Dispersion-Matched Spectrometers for High-Resolution Experiments

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- Introduction “International Expert-Meeting, Quo Vadis?”
- Projectile Fragment Separators coupled to / used as Spectrometers
- Dispersive Spectrometers
- Energy-Loss (dispersion-matched) Spectrometers ($R_{16}=R_{26}=0$)
- New Features of the Ion-Optical Code MIRKO
International Expert Meeting, Quo Vadis?

**Participation:** By invitation only
World Experts in the field and Newcomers

**Present Goals** of the Fragment Separator International Experts Meetings:
- stimulate collaboration in design, construction and operation of in-flight fragment separators
- solve technical and scientific challenges
- have open and frank discussion, exchange new ideas

**Possible Future Orientation** under the conditions that the different new facilities have quite different construction times:
- a *young generation* of experts have to be recruited and trained
- together we should *avoid duplication* of existing or already planned facilities our experts are capable of finding unique properties and experiments for each facility
- form a *network for separator / spectrometer operation and experiments*
- ... please find more ideas!
The Super-FRS Facility

High energies open unique research potentials:

1. Hypernuclei
2. Mesic nuclei ($\pi^-, \eta'$)
3. Delta excitation
4. New decay modes
The group designing and constructing the facility should have its scientific share and run the most demanding experiments.

Super-FRS Collaboration

Scientific Program of the Super-FRS Collaboration: Report of the collaboration to the FAIR management

DOI: 10.15120/GR-2014-4
In-Flight Separator coupled to a Spectrometer

Standard Operation Mode

Pre-Separator → Main-Separator → Beamline Spectrometer

Examples: Big-RIPS -- Zero-Degree Spectrometer --- SHARAQ --- SAMURAI
A1900 – S800
FRS – ESR --- Ion-Catcher --- ALADIN
ARIS + Beamline + HRS
Super-FRS – E-Buncher – GLAD -- HRS

A versatile system is advantageous to explore new operation modes and unique experiments
Super-FRS is a Powerful Separator and a High Resolution Spectrometer

Super-FRS

Production Target

Primary Beams
\( ^{238}\text{U}^{92+} \) 1500 A MeV
SIS100/300

Spectrometer Experiments

Low Energy Branch

High Energy Branch

HISPEC DESPEC LASPEC MATS

R3B

To Storage Rings

ILIMA EXL ELISE AIC

NUSTAR

GSI
Energy-Buncher of Super-FRS is a Powerful High Resolution Spectrometer
Which ion-optical resolution yields the required A- and Z-resolution?


FRS: $\varepsilon = 20 \pi \text{ mm mr and } 2\% \text{ dp/p transmission}$
Experiment to study the contribution of tensor interaction via the $^{16}\text{O}(p,d)$ reaction at 400-1200 MeV/u

J. Ong, S. Terashima, I. Tanihata
High-Resolution Momentum Measurements with a Dispersive FRS Mode at all Focal Planes
High-Resolution Momentum Measurements with a Dispersive FRS Mode at all Focal Planes

\[ R_{io} = \frac{p}{\Delta p} = \frac{R_{16}}{2R_{11}x_0} = 16500 \]
Limitation of Energy Spread of the Protons from the Accelerator

\[ \sigma_E(d,F4) \text{ MeV} \]

\[ \sigma_E(p)_{\text{SIS-18}} \text{ [%]} \]

- 0.001 mg/cm\(^2\)

\[ \sigma_E(p)_{\text{SIS-18}} = 0.1 \text{ [%]} \]
Limitation of Target Thickness

$^{16}\text{O}(p,d)$ at 400 MeV/u

$\varepsilon_{\text{SIS}-18} = 0$

Target Thickness [mg/cm$^2$]
Deuteron spectra (high performance of FRS)

Proton beam @400 MeV/u  \[ \text{Pom (p,d)} \quad \theta_{\text{lab}} = 0^\circ \]

POM Target \((\text{CH}_2\text{O})_n\)

\[ ^{16}\text{O}(p,d)^{15}\text{O} \]

\[ ^{11}\text{C}(\text{g.s.}) \]

\[ ^{15}\text{O}_{1/2^+} + ^{15}\text{O}_{5/2^+} \]

\[ ^{15}\text{O}_{3/2^+} + ^{11}\text{C}_{1/2^-} \]

F. Farinon
Limitations for High-Resolution Spectrometer Experiments with Exotic Heavy Ions

Challenges due to:

- Phase-Space of Primary Beams (see (p,d) reaction @ FRS)
- Large Phase of Exotic Nuclei
- Atomic Interaction in Targets, Degraders and Detectors
- Required High Spectrometer Resolving Power
**Principle of an Energy-Loss Spectrometer**

Image size of the final focus is independent of the incident momentum spread if

\[ 2R_{16} = -2R_{11}^{-1}R_{16} \]

Analogous one can find conditions for the angular distribution generated in the secondary target.

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**Diagram**

**Analyzer**

\[ p_0 - \Delta p \rightarrow x_1 \]
\[ p_0 \rightarrow 0 \]
\[ p_0 + \Delta p \rightarrow -x_1 \]

**Target**

\[ p_0 - \Delta p - \Delta p_2 \]
\[ p_0 - \Delta p_2 \]
\[ p_0 + \Delta p - \Delta p_2 \]

**Spectrometer**

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Point - to - point image condition: \( R_{12} = (x, x') = 0 \)

\[
\begin{align*}
\delta & \geq 1 \\
\delta & \leq 2
\end{align*}
\]

\[
x_1 &= R_{11} x_0 + R_{16} \left( \frac{p - p_0}{p_0} \right) \\
x_2 &= R_{11} x_1 + R_{16} \left( \delta - \frac{\Delta p_2}{p_0} \right) \\
x_2 &= R_{11} x_0 + \left( R_{11} R_{16} + R_{16} \right) \delta - R_{16} \frac{\Delta p_2}{p_0} = 0
\]

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The Stages of an In-Flight Separator coupled to a Spectrometer

Standard Operation Mode

Pre-Separator

Main-Separator

Beamline Spectrometer

Energy-Loss Spectrometer (dispersion matched)

Analyzer

Spectrometer
Low-Energy Branch of the Super-FRS

Dispersion-Matched: Main Separator—Energy Buncher

SIS-18
SIS-100
E-Loss Spectrometer
Super-FRS LEB-S-EB-Dispersion-Matched


\[ R_{16} = R_{26} = R_{21} = 0 \]

H. Geissel et al. NIM B, 2013
Active Target in the Dispersion-Matched Spectrometer

IKAR in a Dispersion-Matched Spectrometer
(E. Maev)

$^8\text{B}$

previous preliminary results (A. Inglesi, P. Egelhof)

$E = 674\text{ MeV/u}$

S358 data corrected for inelastics
- S358 GG fit (no halo): $R_p = 2.38\text{ fm}$, $\chi^2 = 1.6$
- S358 GG fit (1p halo): $R_p = 2.66\text{ fm}$, $\chi^2 = 0.5$

$^{8}\text{B}$
IMS Brho-Tagging
M. Diwisch, PHD 2015
See Talk Timo Dickel
Investigation of the Layout of the E-Buncher

Role of Resolving Power and Image Aberrations

Entrance Emittance = 300 \, \pi \, \text{mm mrad}

\begin{align*}
\text{Range Straggling} & \quad \text{Resolving Power} \\
\hline
\end{align*}

- SR78Ni3rd
- SR78Ni1st

\begin{align*}
p_0 + \delta & \quad \rightarrow \quad p_1 \\
p_0 & \quad \rightarrow \quad p_1 \\
p_0 - \delta & \quad \rightarrow \quad p_1
\end{align*}
Novel Method of Energy Bunching and Position Compression

◆ OEDA Project: S. Shimoura et al. RIKEN
The calculated optical design can be directly converted in a geometrical layout of a new facility.
New Features of MIRKO
B. Franczak, H. Geissel to be published in NIM

Super-FRS
New Proposals:

1. Higher Energies for all HI
2. Factory for Exotic- and Hypernuclei
3. 4-Stage Spectrometer
New Features of MIRKO

B. Franczak, H. Geissel to be published in NIM

◆ Realistic Apertures, changes of $l_{eff}$ preserving the length

Entrance Cloud

Rectangular

Elliptical

Hyperbolic Apertures
MIRKO & Degraders
Overall Dispersive vs. Dispersion-Matched
B. Franczak, H. Geissel

Energy Degrader

FRS:
Dispersion-matched

Overall dispersive
Initial spread $\sigma_{66}=4e^{-4}$, „Degrader“: E-loss $dE/E=2/800$, straggling $\delta p/p=4e^{-4}$

4 x dispersive

2 x dispersive

overall achromatic
New Features of MIRKO

Transmission Optimization (Pion Dipole Magnet at FRS F2)

Fit conditions at different positions

Factor of 5 Improvement
New Features of MIRKO

◆ Isochronous Mode of the ESR, Limitations

![Graph showing iso-energetic mode with m/q = 2.50 and 2.61]
Summary

🌟 Our Int. Expert Meeting has a good future, new challenges are on the horizon

🌟 Recent in-flight separator / spectrometer experiments provide excellent scientific results, e.g.:
- totally dispersive (FRS, the role of tensor force)
- mesic atoms / nuclei (BigRIPS, FRS)
- delta-excitation with exotic nuclei (FRS)

🌟 The coupling of in-flight separators with high-resolution systems has unique scientific potential:
- e.g. dispersion-matched spectrometers (A1900-S800, BigRIPS-Sharaque)
- storage rings (FRS-ESR)
- ion-catcher traps (MR-ToF, Penning) (A1900-LEBIT, FRS-Ion-Catcher, BigRIPS-SLOWRI)