Outline: Projectile fragmentation

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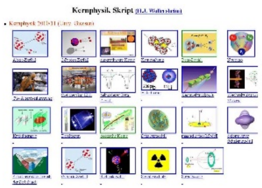


1. fragmentation cross section
2. nuclear reaction rates
3. in-flight separation of **R**adioactive **I**on **B**eams
4. fragment separator at GSI and FAIR
5. identification of **RIB**s

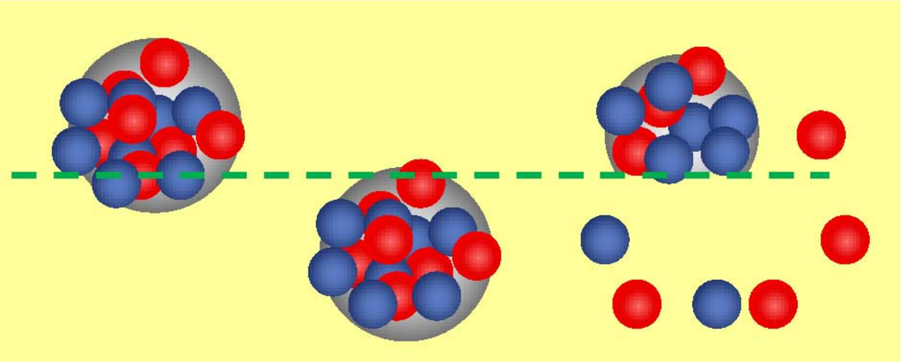
Projectile fragmentation reaction

Discovery

at Bevalac @ LBL (Lawrence Berkeley Laboratory)

D.E. Greiner et al., Phys.Rev. Lett. 35 (1975) 152

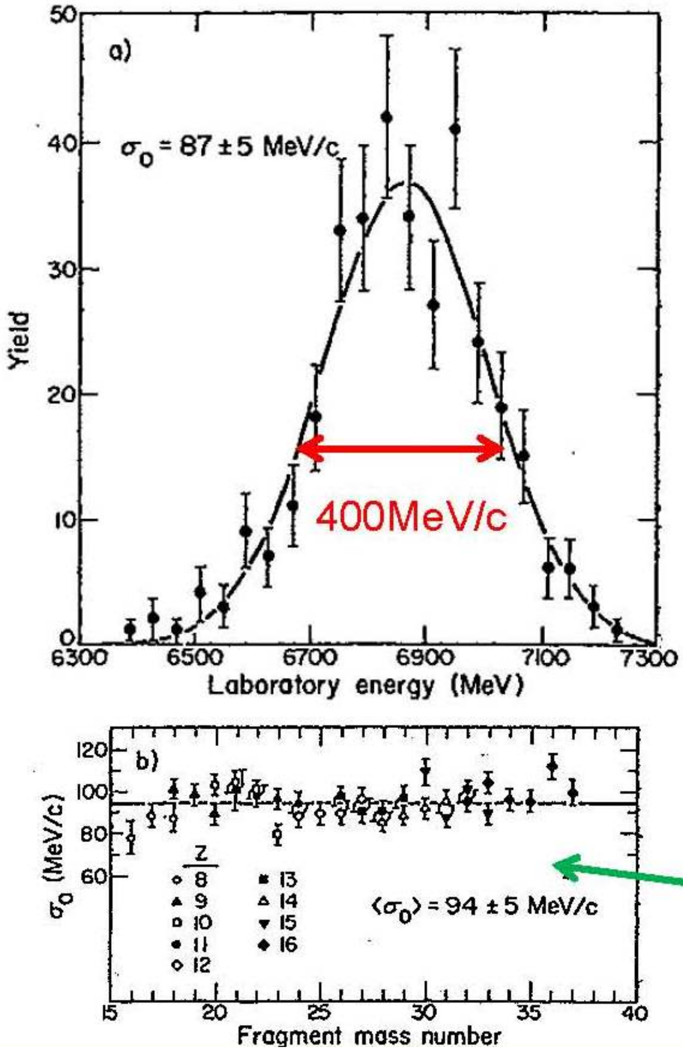
^{12}C, ^{16}O (2.1 AGeV) + Target (Be, C, Al, Cu, Ag, Pb)



- Several fragments are produced in reactions
- Velocity of fragments is almost the same as that of the beam
- Momentum distribution is narrow, and has no significant correlation with target mass and beam energies

Projectile fragmentation reaction

Momentum distribution of fragments (example ^{34}S fragments from ^{40}Ar + C @ 213 AMeV)



^{34}S fragments: 400 MeV/c narrow
^{40}Ar beam: 26600 MeV/c

Momentum distribution of fragments are represented by a simple formula based on the Goldhaber model

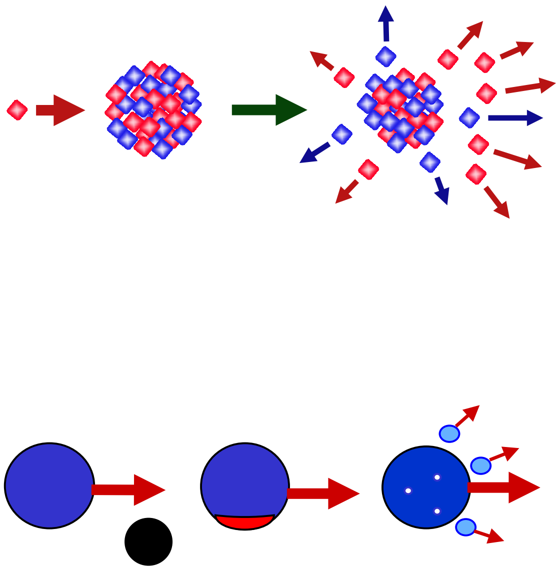
$$\sigma = \sigma_0 \cdot \sqrt{\frac{F \cdot (A-F)}{(A-1)}}$$

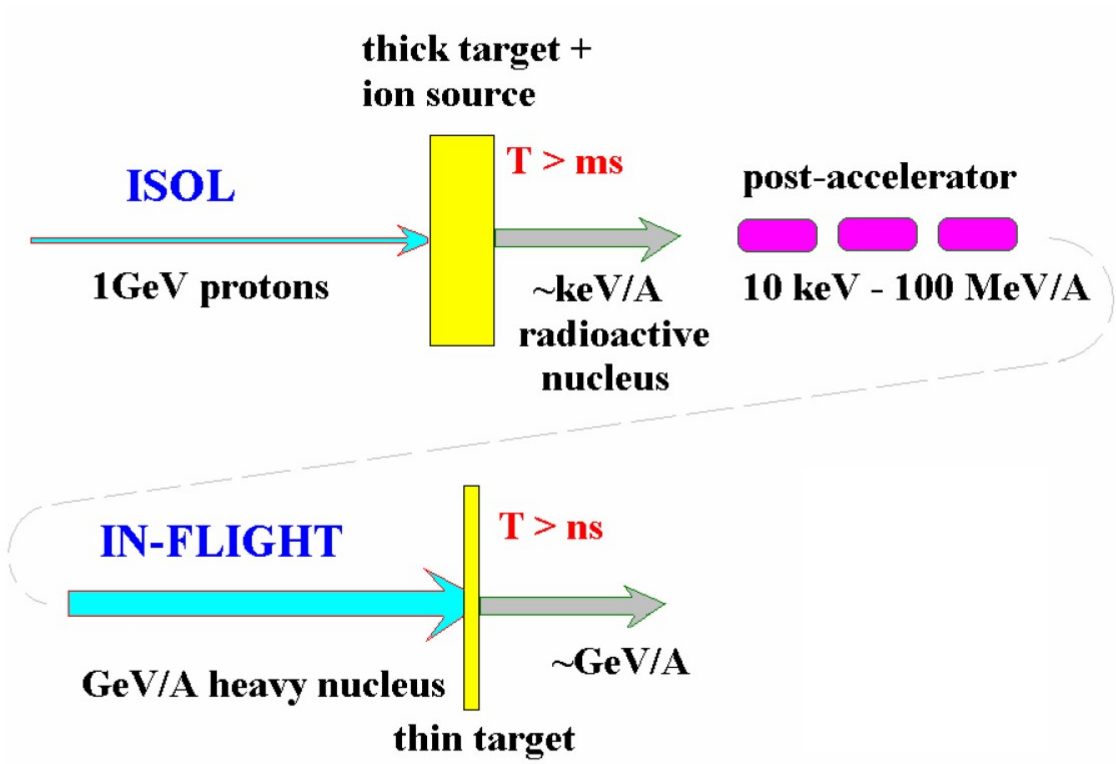
A: beam mass number
F: fragment mass number

σ_0 = 90 MeV/c

Spallation & projectile fragmentation reactions route to exotic nuclei

Spallation





Fragmentation

ISOL = Isotope Separator On Line

High-energy proton-induced nuclear reactions

Some early high-energy proton accelerators:

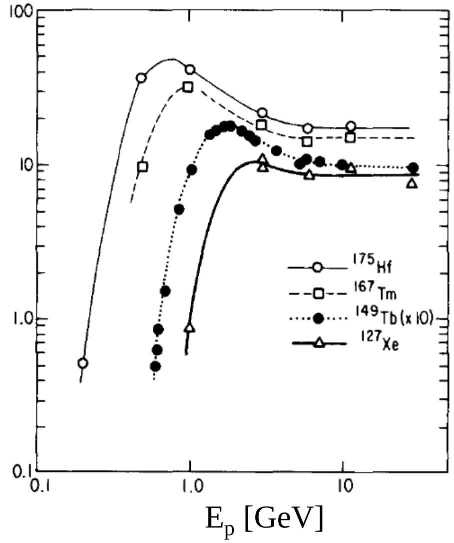
Facility	Energy	from year
Bevatron (Berkeley)	6 GeV	1954.....
AGS (Brookhaven)	11 GeV	1960.....
Fermilab (Chicago)	>300 GeV	1967.....

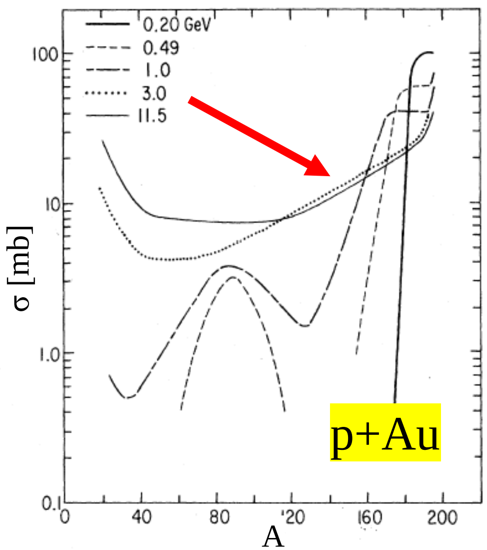
They were also used to bombard various stable target materials.

These targets were analyzed with radiochemical methods,
i.e. γ-spectroscopy with or without chemical separators

→ **Production cross sections and (some) kinematics for suitable radioactive isotopes**

High-energy proton-induced nuclear reactions

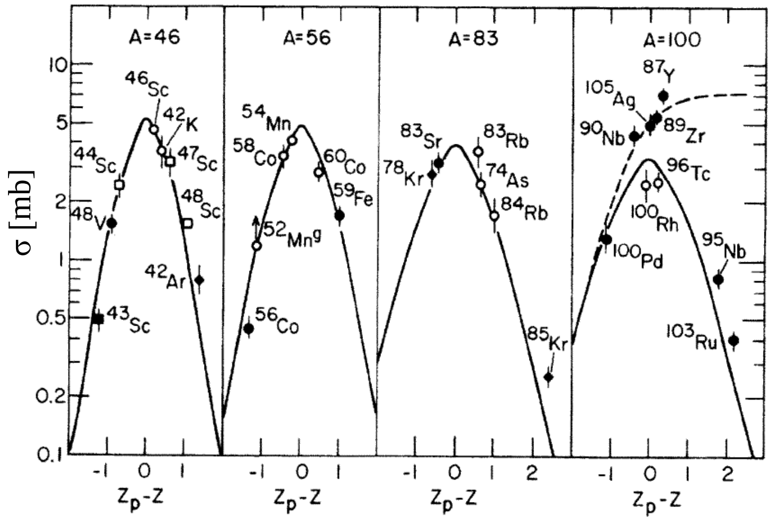




Important findings:

- Energy-independence of cross sections

- Bell-shaped Z-distribution for constant A

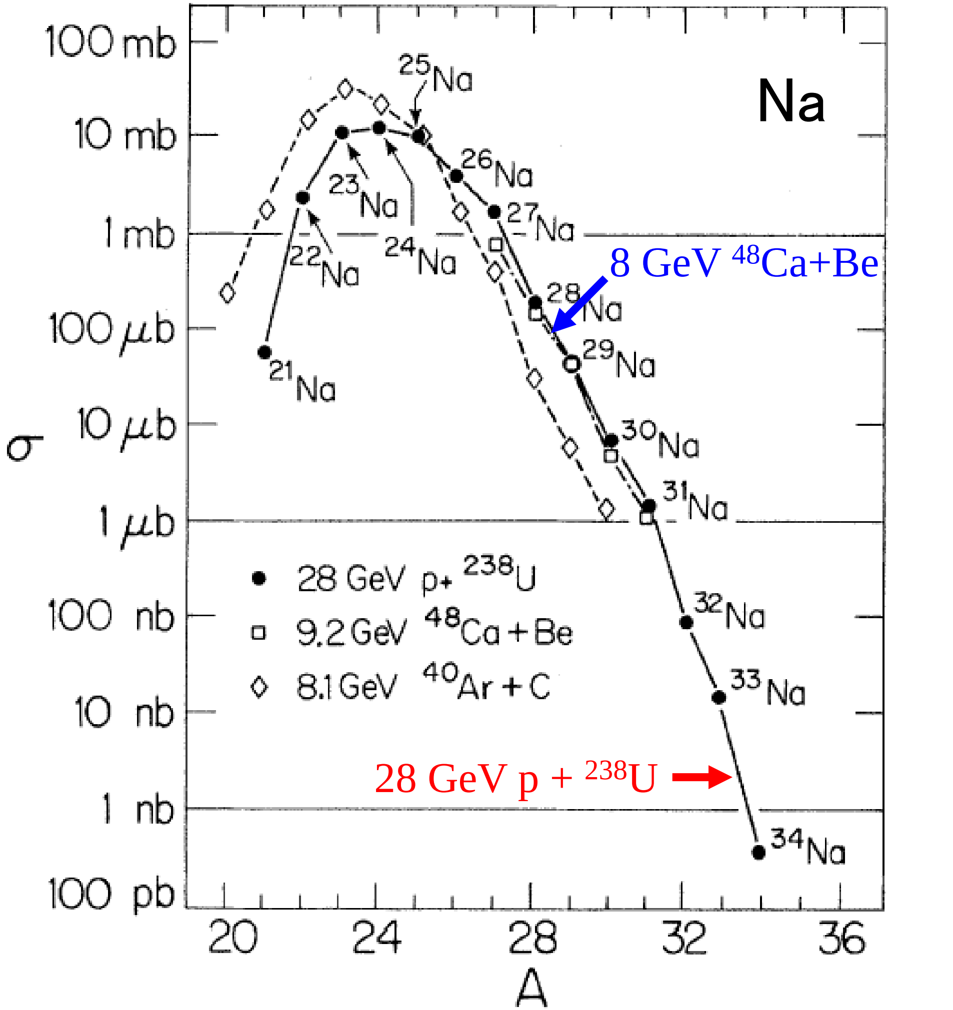


- Mass yields: exponential slope

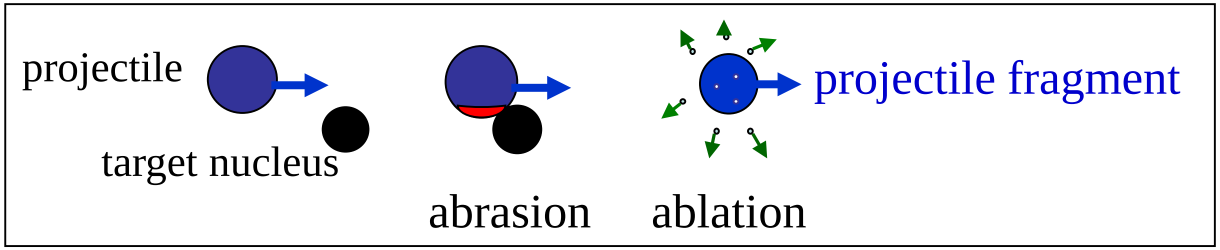
Proton- versus heavy-ion induced reactions

Proton- and heavy-ion induced reactions give very similar isotope distribution:

Target fragmentation:	GeV p + A_{target} → A
Projectile fragmentation:	GeV/u A_{proj} + p → A
are equivalent	



Projectile fragmentation reactions



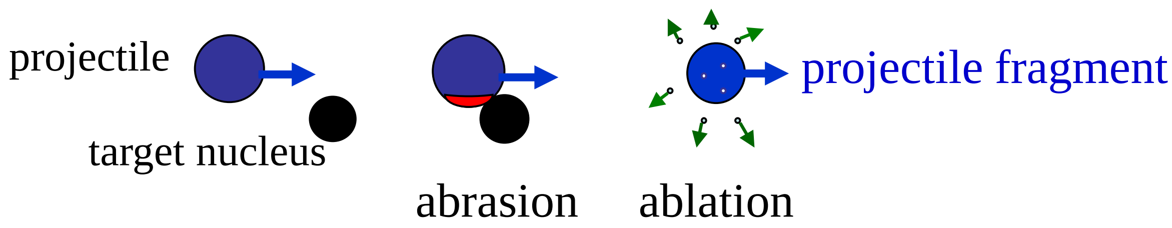
At GeV energies nucleons can be regarded as a classical particles

- Nucleon-nucleon collisions can be treated classically using measured free nucleon-nucleon cross sections (intra-nuclear cascade).
- In these collisions very *little transfer momentum* is exchanged.
- After the cascade the residual nucleus is *highly excited*.
- Heavy-ion projectiles can be treated as a bag of individual nucleons.

Physical models: Two-step approach

Step 1: **Abrasion** models or **Intranuclear-cascade** models (10^{-23} s)
Step 2: **Ablation:** nucleons evaporated (final fragment 10^{-19} s)

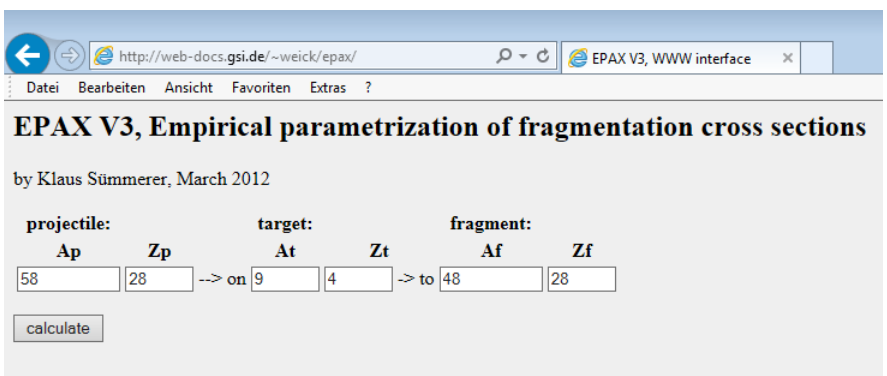
Projectile fragmentation reactions abrasion-ablation model

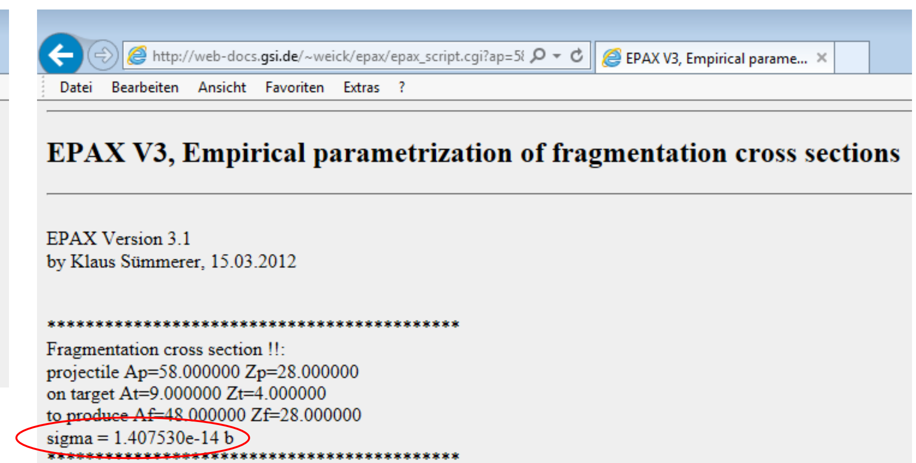


Empirical parameterization of fragmentation cross section:

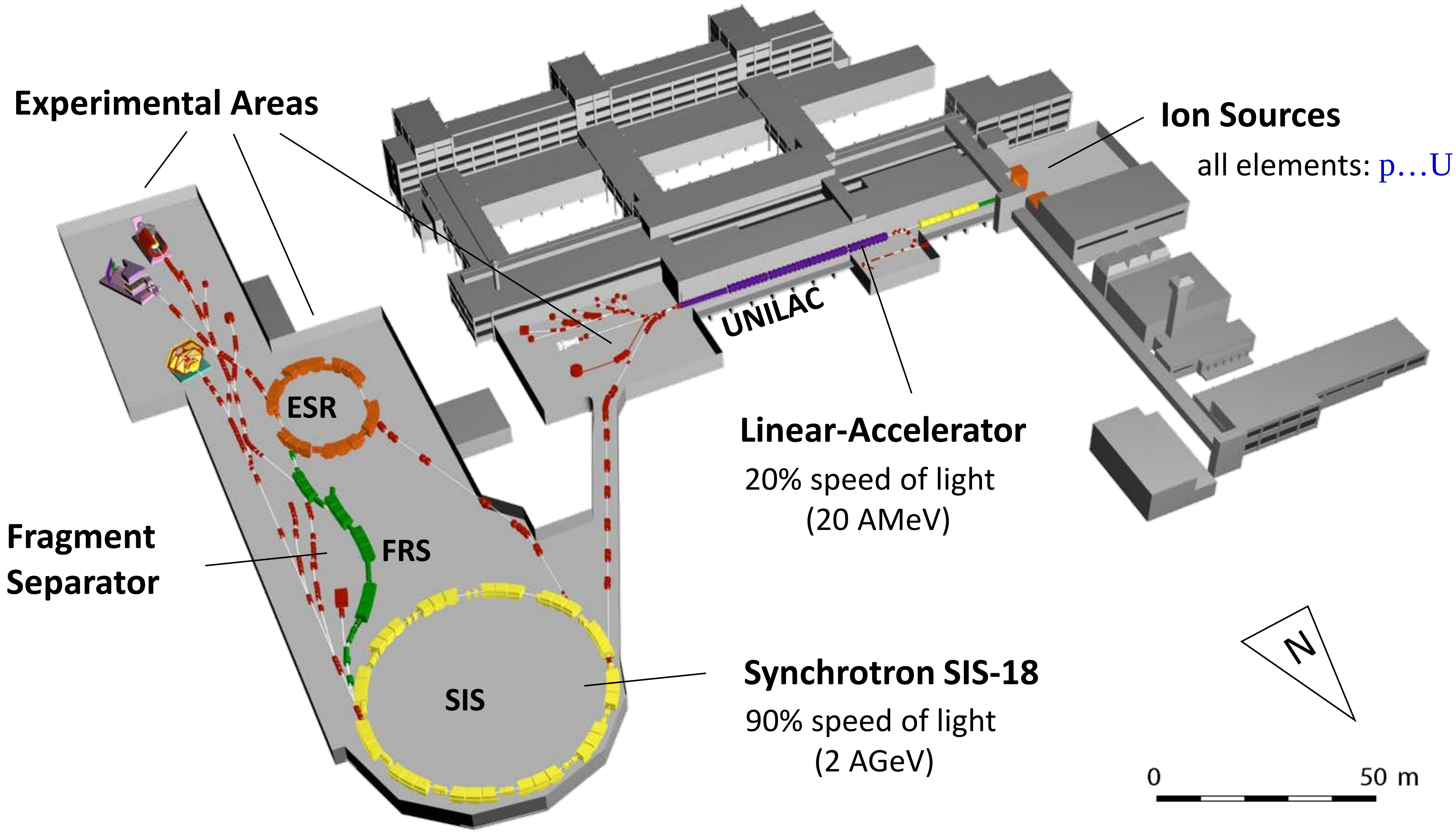
EPAX v.3 K. Sümmerer, Phys. Rev. C86 (2012) 014601

http://web-docs.gsi.de/~weick/epax/

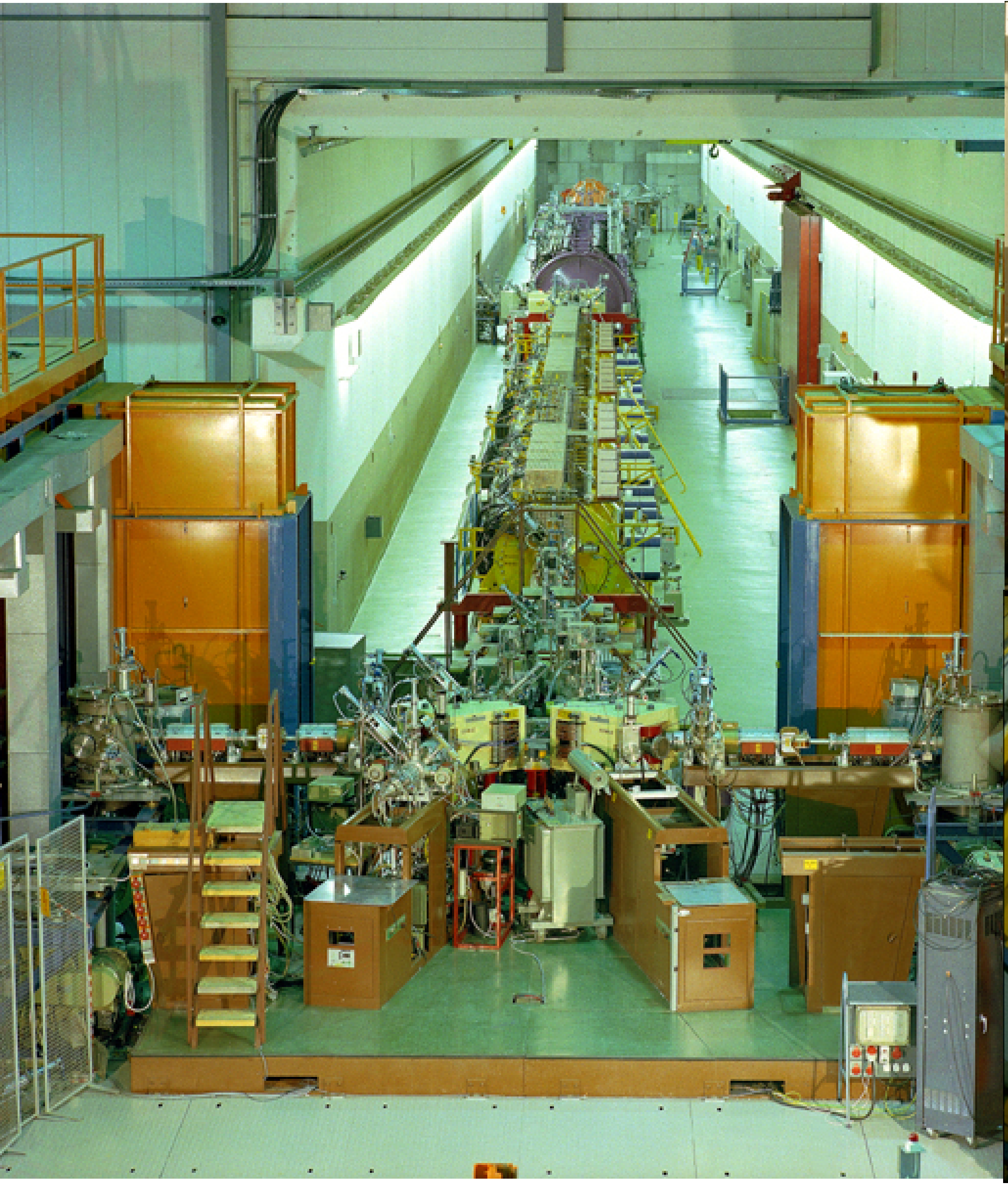


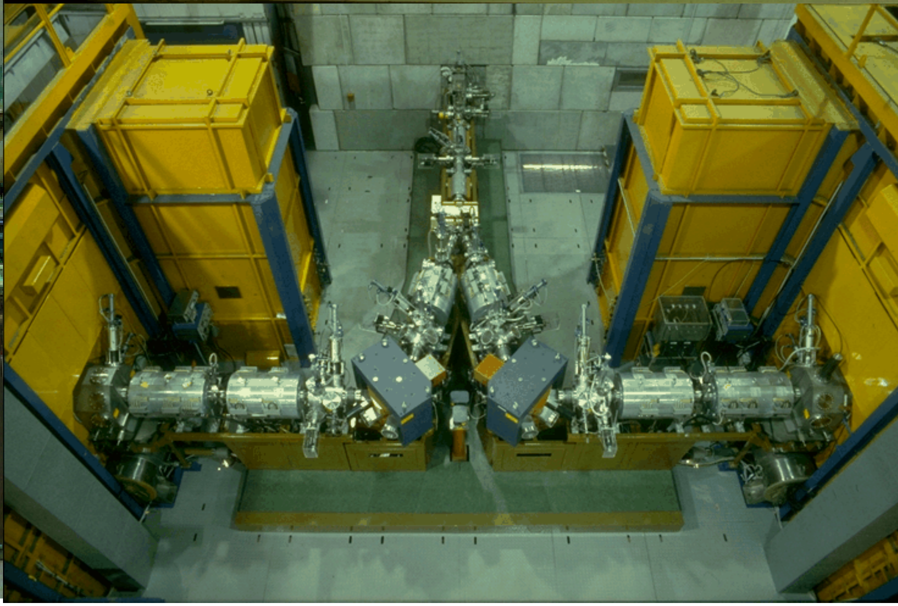


The accelerator facility at GSI

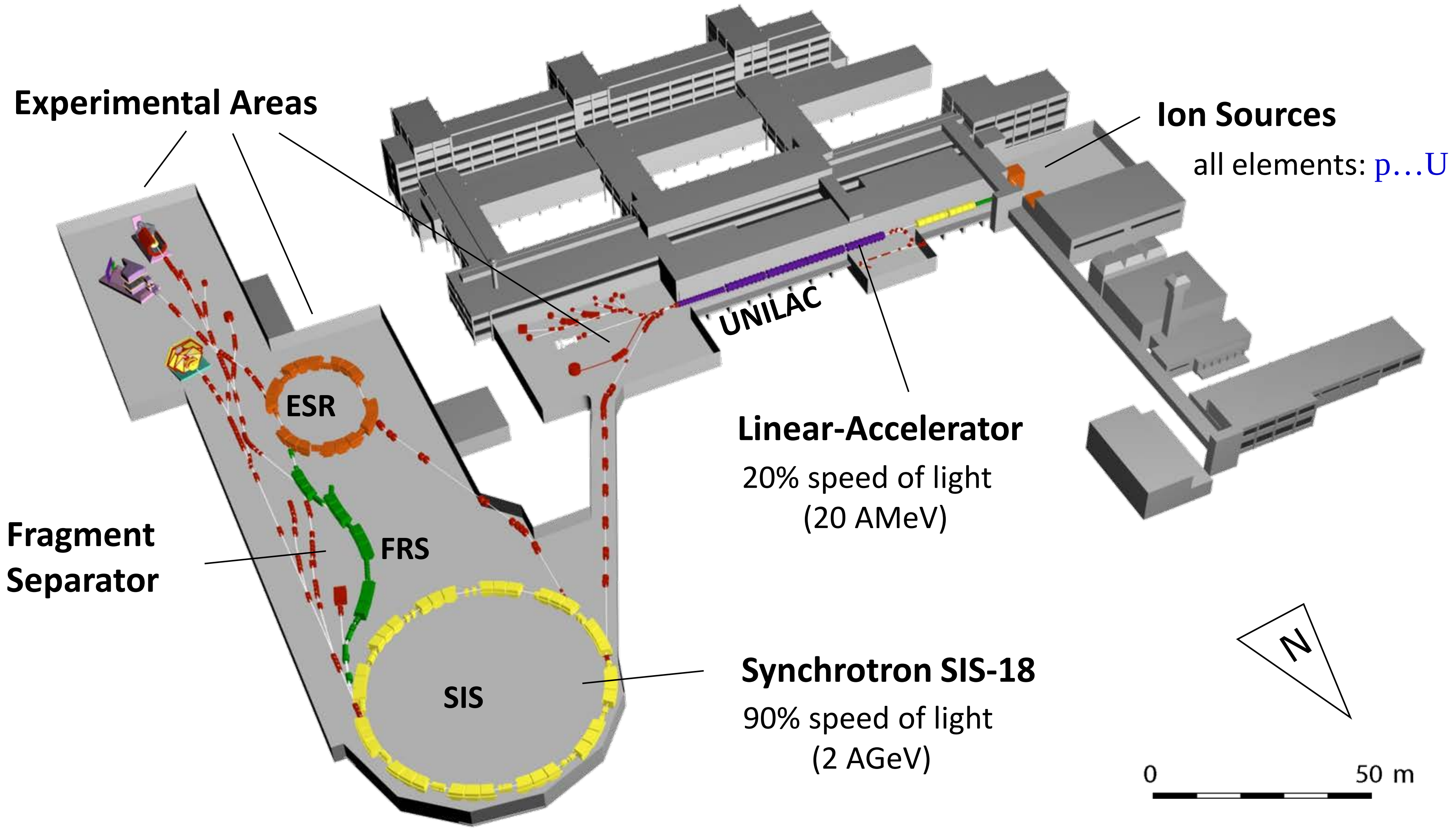


UNILAC accelerator





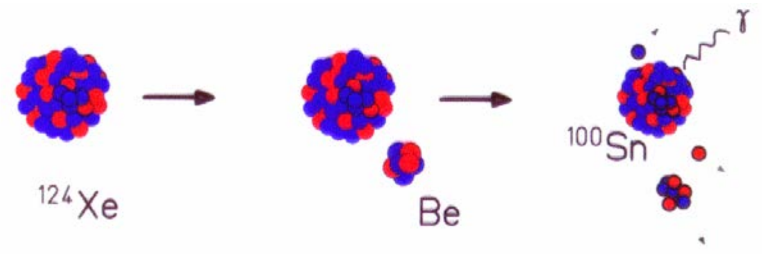
The accelerator facility at GSI



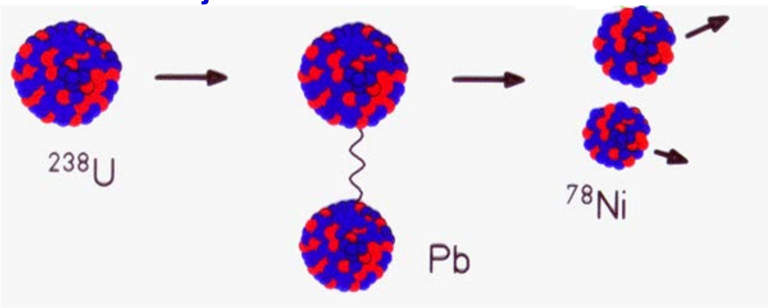
Where do we do the experiments?

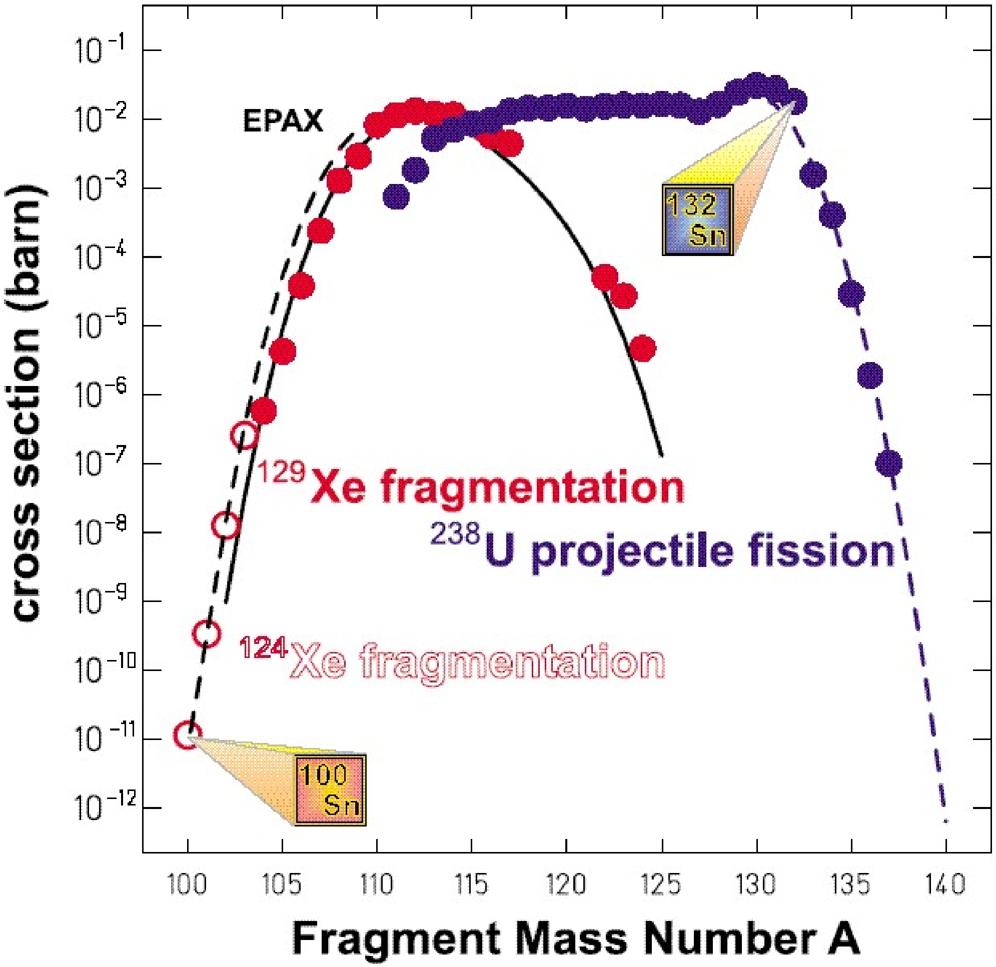
Projectile fragmentation reactions

Projectile Fragmentation



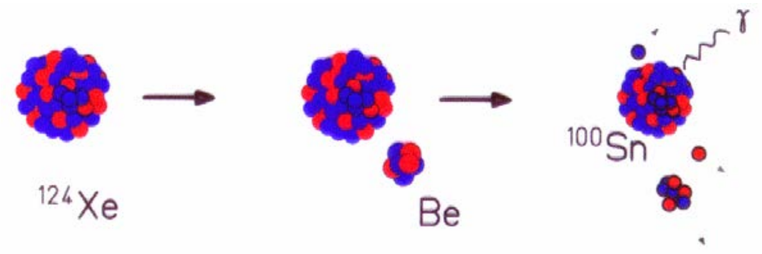
Projectile Fission



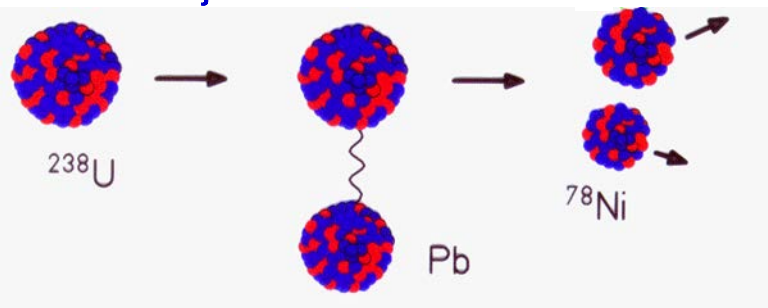


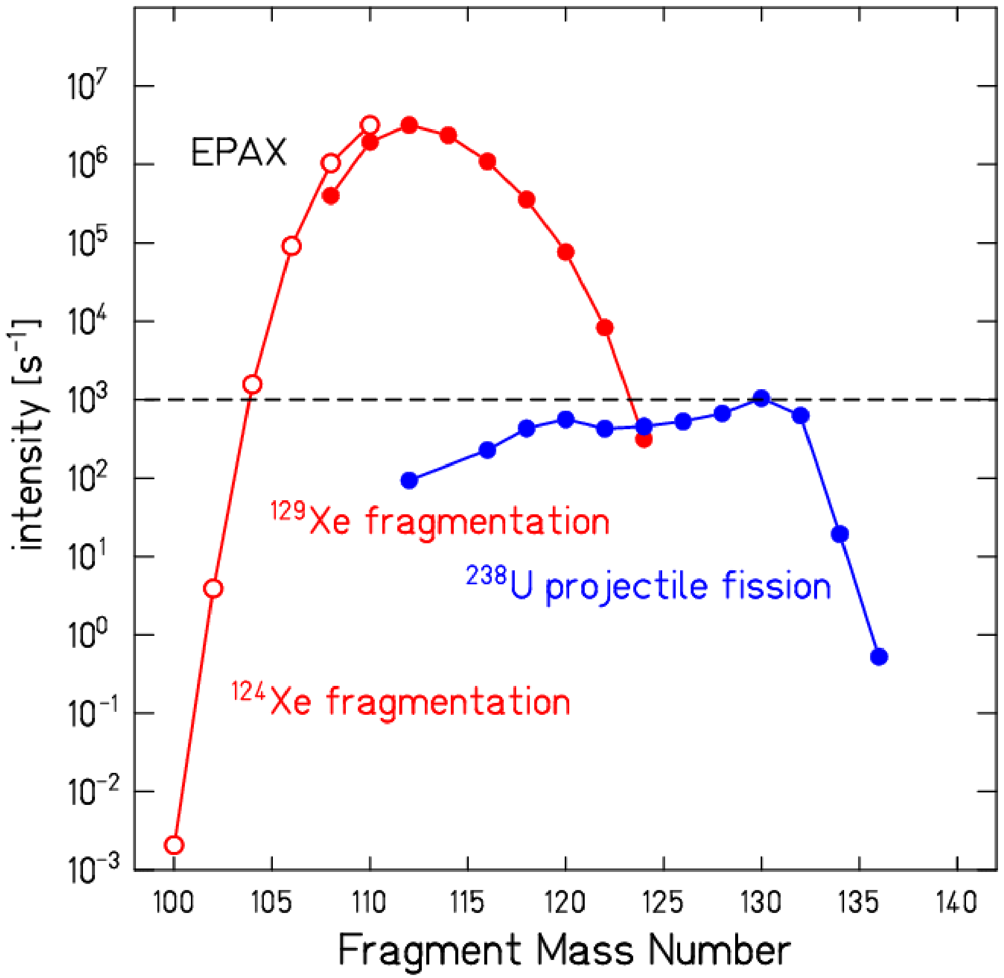
Secondary beam intensities at S4

Projectile Fragmentation



Projectile Fission



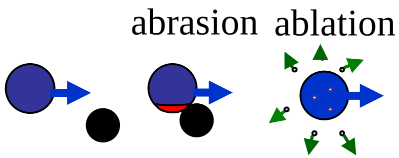


transmission SIS-FRS: 70%
primary Xe-beam intensity: $2.5\cdot10^9$[s^{-1}]
Be-target thickness: 4g/cm^2
transmission through FRS: 60%

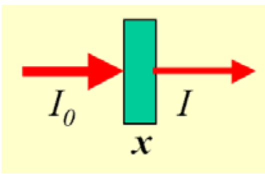
primary U-beam intensity: 10^9[s^{-1}]
Pb-target thickness: 1g/cm^2
transmission through FRS: 2%

Nuclear reaction rate

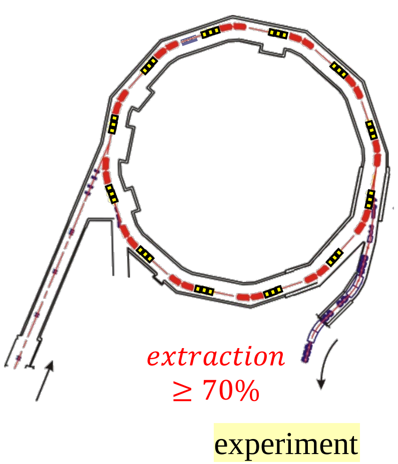
➢ **nuclear reaction rate [s^{-1}] = luminosity [atoms cm^{-2} s^{-1}] * σ_f [cm^2]**



➢ **σ_f [cm^2] for projectile fragmentation + fission**

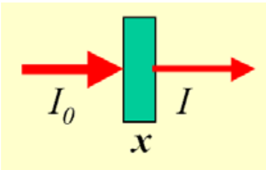


➢ **luminosity [atoms cm^{-2} s^{-1}] = projectiles [s^{-1}] * target nuclei [cm^{-2}]**



Ion	SIS-18 (2008)	SIS-100 (expected)	
$^{20}Ne^{10+}$	$2\cdot10^{11}$	$^{20}Ne^{7+}$	$1.6\cdot10^{12}$
$^{40}Ar^{18+}$	$1\cdot10^{11}$	$^{40}Ar^{10+}$	$1.4\cdot10^{12}$
$^{58}Ni^{26+}$	$9\cdot10^{10}$	$^{58}Ni^{14+}$	$1.3\cdot10^{12}$
$^{84}Kr^{34+}$	$8\cdot10^{10}$	$^{84}Kr^{17+}$	$1.2\cdot10^{12}$
$^{132}Xe^{48+}$	$7\cdot10^{10}$	$^{132}Xe^{22+}$	$1.3\cdot10^{12}$
$^{197}Au^{65+}$	$5\cdot10^{10}$	$^{197}Au^{25+}$	$1.2\cdot10^{12}$
$^{238}U^{73+}$	$1.6\cdot10^{10}$	$^{238}U^{92+}$	$1.4\cdot10^{10}$
$^{238}U^{28+}$	$1.4\cdot10^{10}$	$^{238}U^{28+}$	$5.0\cdot10^{11}$

Nuclear reaction rate



density ρ

Primary reaction rate:

$$\phi_f[s^{-1}] \cong \phi_p[s^{-1}] \cdot \frac{x[g/cm^2] \cdot 6.02 \cdot 10^{23}}{A_t[g]} \cdot \sigma_f[cm^2]$$ (thin target)

Example: ^{238}U ($10^9 s^{-1}$) on ^{208}Pb ($x=1 g/cm^2$) ⟶ ^{132}Sn (σ_f=15.4mb) reaction rate: 44571 [s^{-1}]

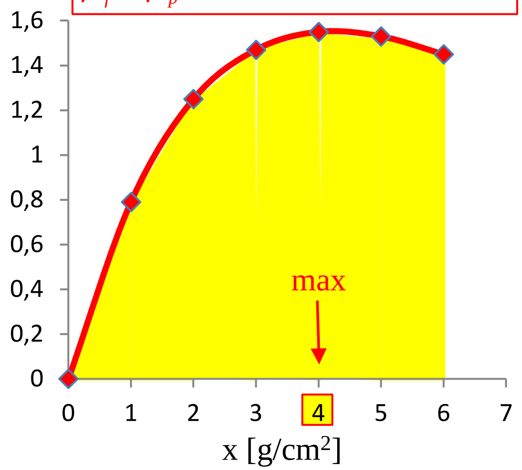
Example: ^{124}Xe ($10^9 s^{-1}$) on ^{9}Be ($x=1 g/cm^2$) ⟶ ^{104}Sn (σ_f=5.6μb) reaction rate: 375 [s^{-1}]

The ***optimum thickness*** of the production target is limited by the loss of fragments due to secondary reactions

Primary + secondary reaction rate:

$$\phi_f[s^{-1}] = \phi_p[s^{-1}] \cdot \frac{6.02 \cdot 10^{23} \cdot \sigma_f[cm^2]}{A_t[g]} \cdot \frac{1}{\mu_f - \mu_p} \cdot \left(e^{-\mu_p \cdot x[g/cm^2]} - e^{-\mu_f \cdot x[g/cm^2]}\right)$$

$$\frac{1}{\mu_f - \mu_p} \cdot \left(e^{-\mu_p \cdot x[g/cm^2]} - e^{-\mu_f \cdot x[g/cm^2]}\right)$$



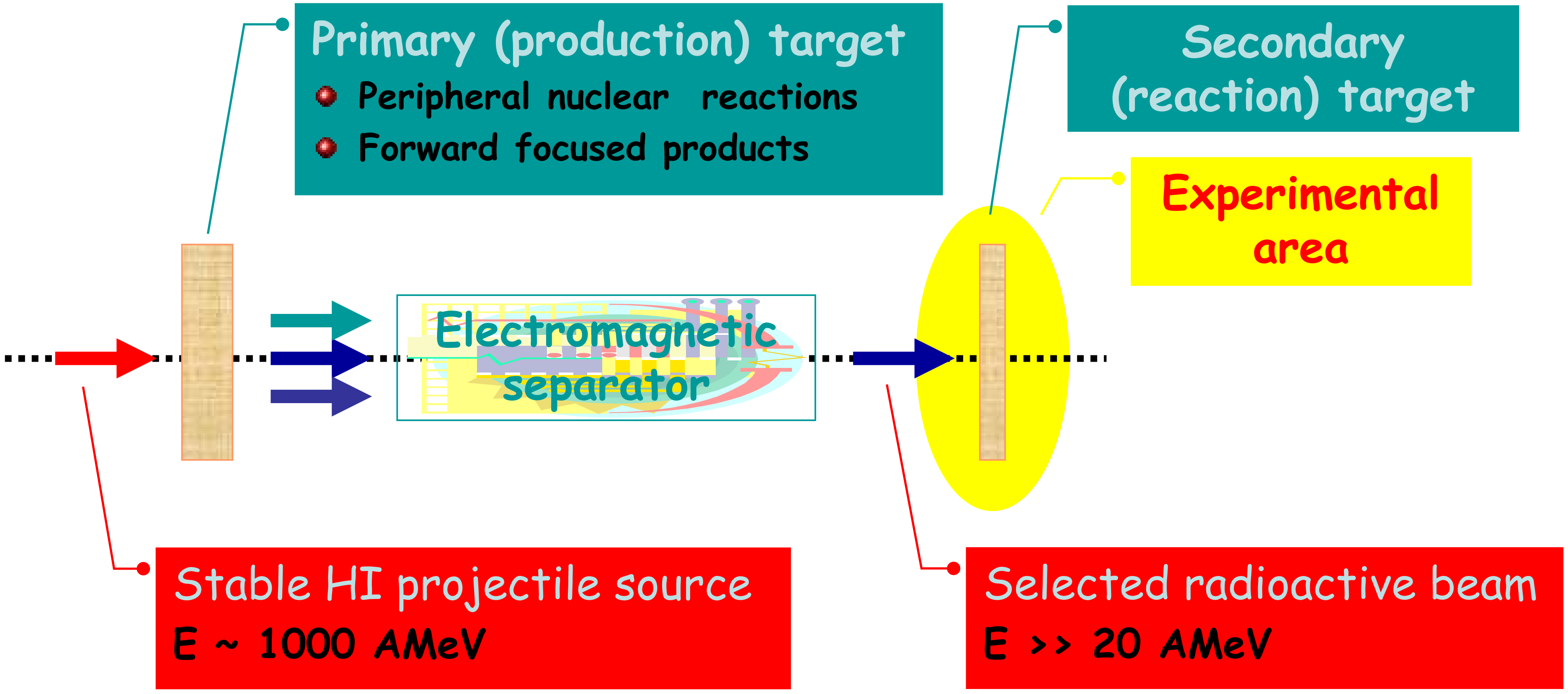
with $$\mu = \frac{6.02 \cdot 10^{23}}{A_2[g]} \cdot \sigma_{reaction}[cm^2]$$

Example: ^{124}Xe on $^{9}Be \rightarrow {}^{104}Sn$, $\sigma(^{124}Xe + {}^{9}Be) = 3.65[b] \rightarrow \mu_p = 0.244[cm^2/g]$

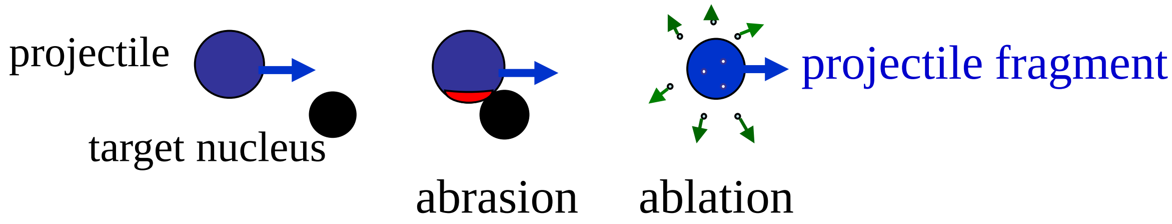
$\sigma(^{104}Sn + {}^{9}Be) = 3.44[b] \rightarrow \mu_f = 0.230[cm^2/g]$

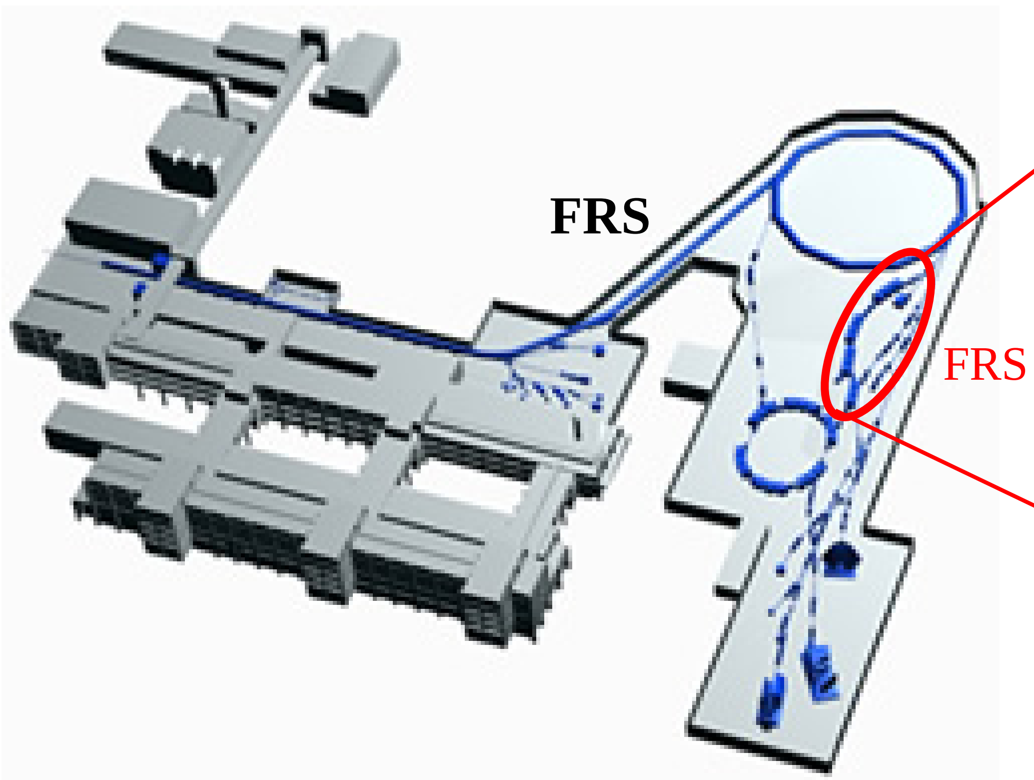
$$\phi_f[s^{-1}] = \phi_p[s^{-1}] - \phi[s^{-1}] = \phi_p[s^{-1}] \cdot \left\{1 - e^{-N_t[cm^{-2}] \cdot \sigma_f[cm^2]}\right\}$$ (thick target)

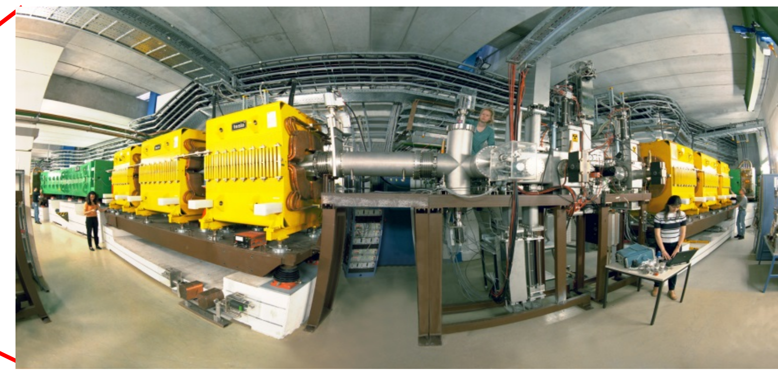
In-flight separation of Radioactive Ion Beams



Fragmentation at relativistic energies







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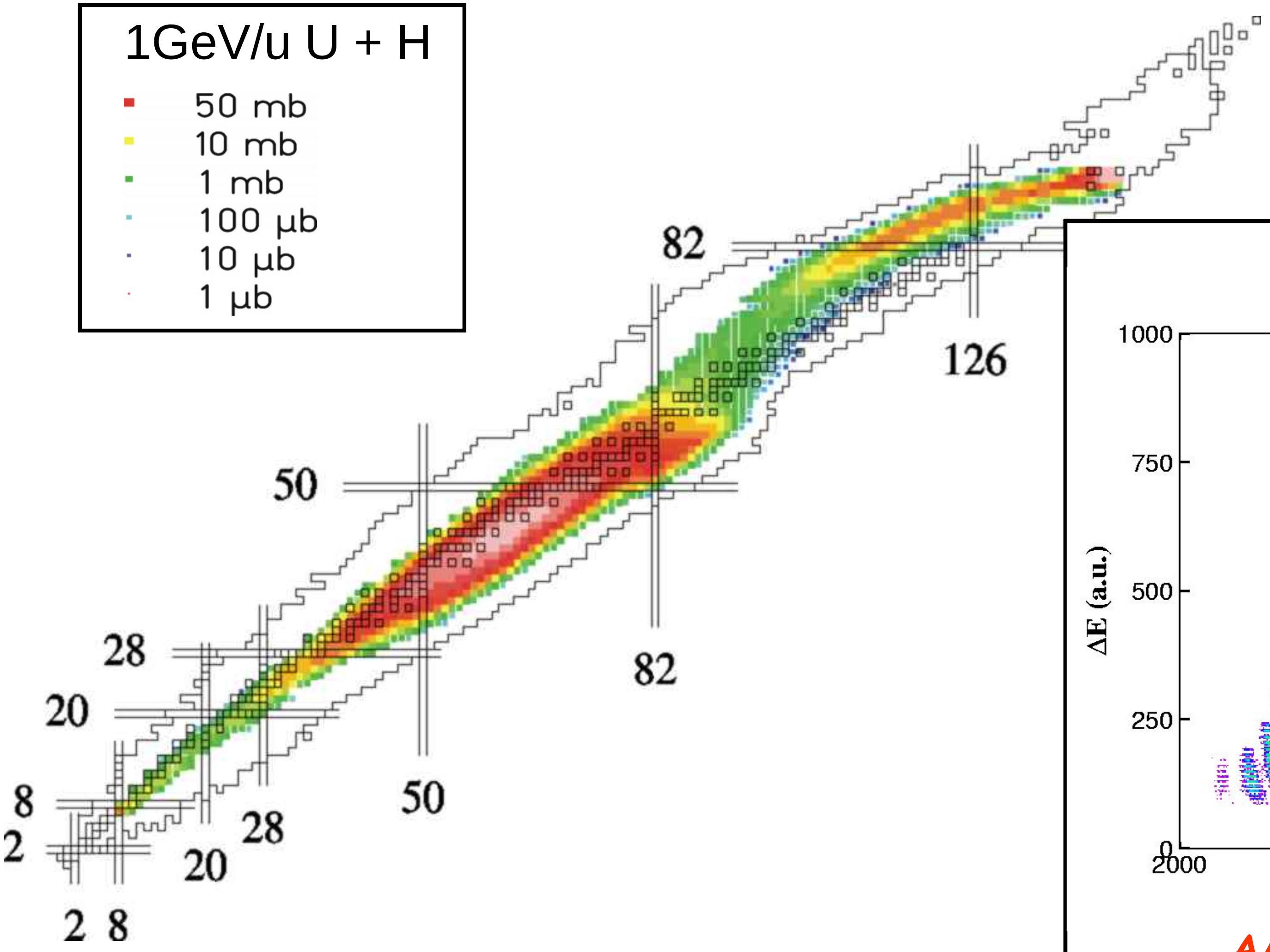
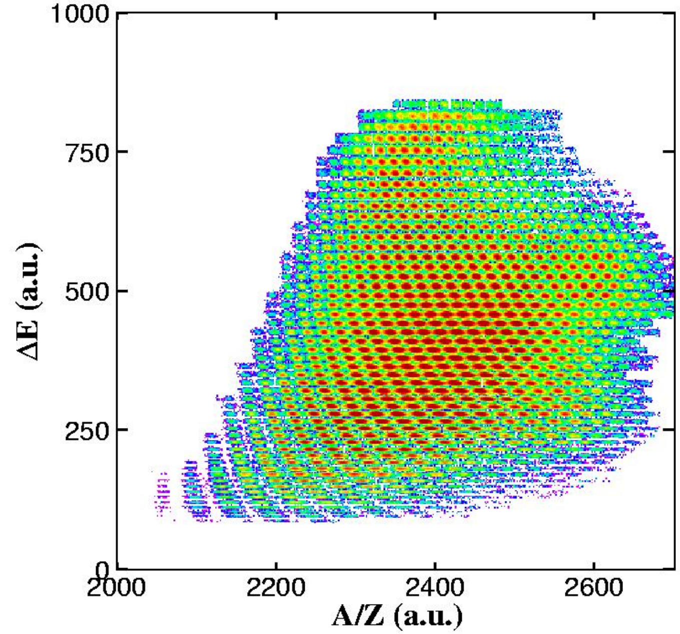
Radioactive Ion Beams at GSI

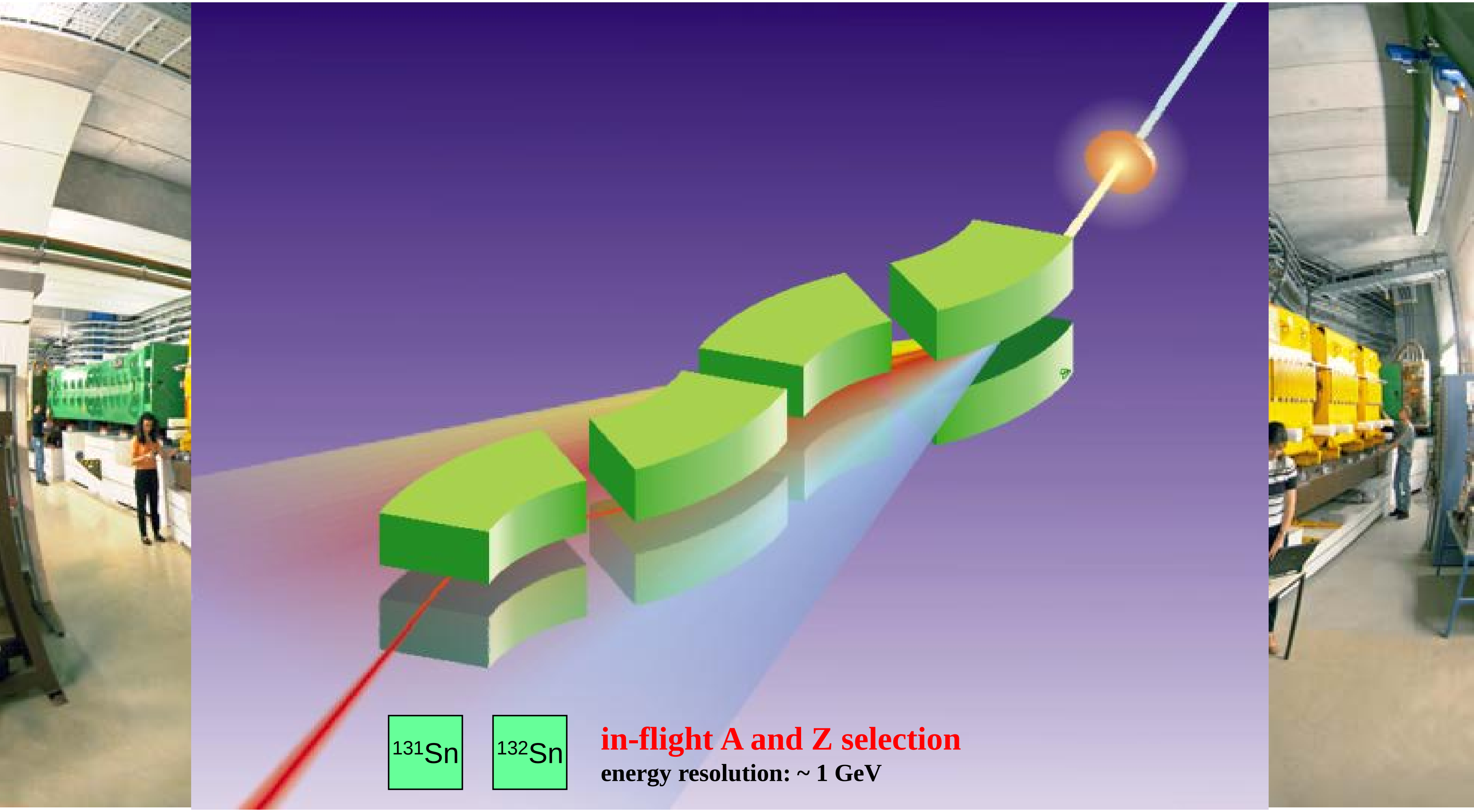


About 1000 nuclear residues identified



A/Z-resolution ~10^{-3}

FRagment Separator at GSI



in-flight A and Z selection

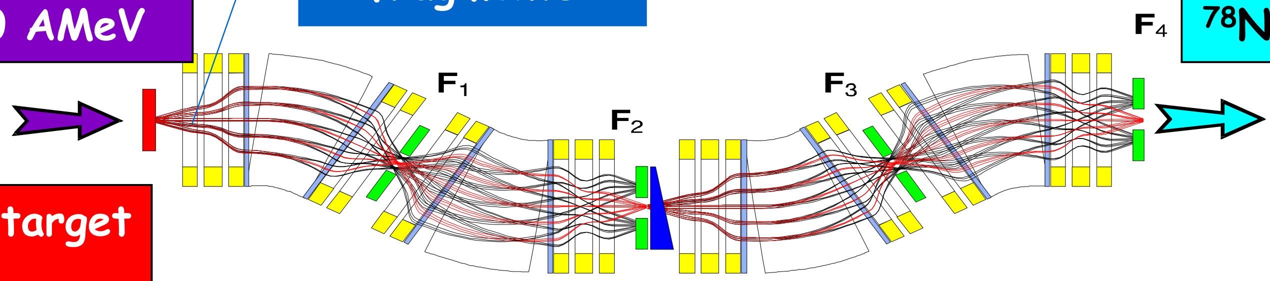
energy resolution: ~ 1 GeV

Rare isotope selection at FRS: **Bρ-ΔE-Bρ** selection

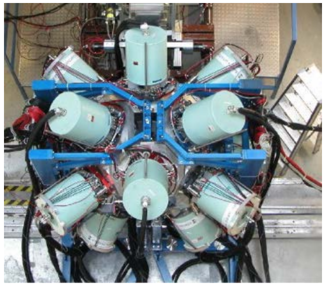
primary beam
^{86}Kr ~700 AMeV

fully striped fragments

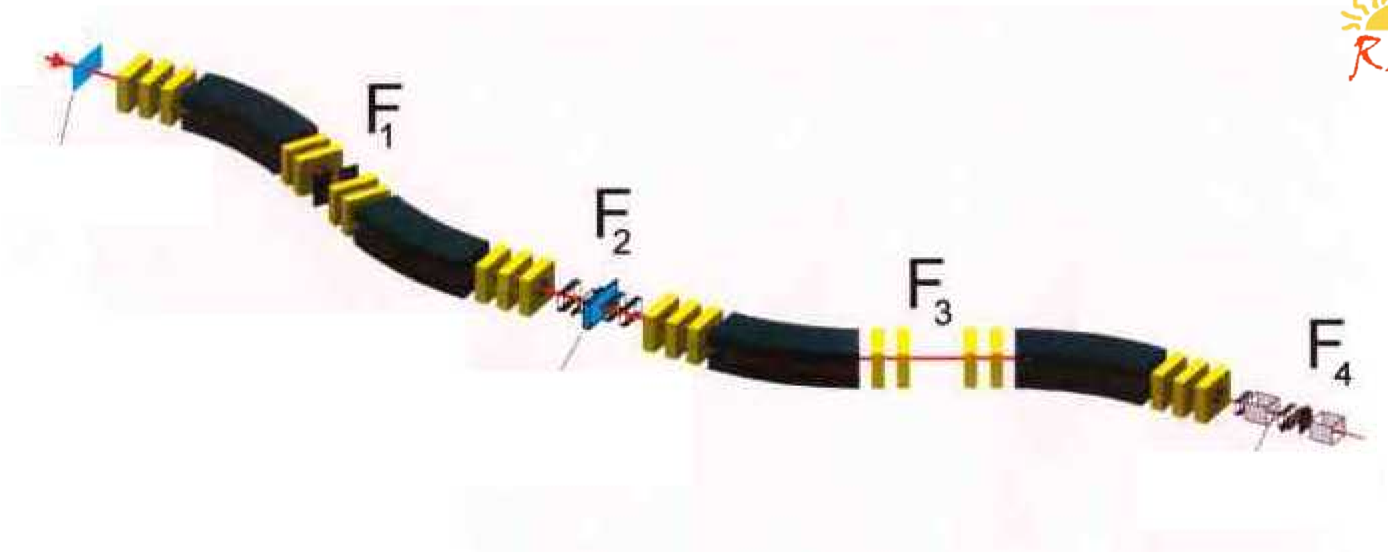
production target
^{9}Be



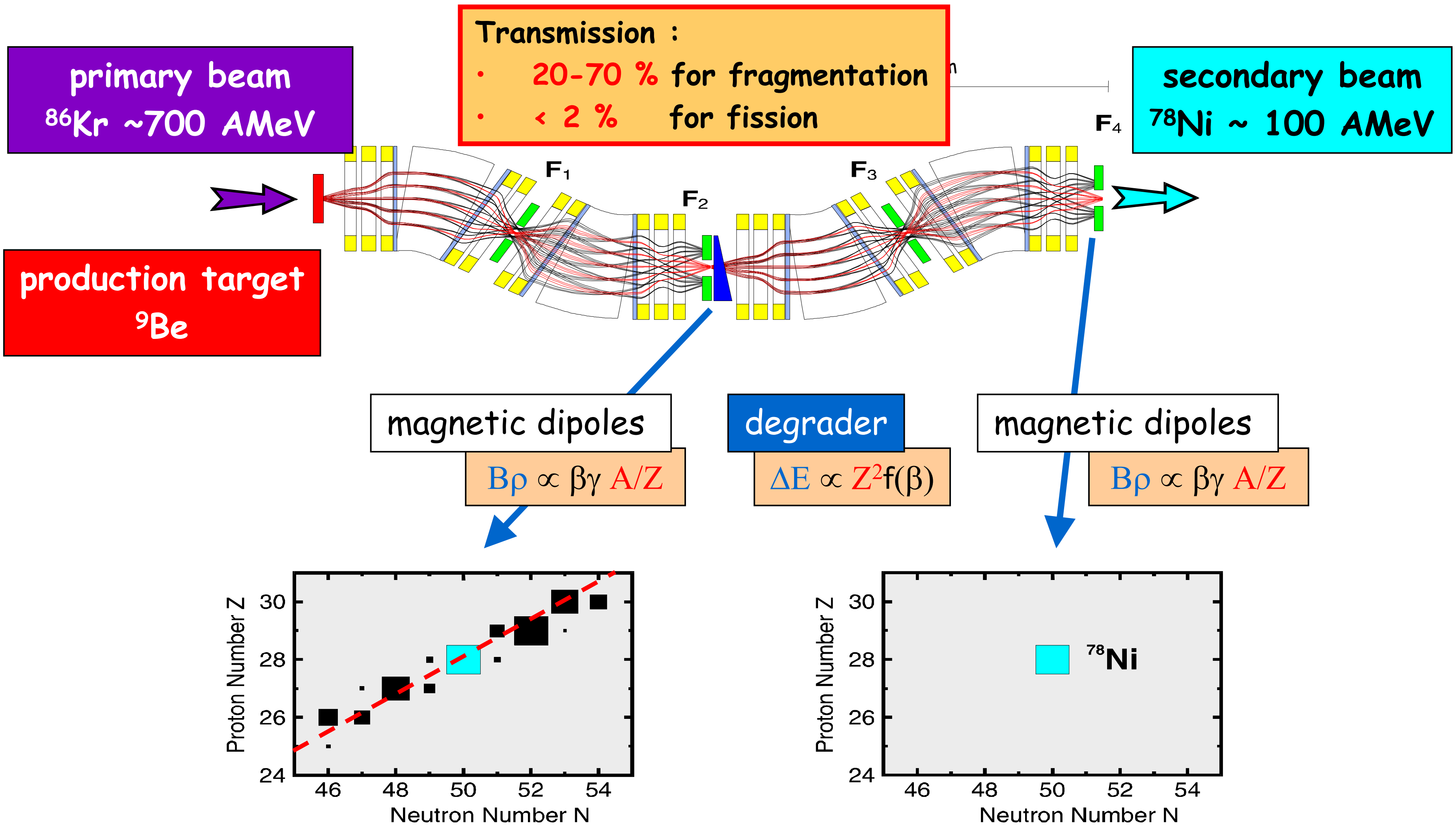
secondary beam
^{78}Ni ~ 100 AMeV



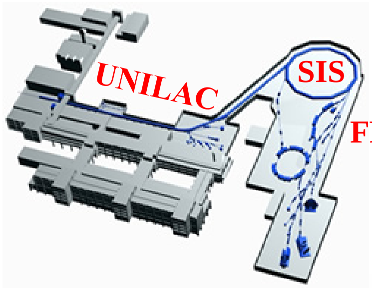
RISING

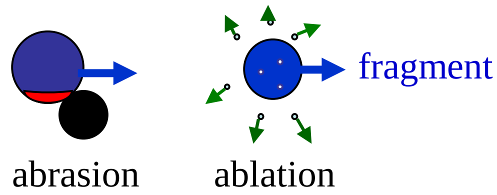


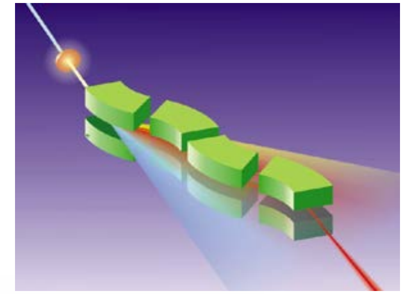
Rare isotope selection at FRS: Bρ-ΔE-Bρ selection



Production, separation, identification







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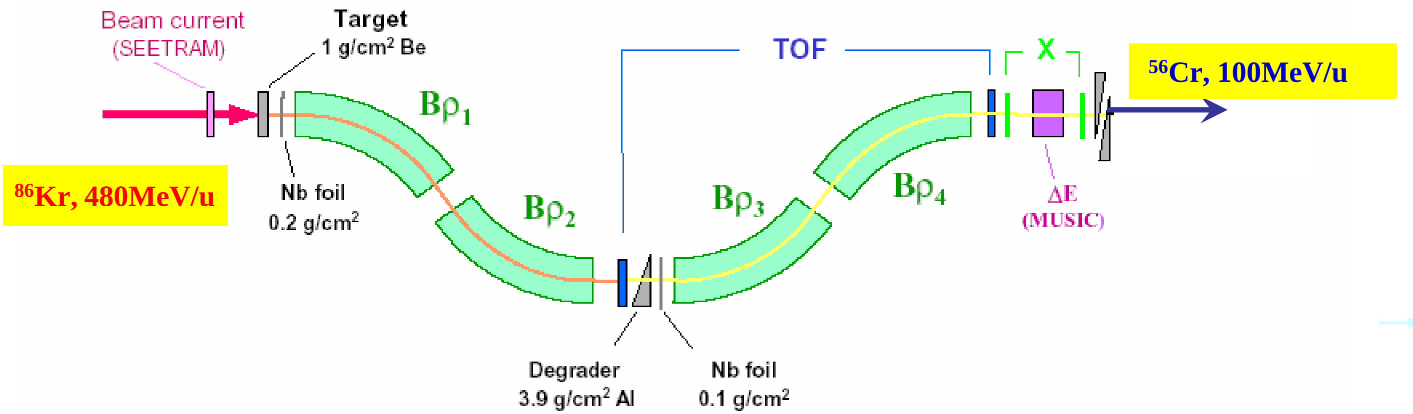
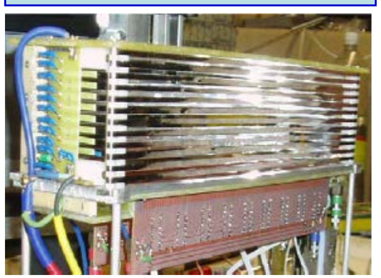
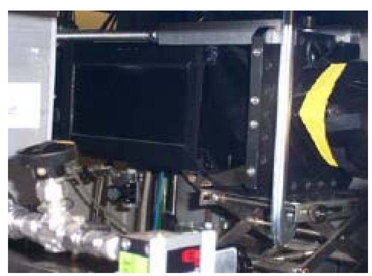
Separator



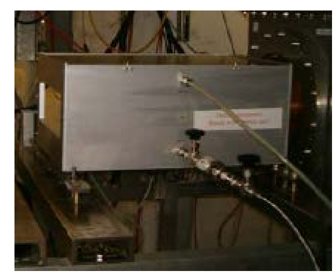
Standard FRS detectors



TPC-**x,y position** @ S2,S4

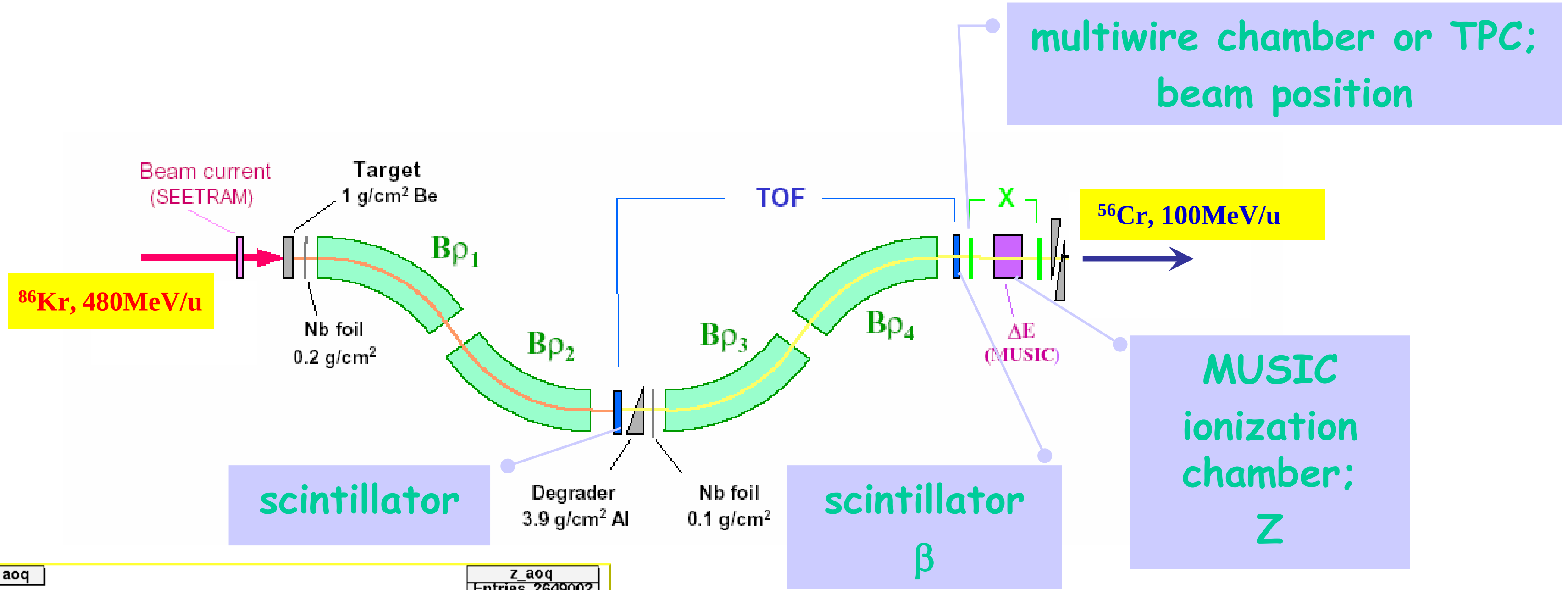


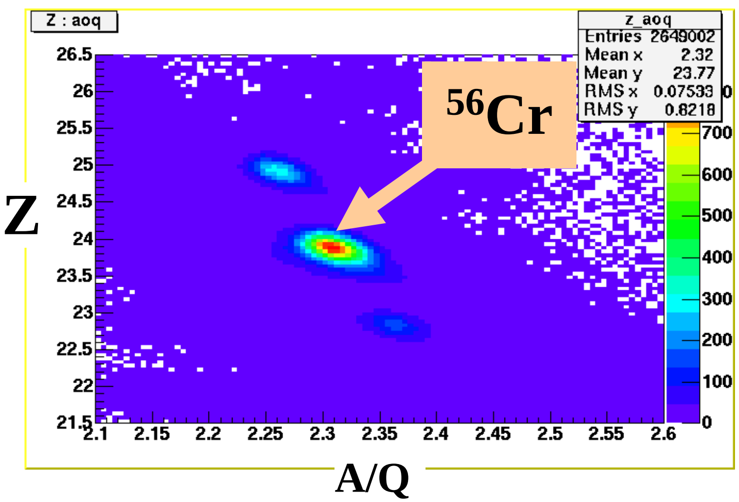
Plastic scintillator (**TOF**) @ S4

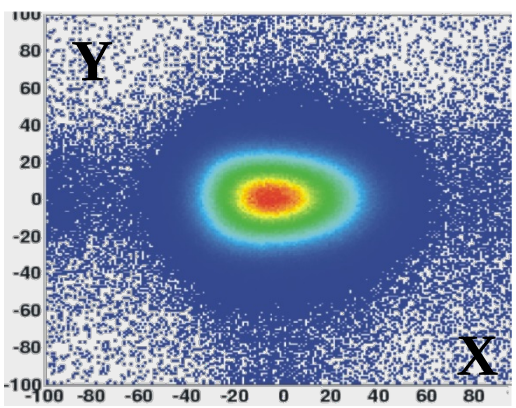


MUSIC (**ΔE**) @ S4

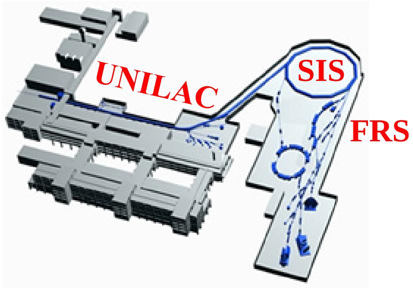
Production, separation, identification

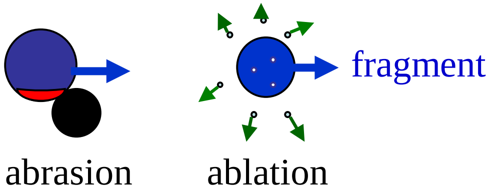


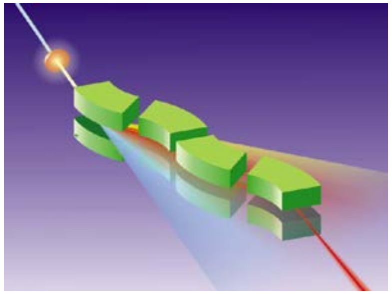




Production, separation, identification







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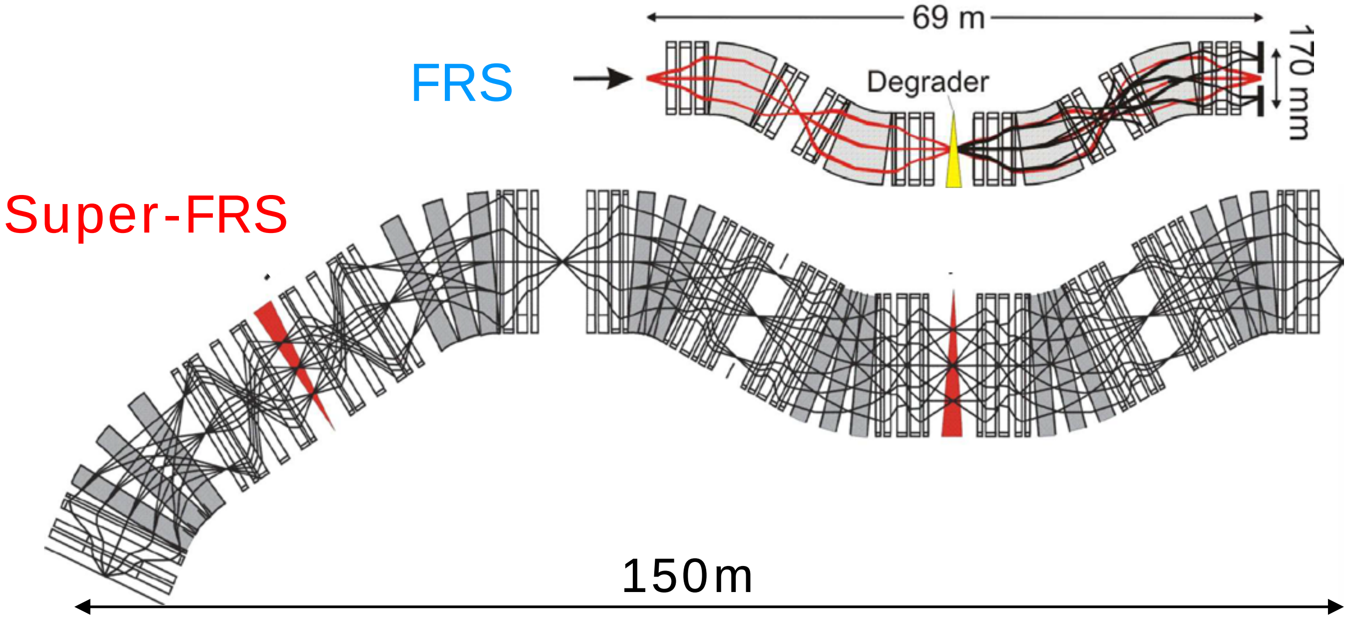
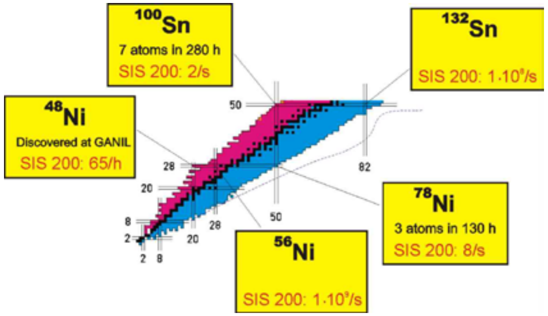
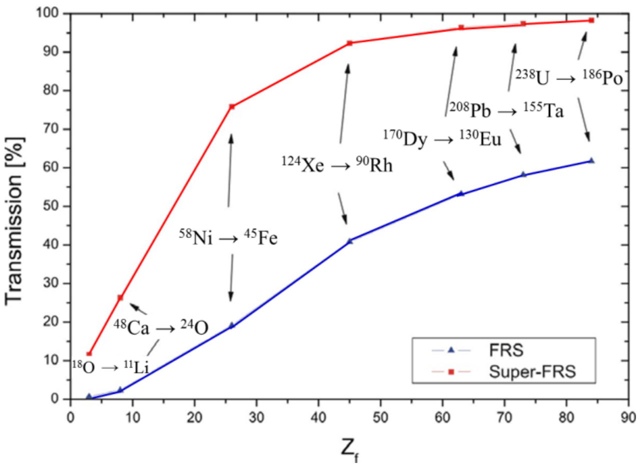
Comparison of FRS with Super-FRS

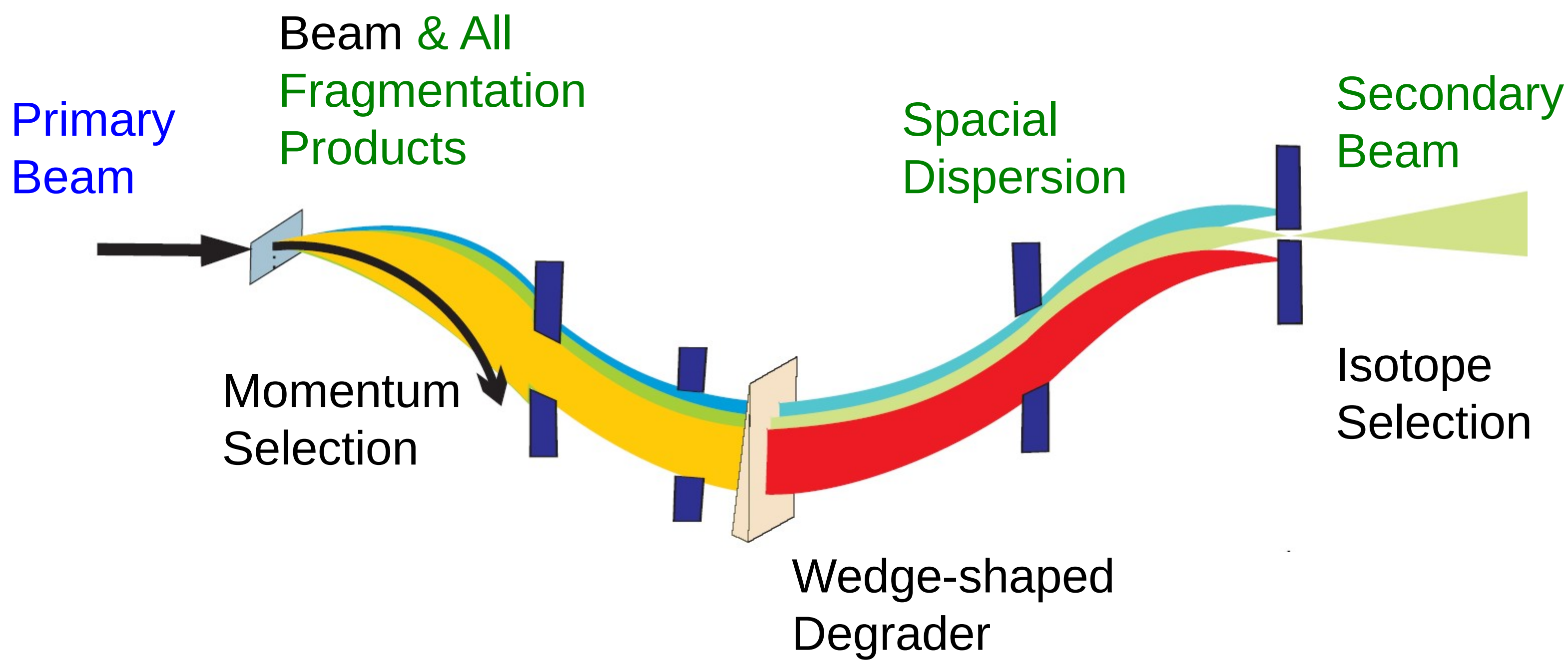


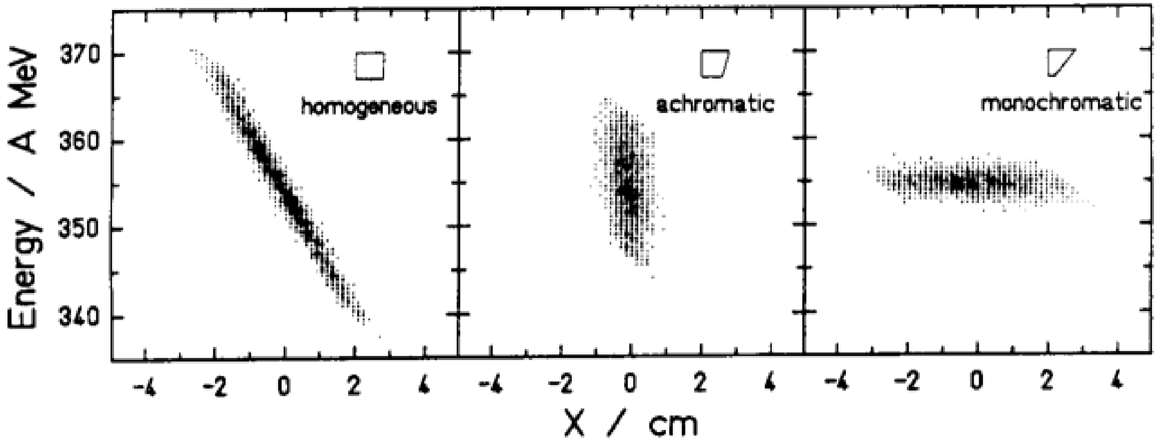


	$B\rho_{max}$	$\Delta p/p$	$\Delta\Phi_x$, $\Delta\Phi_y$	resolving power	gain factor ^{19}C	^{132}Sn
FRS	18 Tm	1.0 %	±13, ±13 mrad	1500	1	1
Super-FRS	20 Tm	2.5 %	±40, ±20 mrad	1500	5	10
				including primary rate	250	20 000



FRagment Separator

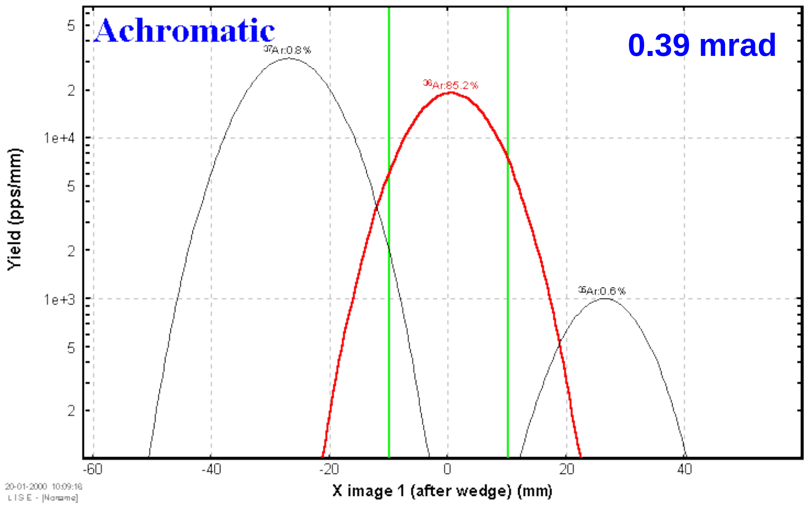


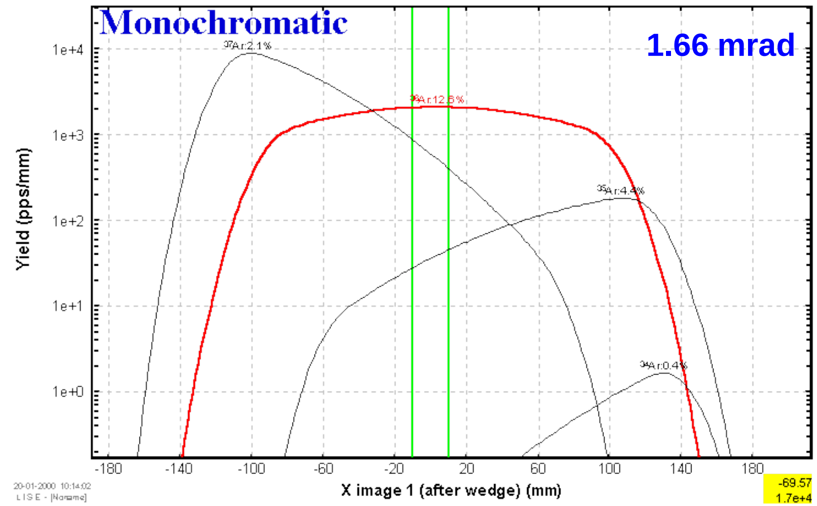


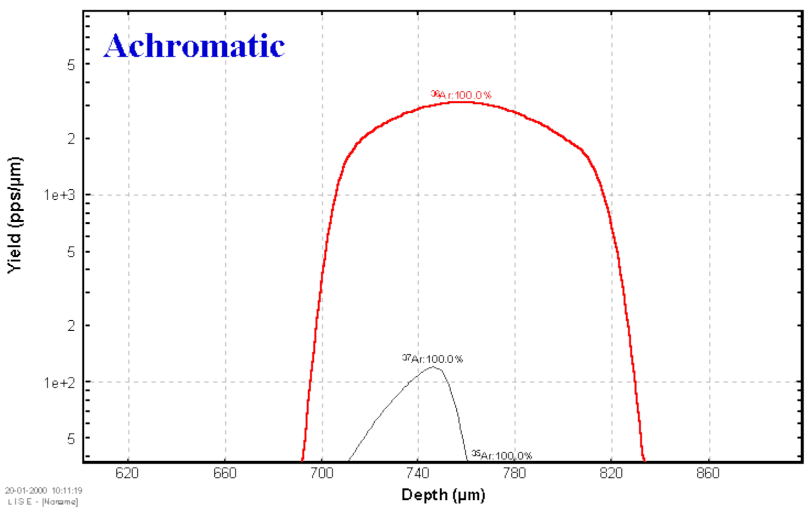
^{19}Ne at 600AMeV:
Phase-space imaging of differently shaped degraders within the achromatic ion-optical system. The results for a homogeneous, an achromatic, and a monoenergetic degrader are given. All degraders have the same thickness on the optical axis (d/r=0.5)

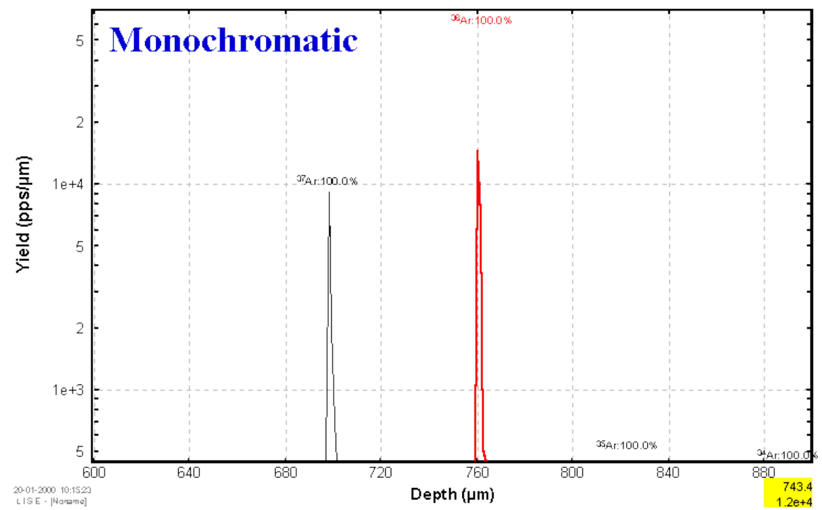
Fragment separation settings

^{40}Ar 50MeV/u + Ta (100µm), wedge shaped Al (200µm) degrader

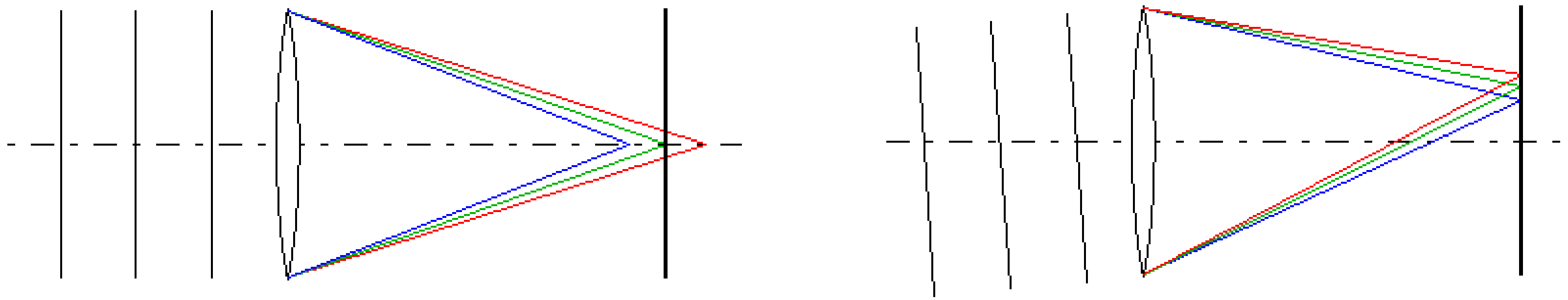








Optics: chromatic aberration



When different colors of light propagate at different speeds in a medium, the refractive index is wavelength dependent. This phenomenon is known as dispersion.

Longitudinal (axial) chromatic aberration:
The focal planes of the various colors do not coincide.

Transverse (lateral) chromatic aberration:
The size of the image varies from one color to the next.