Secondary Beams and Targets

K. Knie, GSI
Introduction:
primary / secondary beam
ISOL method,
in-Flight fragment separators

Secondary beams at FAIR:
Radioactive Isotope Beams: SuperFRS
Antiprotons: Target, Magnetic Horn and pbar Separator
Target handling, Radiation Protection

“Ternary” Beams:
Muon Beams
Neutrino Beams (CNGS, NuMi...)
Primary / Secondary Beams

- Ion source
- Accelerator
- Ion optical system / separator
- Stable nuclides or long loved radionuclides
- Experiment
Primary / **Secondary** Beams (ISOL)

**Diagram:**
- Ion source
- Accelerator
- Target
- Ion optical system / separator
- (short lived) radionuclides
- Experiment
Primary / Secondary Beams: In-Flight

ion source → accelerator → target → ion optical system / separator

(very) short lived radionuclides
\(\pi, K, p\bar{a}r, \mu\)

experiment
In-Flight / ISOL Facilities

Alexander Gottberg, IPAC 2018
Production Mechanism

Spallation (ISOL only):
few nucleons lighter than target

![Diagram of spallation process]

Projectile fragmentation:
neutron deficient (evaporation of neutrons after collision)

![Diagram of projectile fragmentation process]

Projectile fission:
neutron rich ($N/Z$ similar heavy projectile)

![Diagram of projectile fission process]
ISOLDE (CERN)

ISOLDE n-spallation source: Ta(W)-rod mounted below the UC target (before irradiation)

T. Stora, FAIR-CERN meeting, 2007

Path of an atom travelling out of a foil target to the ion source (RIBO code, (Santana-Leitner, 2005))
$$I_{\text{RIB}} = \varepsilon \cdot I_{\text{prod}} = \varepsilon \cdot \int_{\text{target}} \sigma(E) \, N_{\text{target}}(l) \, I_{\text{primary}}(l) \, dl$$

- $I_{\text{RIB}}$ - rare ion beam intensity [s$^{-2}$]
- $\varepsilon$ - overall efficiency
- $I_{\text{prod}}$ - production rate of a reaction product [s$^{-2}$]
- $\sigma$ - reaction cross-section [barn = $10^{-24}$cm$^2$]
- $N_{\text{target}}$ - target atoms per exposed area [cm$^{-2}$]
- $I_{\text{primary}}$ - primary beam intensity

$\varepsilon = \varepsilon_{\text{release}} \cdot \varepsilon_{\text{ionization}} \cdot \varepsilon_{\text{transport}} \cdot \varepsilon_{\text{cool–bunch}} \cdot \varepsilon_{\text{breeding}} \cdot \varepsilon_{\text{post–accel}}$

- $\varepsilon_{\text{release}}$ - probability of not-decaying during the time of extraction from the target/ion source unit
- $\varepsilon_{\text{ionization}}$ - probability of ionization of desired species by chosen ionization mechanism
- $\varepsilon_{\text{transport}}$ - efficiency of mass selection and transport to experimental setup
- $\varepsilon_{\text{cool–bunch}}$ - cooling and bunching efficiency (when applicable)
- $\varepsilon_{\text{breeding}}$ - charge state breeding efficiency
- $\varepsilon_{\text{post–accel}}$ - post acceleration efficiency

Typically $10^{-3}$ to $10^{-8}$ !!!

Typically 5% to 90%
T. Stora, FAIR-GSI meeting 2007
Fragment Separators (in-Flight)

$B \cdot \rho = \frac{p}{(q \cdot e)} \approx \frac{(2E \cdot m)^{1/2}}{(q \cdot e)}$

1\textsuperscript{st} part: $m/q$ or $A/q$ selection, charge states $\neq q$ lost
no isobaric selection ($E$ similar for isobars)!

Degrader: $dE/dx$ depends on projectile’s $Z$.

2\textsuperscript{nd} part: $E$ selection, i.e. $Z$ selection. ($A/q'$ is the same for isobars)
charge states $\neq q'$ lost
Fig. 8. The two kinds of mass spectrometry applied at the ESR by measuring the revolution frequencies of stored exotic ions. Left hand side: Schottky mass-spectrometry. Here the ions are electron-cooled, therefore their velocity spread \(\Delta v\) gets negligibly small. Their revolution frequencies are measured by pick up plates mounted in the ring aperture. This technique has been successfully applied at longer-lived exotic nuclei. Right hand side: Isochronous mass-spectrometry. Un-cooled ions circulate at the transition energy \(\gamma_t\). Their revolution times are measured by a time-of-flight technique. This method is in particular suited for short-lived nuclei with half-lives in the millisecond- or even microsecond range.
Fig. 9. Schottky spectrum of fragments from a primary $^{209}\text{Bi}$ beam, stored and electron-cooled in the ESR. The main spectrum shows the difference between the 30th harmonic of the revolution frequencies of the many stored ion species and of a local oscillator operating at about 60 MHz. It covers roughly the full acceptance of the ESR. The inset shows a zoom into the spectrum with the well-resolved ground and isomeric state of bare $^{143}\text{Sm}^{62+}$, each of them populated by one single ion. Parts of this figure were originally published in [27,28].

The Super Fragment Separator
SuperFRS @ FAIR

Primary Beams

- $3 \times 10^{11}/s$; 1.5-2 GeV/u; $^{238}\text{U}^{28+}$
- **Factor > 100** over present in intensity (space charge!)

Rare Isotope Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor **1 000 - 10 000** in intensity over present (acceptance)
Phase 1 Physics with Super-FRS and rings: Potential for new masses, lifetimes & isomers with ILIMA

A total of 75 targets of different elements with differing thicknesses can be installed at the target station at the entrance of the fragment separator. Each of the cylindrical targets, which have a diameter of two centimeters, can be moved into the path of the ion beam with millimeter precision using a stepper motor control. If required, the target holder can also be exchanged by remote control.
Figure 2.4-166: Schematic layout of the Super-FRS with beam line and shielding measures. The area from the target up to the intermediate focal plane PF2 of the Pre-Separator is shielded with iron in order to provide a compact radiation protection in the target building. The concrete in the Main-Separator can be partially replaced by soil taking into account an about 20% smaller absorption of the soil.

Figure 2.4-175: Layout of the Super-FRS target building. The top part of the concrete shielding can be removed to access the working platform. Heavy devices can be transported by crane to the nearby hot cell, storage places or directly onto a truck which can drive into the hall.

Figure 2.4-126: Schematic layout of the target area of the Super-FRS. A vertical plug system has been adapted which has proven to guarantee a safe and reliable operation at PSI in a very high radiation field. Routine maintenance at PSI is done about once per year.
Target Handling

Figure 2.4-176: Radiation shielding bottle at PSI [65] to move activated parts to a hot cell. The whole plug is pulled into the bottle which is then transported with a crane.
Superconducting Multiplets

- 25 long multiplets (mainly MS)
- 8 short multiplets (PS)
- Quadrupol triplet / QS configuration
- up to 3 sextupoles and 1 steerer
- Octupole coils in short quadrupoles

- iron dominated, cold iron (≈40 tons)
- common helium bath, LHe ≈ 1.300 l
- warm beam pipe (38 cm inner diameter)
- per magnet 1 pair of current leads
- max. current <300A for all magnets
“After the discovery of ‘antimatter’ and ‘dark matter’, we have just confirmed the existence of ‘doesn’t matter’, which does not have any influence on the Universe whatsoever.”
Motivation for the large pbar Sources: p–pbar Collider (SPS, Tevatron)
Motivation for the large pbar Sources: p–pbar Collider (SPS, Tevatron)

Detection of $W$ and $Z$ boson at CERN:
Nobel Prize 1984 to Carlo Rubbia (right) and Simon van der Meer (left).

Detection of the top quark at Fermilab (1995)
Nobel Prize 2008 to Makoto Kobayashi (left) and Toshihide Maskawa (right) for its prediction.
<table>
<thead>
<tr>
<th>Source</th>
<th>FAIR</th>
<th>CERN (AC+AA)</th>
<th>FNAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(p), E(pbar)</td>
<td>29 GeV, 3 GeV</td>
<td>25 GeV, 2.7 GeV</td>
<td>120 GeV, 8 GeV</td>
</tr>
<tr>
<td>acceptance</td>
<td>240 π mm mrad</td>
<td>200 π mm mrad</td>
<td>≈ 30 π mm mrad</td>
</tr>
<tr>
<td>protons / pulse</td>
<td>$2 \times 10^{13}$</td>
<td>1 - $2 \times 10^{13}$</td>
<td>$\geq 5 \times 10^{12}$</td>
</tr>
<tr>
<td>pulse length</td>
<td>single bunch (50 ns)</td>
<td>5 bunches in 400 ns</td>
<td>single bunch 1.6 µs</td>
</tr>
<tr>
<td>cycle time</td>
<td>10 s</td>
<td>4.8 s</td>
<td>1.5 s</td>
</tr>
</tbody>
</table>
Creation of Antiprotons

\[ m = \frac{E}{c^2} \]
\[ m_p = m_{\bar{p}} \approx 1 \text{ GeV} / c^2 \]

\[ p, > 1 \text{ GeV} \longrightarrow p, > 1 \text{ GeV} \]

\[ p, > 6 \text{ GeV} \longrightarrow p \text{ at rest} \]

\[ m = \frac{E}{c^2} \]
\[ T_{\bar{p}} > 6 \text{ GeV} \]

\[ p \longrightarrow p \bar{p} \]
Collectible pbars

$E_p = 29$ GeV

$p_{\bar{p}} = 3.82$ GeV/c $\pm 3\%$

From $\sim 2.5 \times 10^{-4}$ pbar / (p cm target) $\sim 5 \times 10^{-6}$ (or 2%) are "collectible"
MARS Simulation of the pbar Yields

\[ p = 3.82 \, \text{GeV/c} \]
\[ \Delta p/p = \pm 3\% \]
Collecting pbars: Magnetic Horn

primary beam does not hit the horn

reaction products

B \sim 1/r
Collecting pbars: Magnetic Horn

CERN ACOL Horn, \( I = 400 \text{ kA} \)
MARS Simulation of the pbar Yields

\[ p = 3.82 \text{ GeV/c} \]
\[ \Delta p/p = \pm 3\% \]

\[ \text{yield} = \frac{\text{pbars in the ellipse}}{\text{primary protons}} \]
\[ = 2 \times 10^{-5} \]
Collectible pbars

**Cu target**

0 - 80 mrad
3.82 GeV/c ± 3%
Collectible pbars: Self Absorption

Cu target
0 - 80 mrad
3.82 GeV/c ± 3%

Collectible pbars [1/prim]

Target length [cm]

Cu: $\sigma_{pbar} = 0.8 \text{ b}$
Collectible pbars: MARS/FLUKA

Cu target
0 - 80 mrad
3.82 GeV/c ± 3%

no absorption

Duperray Cu

MARS Cu

Fluka Cu

Cu: \( \sigma_{\text{pbar}} = 0.8 \text{ b} \)
Collectible pbars: MARS

Cu target
0 - 80 mrad
3.82 GeV/c ± 3%

- no absorption
- Duperray Cu
- MARS Cu
- Fluka Cu

Cu: \( \sigma_{\text{pbar}} = 0.8 \, \text{b} \)
Collectible pbars: Graphite Surrounding

Cu: $\sigma_{\text{pbar}} = 8.8 \text{ b}$

C: $\sigma_{\text{pbar}} = 0.42 \text{ b}$

Cu target
0 - 80 mrad
3.82 GeV/c +/- 3%

- no absorption
- Duperray Cu
- MARS Cu
- Fluka Cu
- MARS graphite

Collectible pbars [1/prim]

p

pbar

0E+00  2E-05  4E-05  6E-05  8E-05
0  2  4  6  8  10  12  14  16  18  20  22  24  26

Target length [cm]
pbar Yield: Collection efficiency of the magnetic horn

\[
\text{yield} = \frac{\text{pbars in the ellipse}}{\text{primary protons}}
\]
pbar Yield: Comparison to CERN Data

To injection orbit of collector ring:

\[ \frac{p\text{bar}}{p} = 2 \times 10^{-5} \times 0.8 \times 0.7 = 1.1 \times 10^{-5} \]

Scattering losses/annihilation in air/aluminum

Exp. data from CERN (Baird 1998) to injection orbit:

\[ \frac{p\text{bar}}{p} = 0.45 \times 10^{-5} \times 1.5 = 0.7 \times 10^{-5} \]

Correction for different energies and emmitances
pbar Target and Magnetic Horn

- Ni rod, 110 mm, d = 3 mm
- graphite
- air-cooled AL block
The pbar separator

29 GeV p from SIS 100

pbar separator
240 π mm mrad
p = 3.82 GeV/c
Δp/p = ±3%

Collector Ring
Stochastic cooling:
Δp/p = ± 3 % → ± 0.1 %
Accumulation in next ring
Dose rates during operation
The pbar building

dump

target

7.8 m concrete walls
Target station and transport container

- Transport container is placed in front of target station.
- Door of target station and transport container are opened.
- Component is gripped by a quick coupling system.
- Trolley moves the component via rail system into the transport container.
- Doors are closed.
Overview of transport
„Ternary“ Beams: e.g. CNGS
CERN neutrinos to Gran Sasso

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

732 km
„Ternary“ Beams: e.g. CNGS
CERN neutrinos to Gran Sasso
Thank you for your attention!