-)elastic scattering**
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

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas cell</td>
<td>15</td>
</tr>
<tr>
<td>BCB - EBIT</td>
<td>12</td>
</tr>
<tr>
<td>RFQ-LINAC</td>
<td>70</td>
</tr>
<tr>
<td>Transport to experiment</td>
<td>90</td>
</tr>
</tbody>
</table>

~1% overall efficiency

First successful rare isotope beam experiment with ReA3 in September 2015

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

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

254No++

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

Courtesy: M. Wada
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

M. Laatiaoui et al., Nature 538 (2016) 495  

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+Measurements

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


Courtesy: W.R.Plass
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

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

Courtesy: T. Saito
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)