Simulation of Fragment Separators

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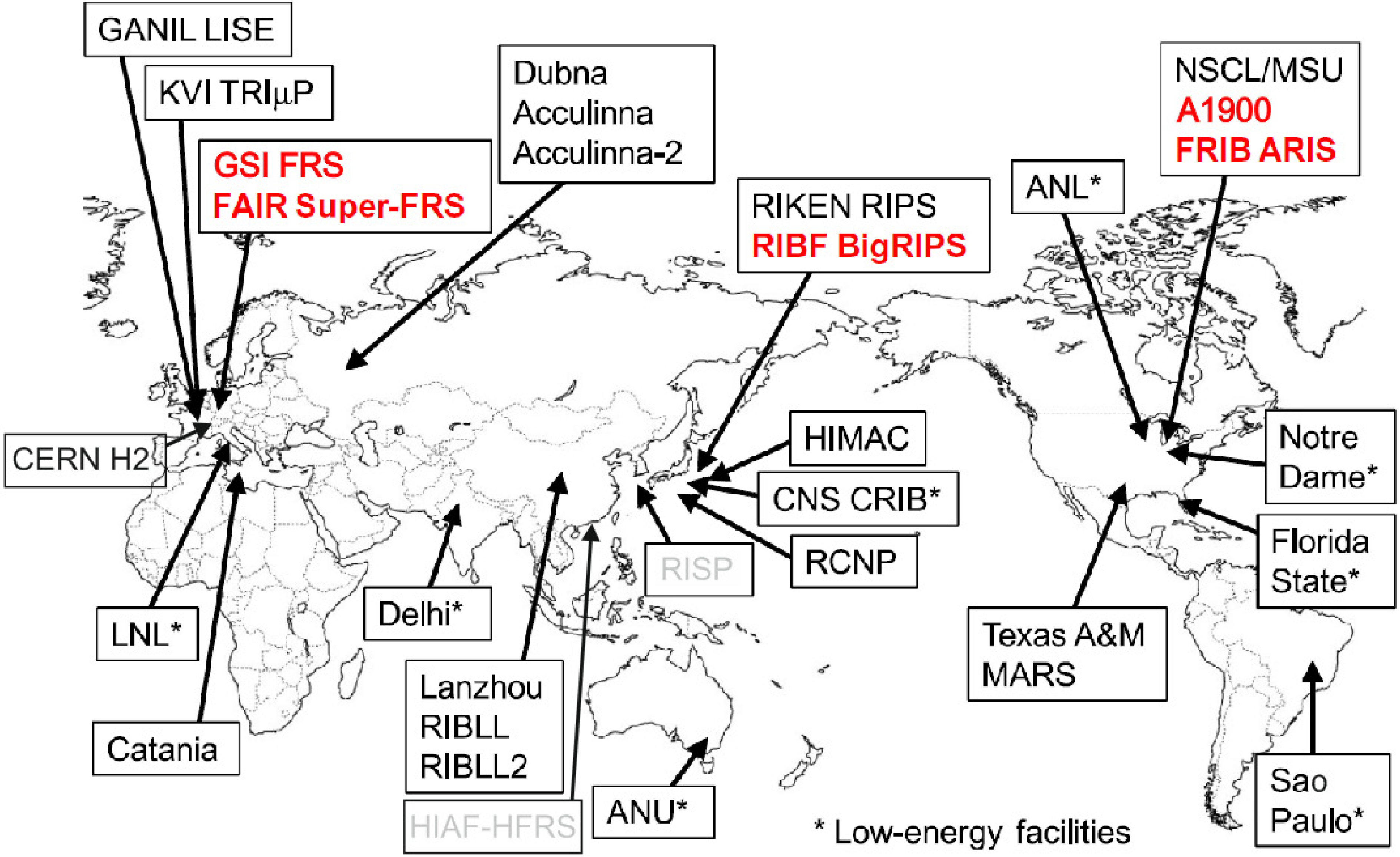
Accelerator Seminar, 21st Feb 2019

Fragment Separators Worldwide
= devices to separate nuclides produced in-flight

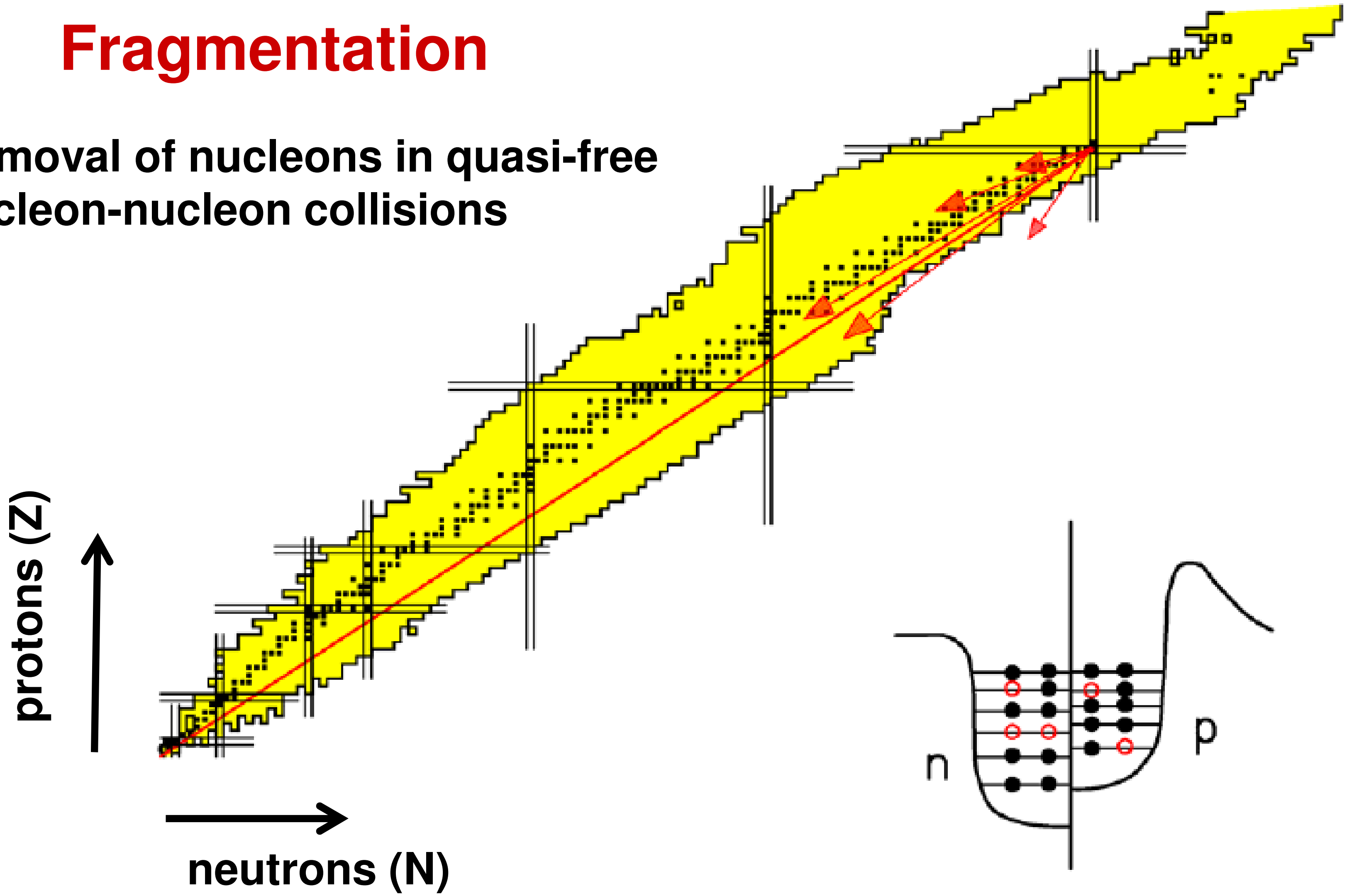


adapted from T. Kubo, NIM B 376,102 (2016)

How to produce Rare Isotopes ?

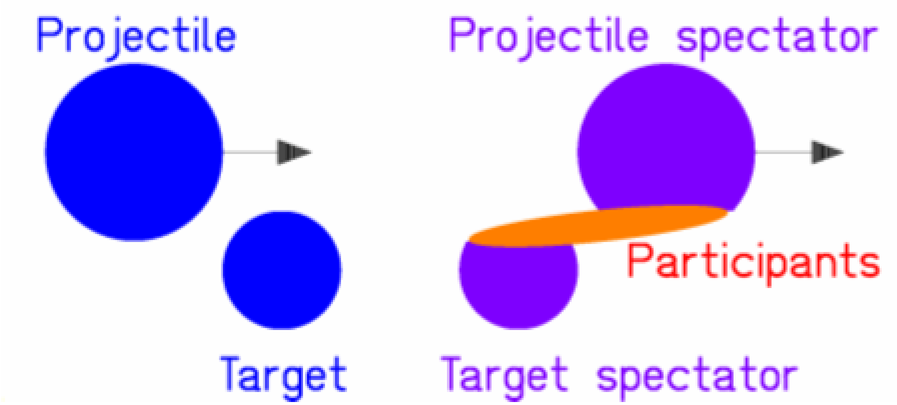
Fragmentation

Removal of nucleons in quasi-free nucleon-nucleon collisions



The Abrasion Model for Fragmentation

Mass loss is given by geometrical cut

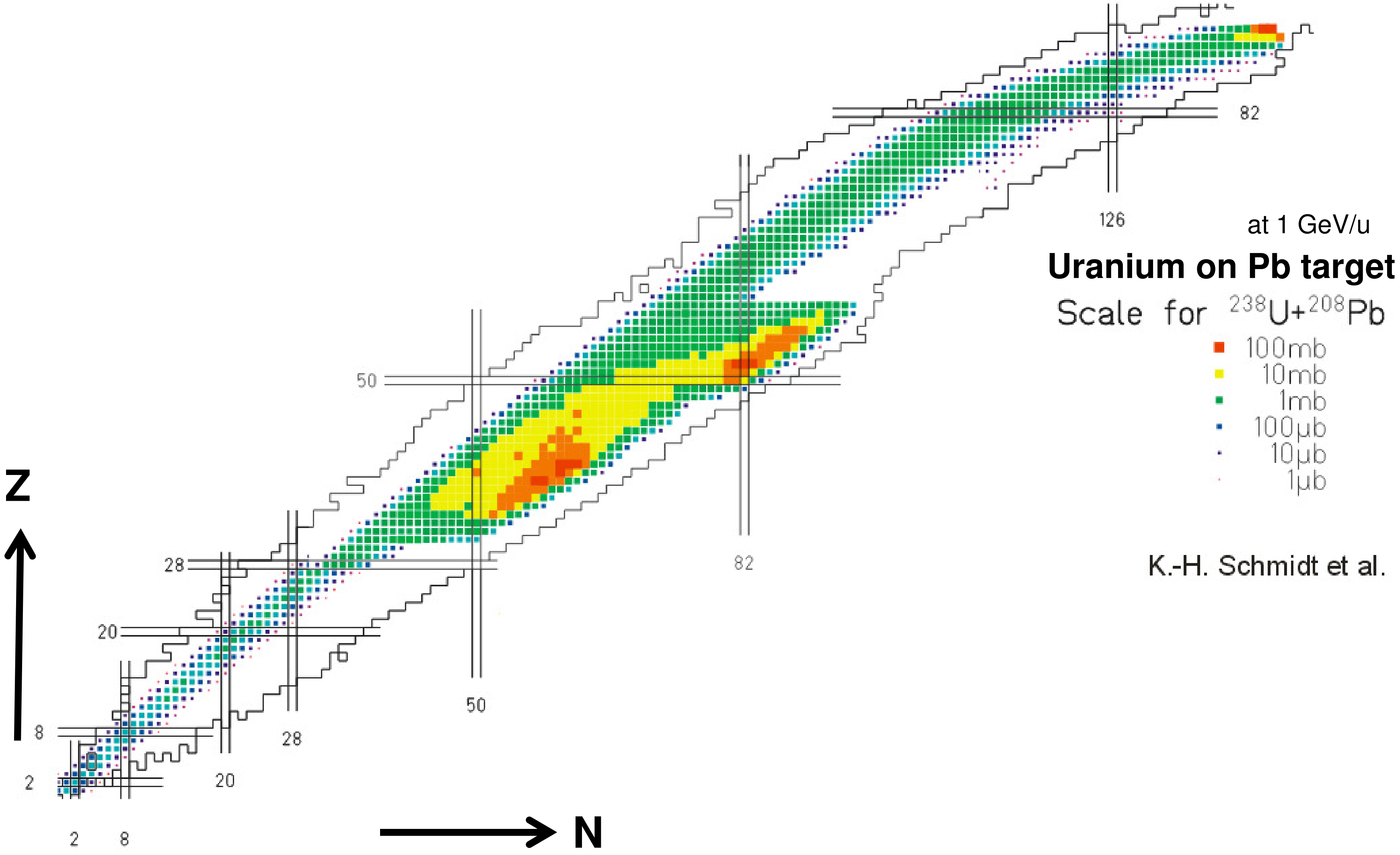


Assumption: Trajectories of nucleons are straight lines.
Masses of projectile spectator and target spectator are given by the geometrical overlap as a function of impact parameter.

Velocity of projectile fragment ≅ velocity of projectile

friction is small

Distribution of Fragments

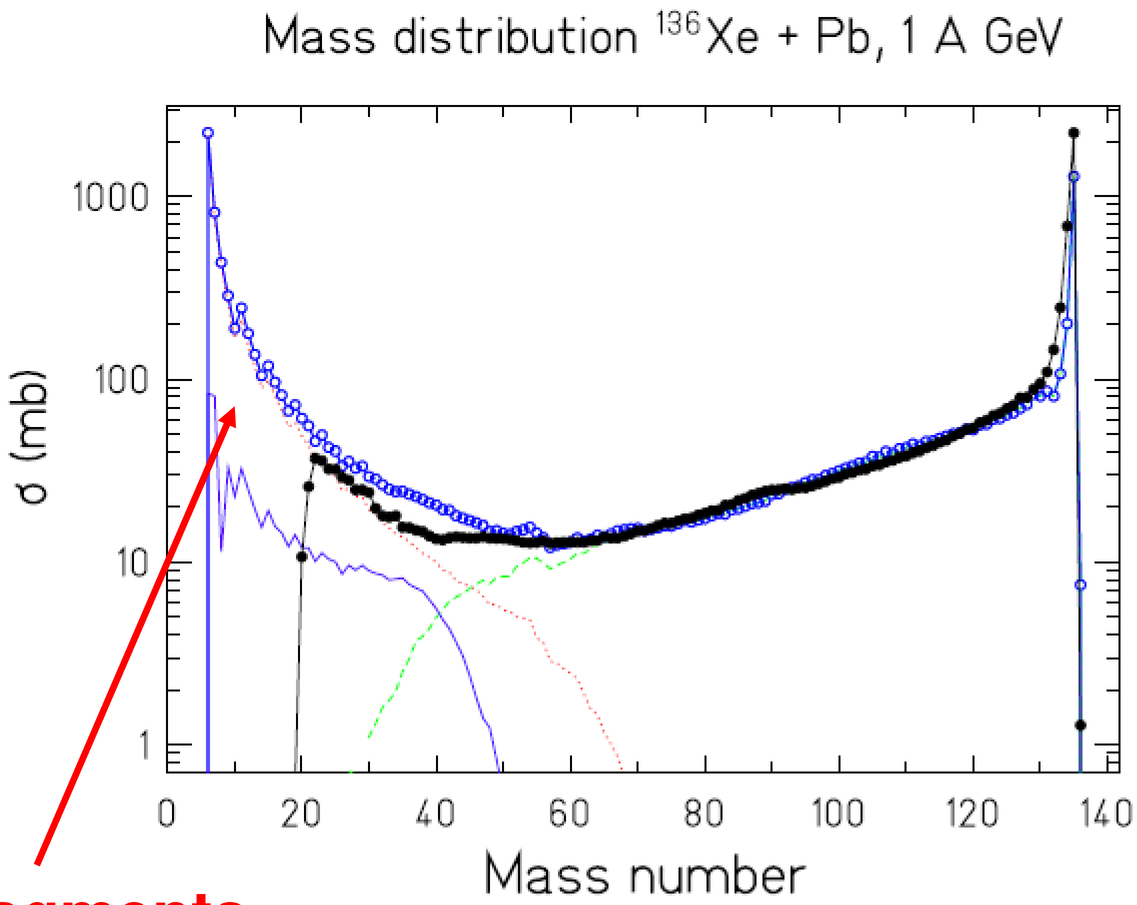


at 1 GeV/u

Uranium on Pb target

K.-H. Schmidt et al.

Mass Distribution



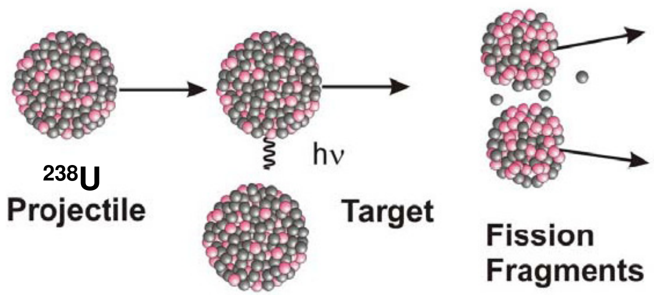
ABRABLA
Experiment

many light fragments
multi-fragmentation

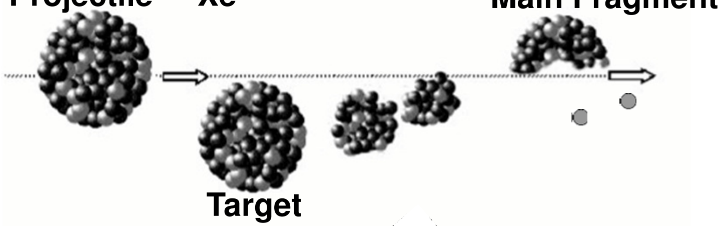
thesis Antoine Bacquias, U. Strasbourg (2008)

Production Cross sections

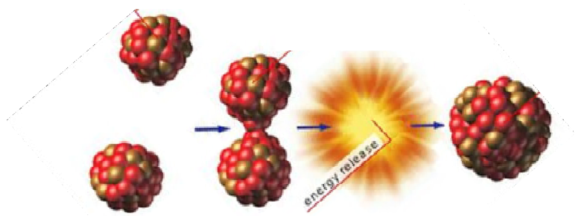
Projectile fission



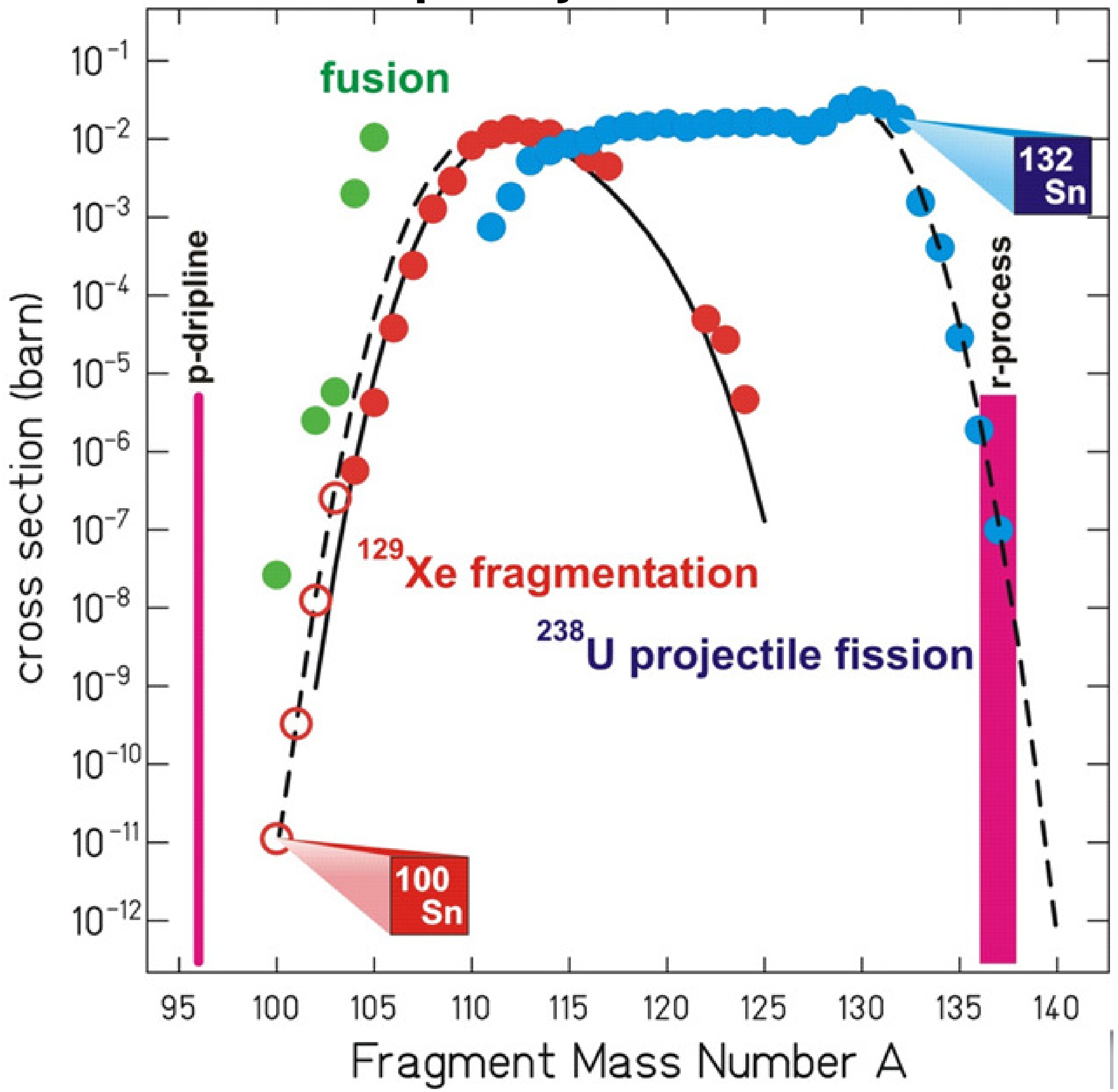
Projectile fragmentation



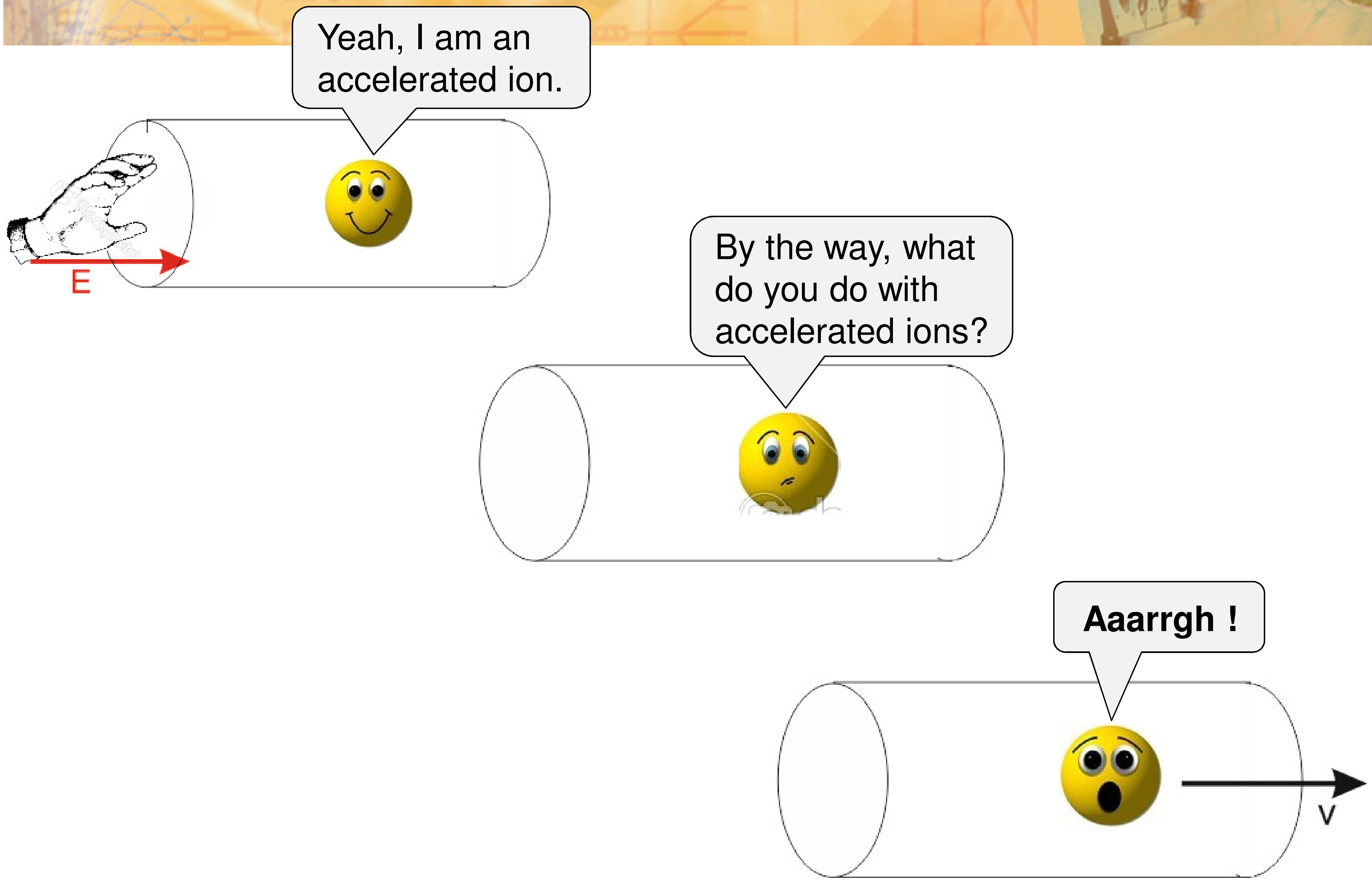
Fusion (only at lower velocity)



Tin isotopes by different methods

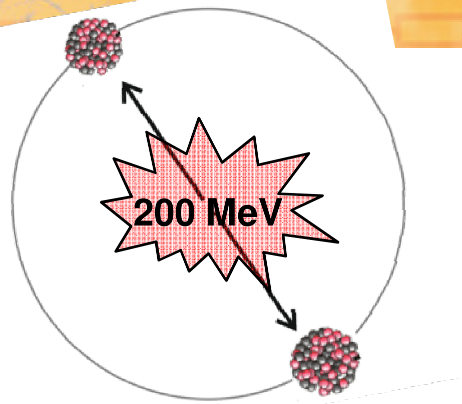


The fate of accelerated ions



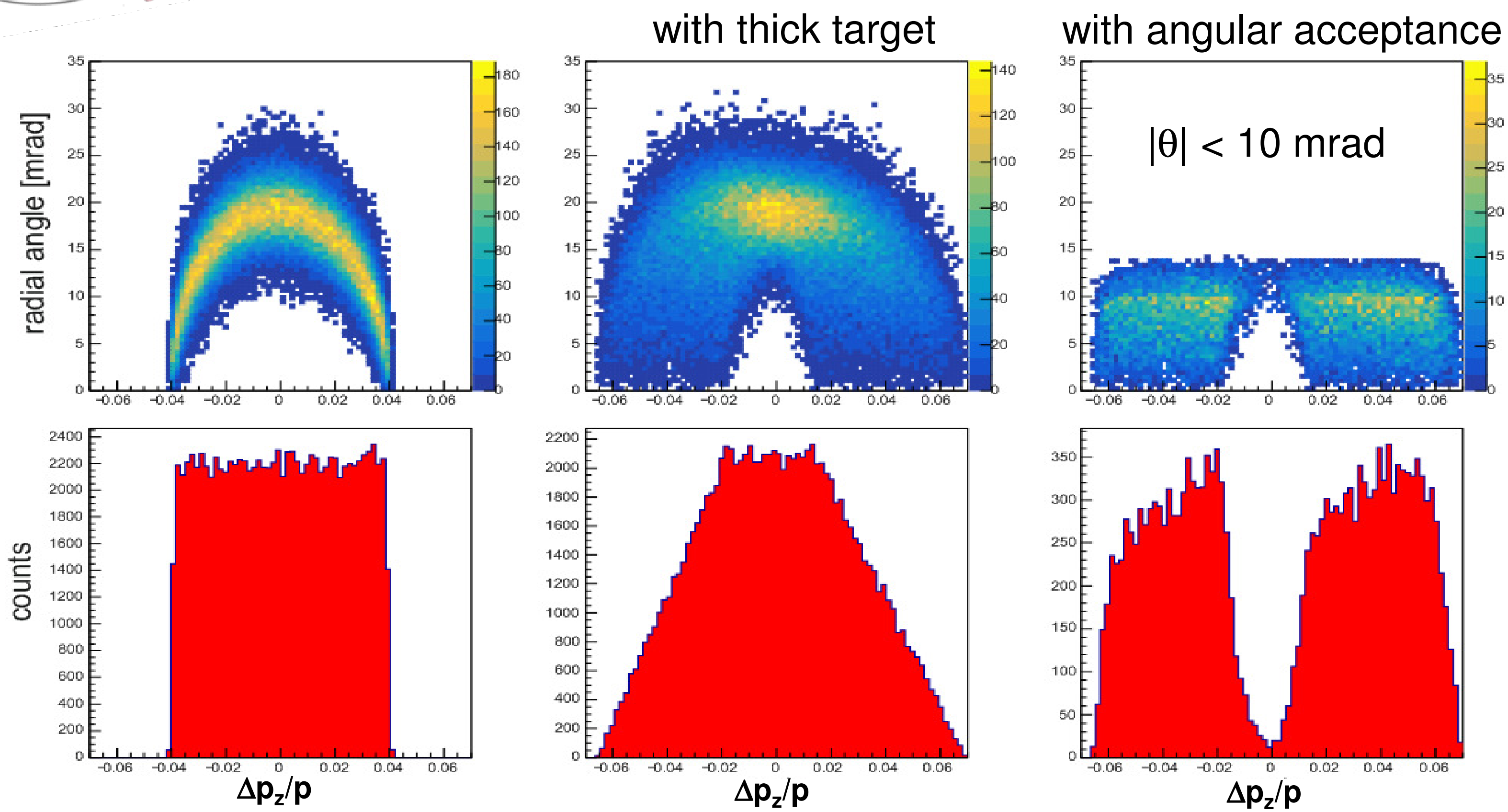
Fission Kinematics

in CoM:



in Uranium fission ~200 MeV are released

in Lab:
^{132}Sn from ^{238}U beam at 1 GeV/u

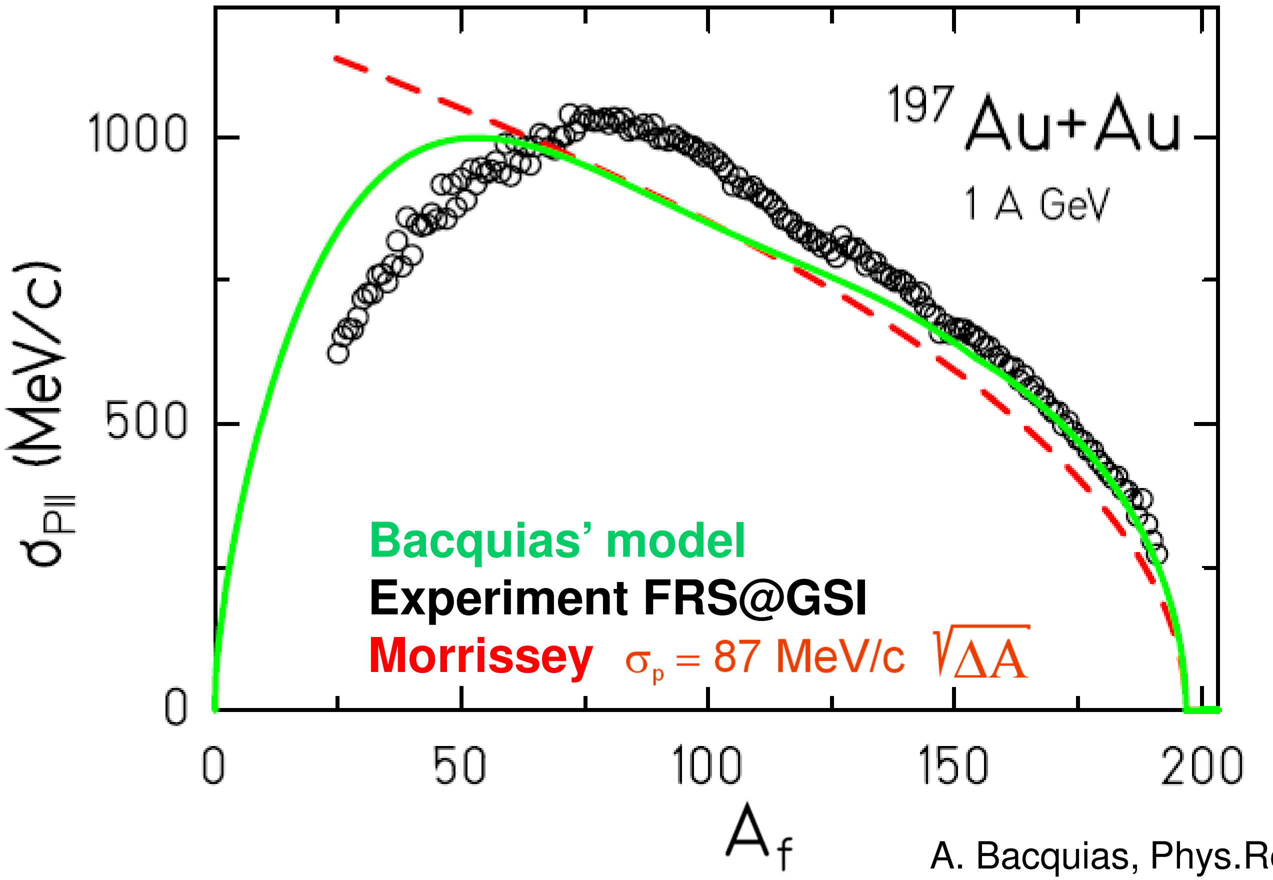


MOCADI simulation

Momentum Distribution in Fragmentation Reaction

$$\sigma^2_{p_{\|}} = \sigma^2_{p_{\|Fermi}} + \sigma^2_{p_{\|recoil}} + \sigma^2_{p_{\|Coul}}$$

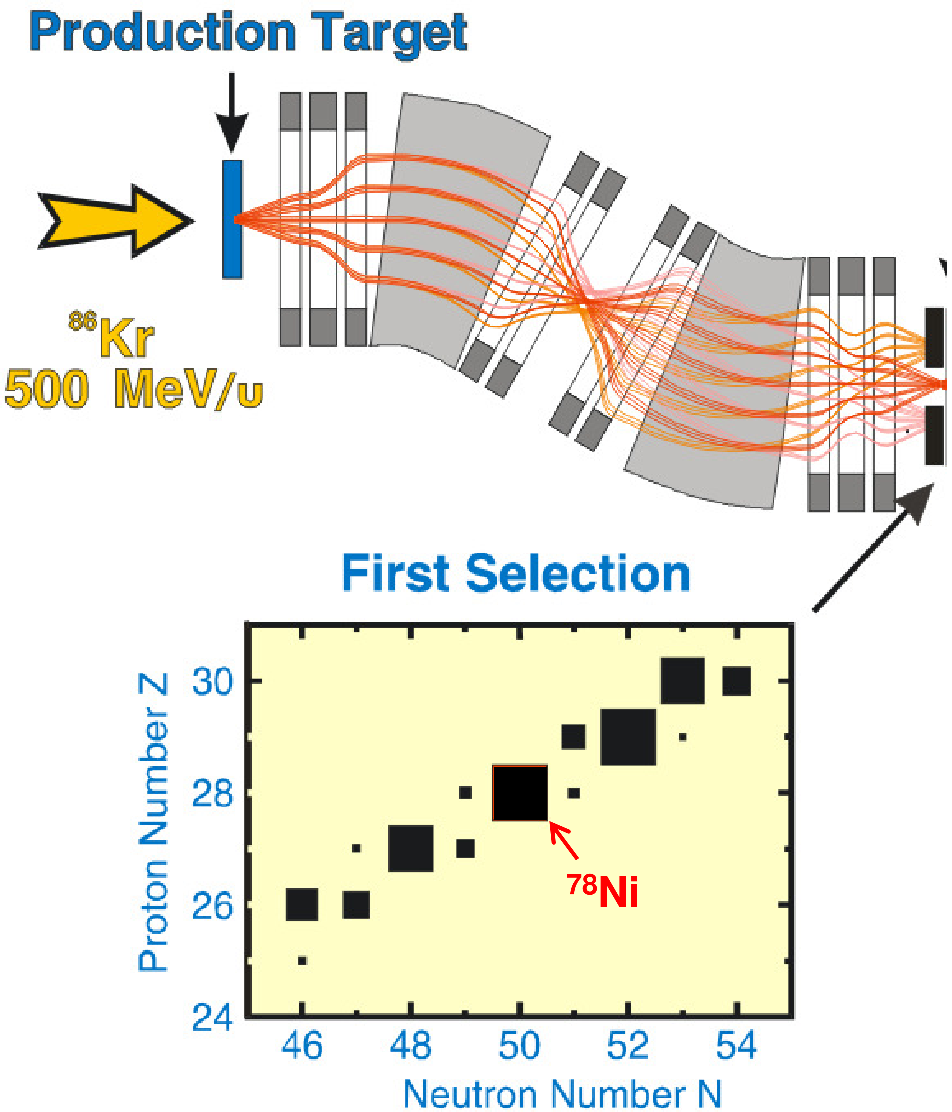
- Fermi momentum of bound nucleons
- Mom. transfer by evaporated nucleons
- Coulomb expansion in multi fragment.



A. Bacquias, Phys.Rev.C 85, 024904 (2012)
exp. data V. Henzl, thesis 2005, U. Prague

Bρ-ΔE-Bρ Separation Method

scheme of FRS @ GSI, L=72m



Bρ-ΔE-Bρ Separation Method

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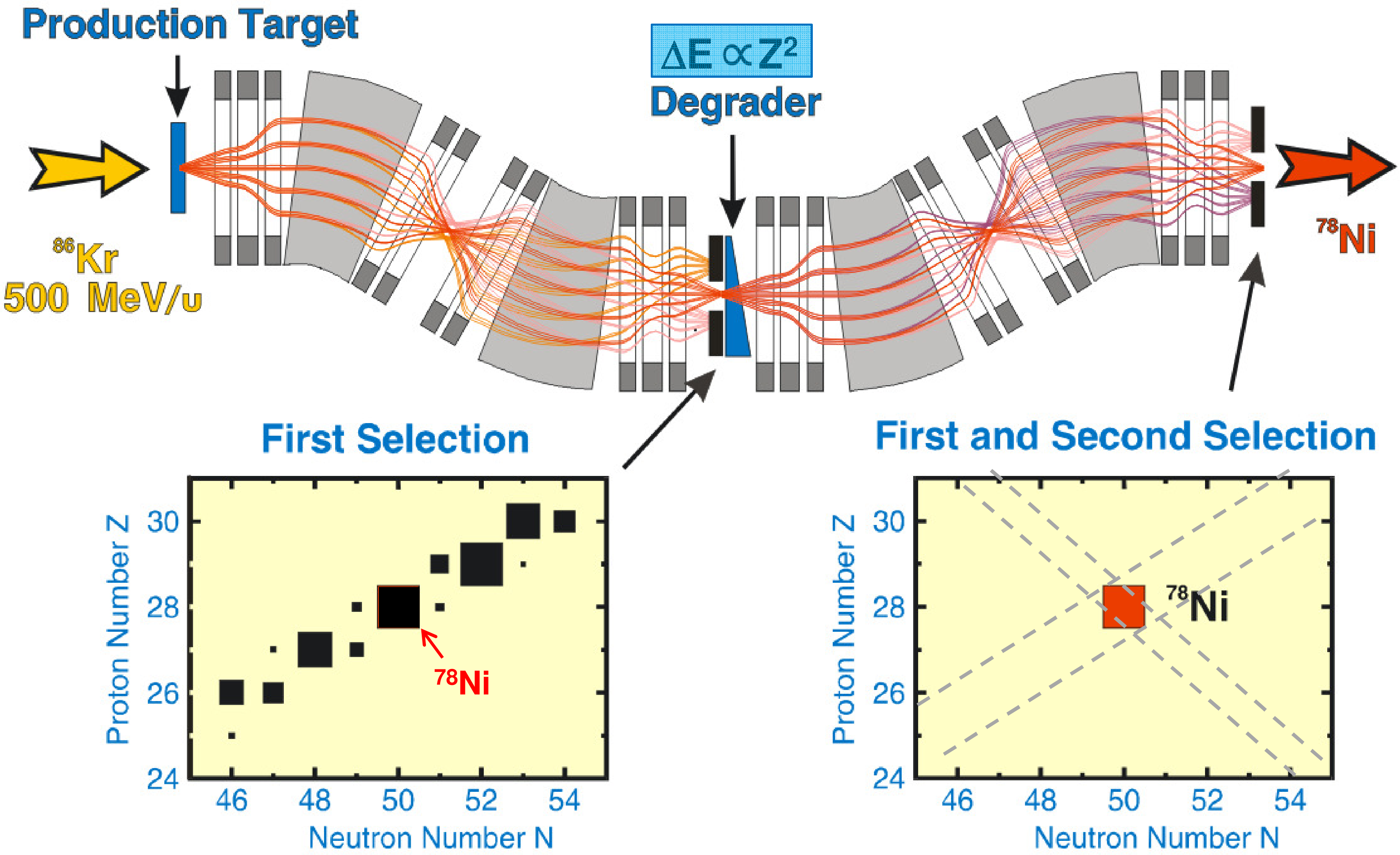
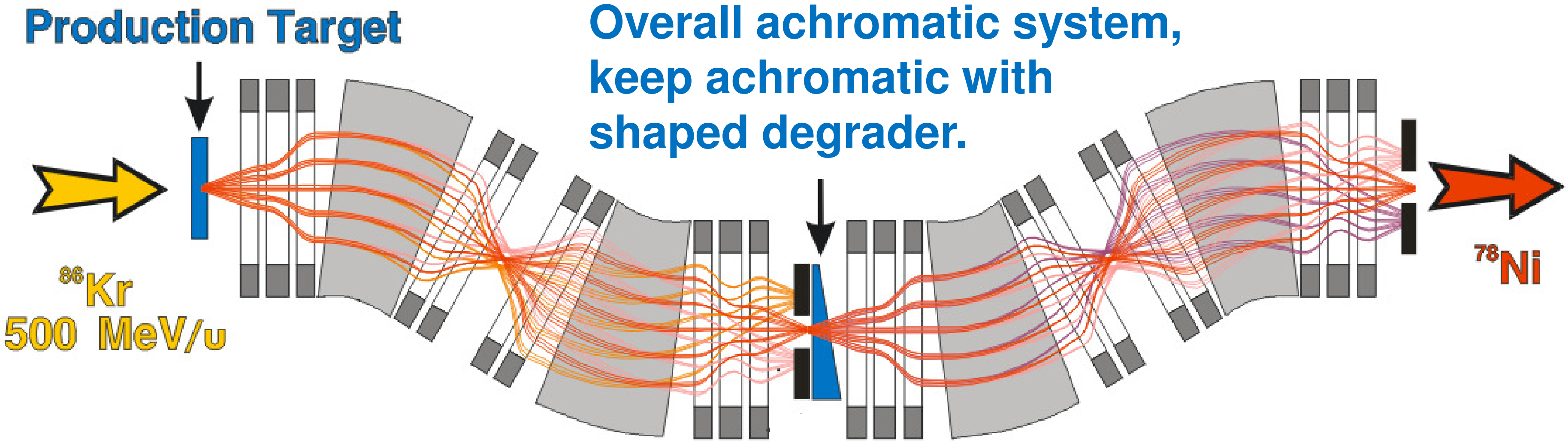


Bρ-ΔE-Bρ Separation Method



Overall achromatic system, keep achromatic with shaped degrader.

$$\Delta p/p_1 = \Delta p/p_2$$
with $p_1 > p_2$

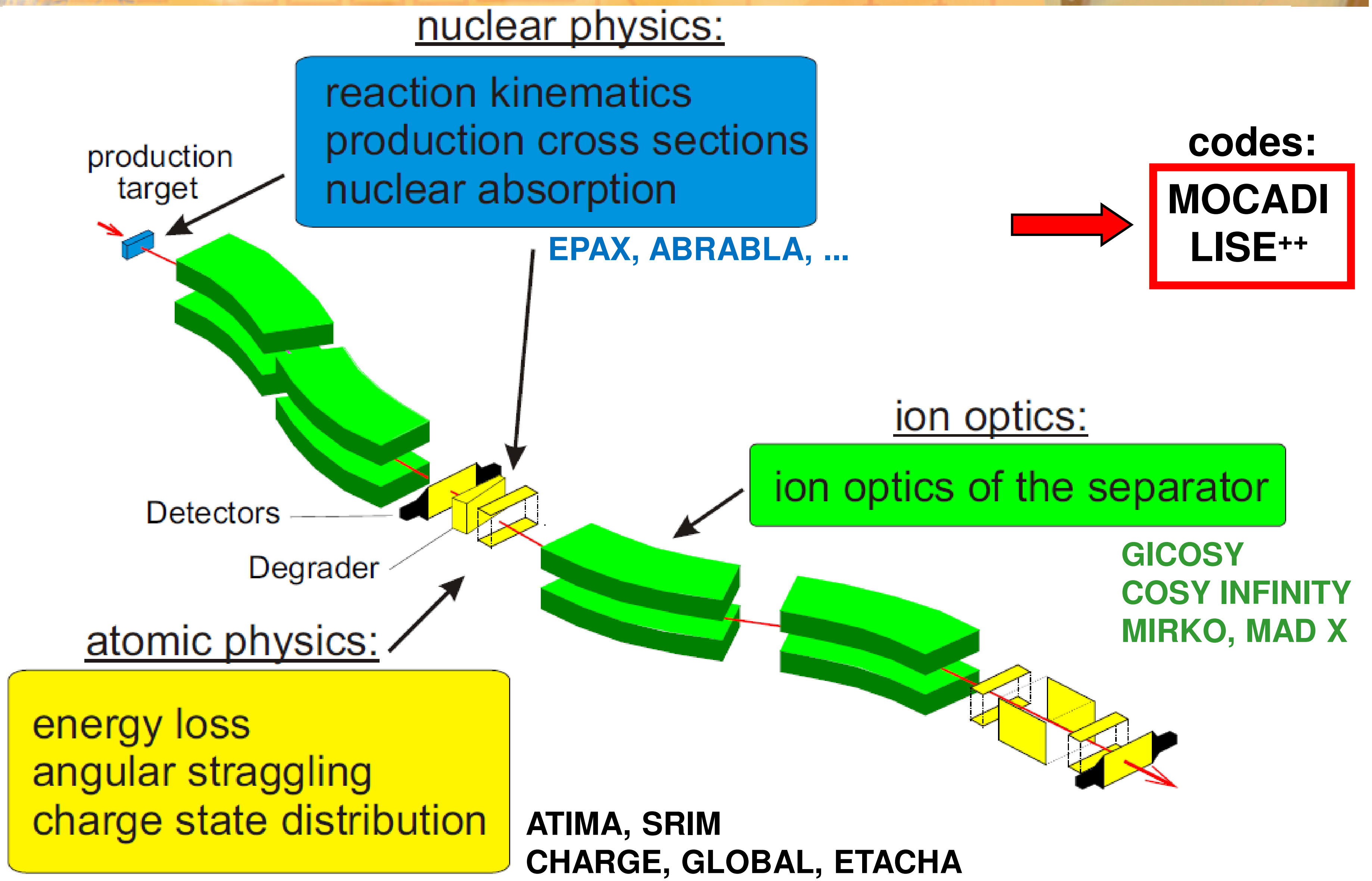
Non-Liouvillean system.

Coupling of longitudinal and transverse emittance,

$\Delta p \rightarrow \Delta p / f \;\; (f>1)$, but $\varepsilon_x \rightarrow \varepsilon_x * f$

In addition angular and energy-loss straggling.

Input for Simulation



Monte Carlo
MOCADI, LISE++ MC

Optimize for beamlines with matter:
Ions always fly in forward direction, no multiplicity,
physics routines adjusted for beamline needs,
GEANT would be orders of magnitude slower.

Parametrized, pre-calculated physics:
Do not evaluate physics for each ion,
optics by transfer matrices, no magnetic fields,
use parametrization in target (EPAX, Goldhaber, Morrissey)
pre-calculated results for energy loss (ATIMA spline tables),

Biasing:
10^{10} ions/s like in reality are impossible for Monte Carlo,
Do not create fragments with probability like in reality,
calculate certain number for one nuclide, biasing is
done by the very different production cross sections.

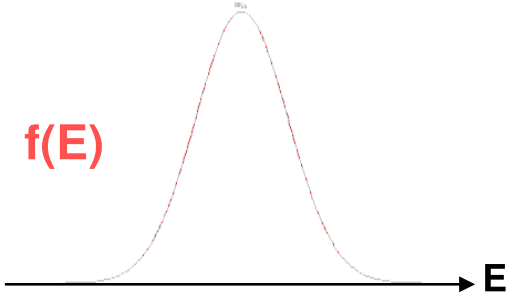
Convolution Technique

Each target, each piece of matter in beamline, each collimator reshapes the distribution in position, angle, energy of an ion species

Example:

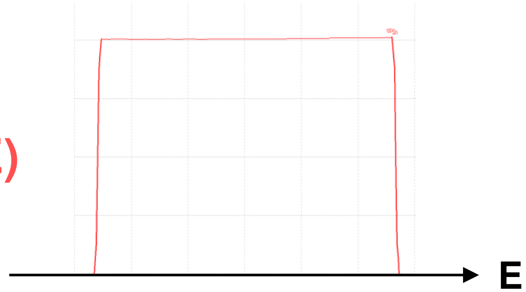
Energy from production in thin target,
Goldhaber distribution, Gaussian shape.

f(E)



Energy loss in thick target,
different dE/dx for projectile (Z_p) and fragment (Z_f),
exit energy depends on reaction position.

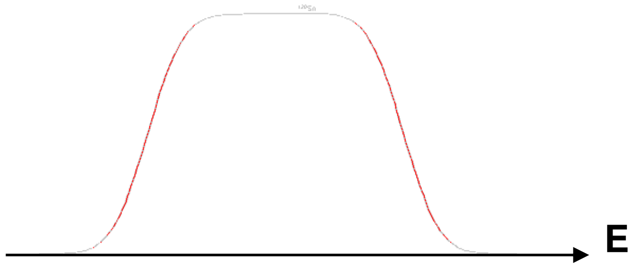
g(E)



Combined effect given by convolution
of the two distributions

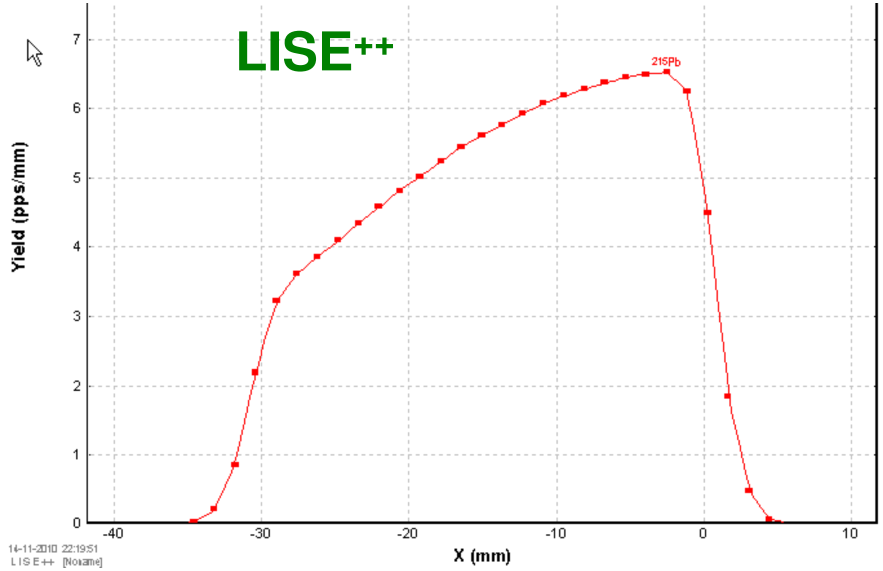
$$h(E) = (g * f)(E)$$

$$= \int_{-\infty}^{\infty} f(E-E') \; g(E') \, dE'$$



Convolution Technique (2)

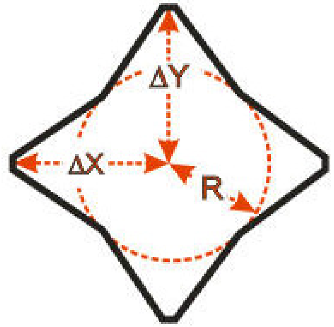
Programs:
LISE++ or Lieschen



x-distribution described by 32 points

+ **Fast, only a low number of points have to be calculated. Calculation of all fragments possible while watching.**
+ **Parametrization on log scale, even small tails are still visible**
- **Becomes very difficult with many cross correlations.**
- **Usually limited to linear transformations (only 1st order optics).**

Simplification to Blocks

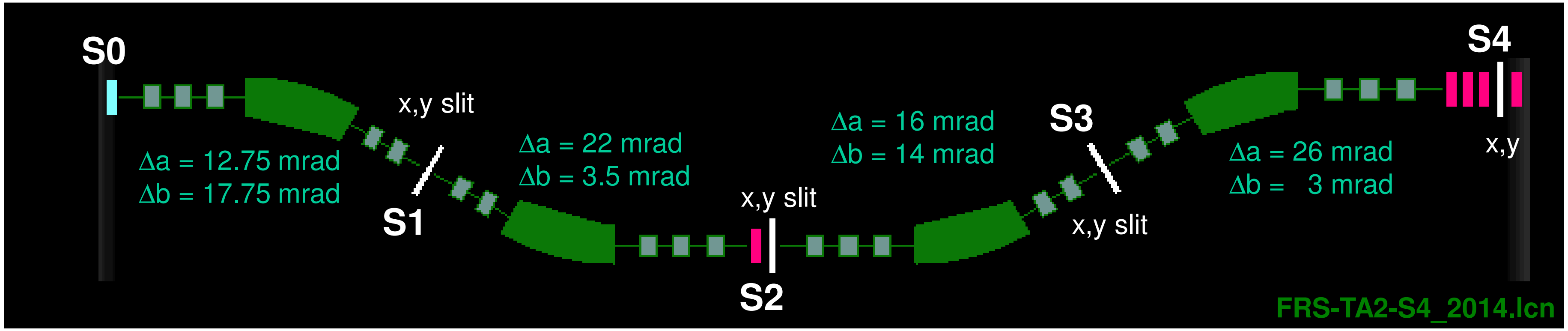


Example FRS:

Star shaped vacuum chamber is difficult to describe in convolution technique.
Only use independent cuts in x or y distribution.

Details cannot be taken into account → do not try.
Replace single aperture cuts by effective cut for whole section.

One cut in x, y after each separator stage,
one angular acceptance a_{max}, b_{max} for each stage (S0-S1, S1-S2, S2-S3, S3-S4).



Values in LISE adjusted to results of MOCADI simulation.
In normal FRS operation agreement of transmission within 20%

Transfer Matrix Description

Ion-optical coordinates

$$x,\ a = p_x/p_0\ ,\ y,\ b = p_y/p_0\ ,\ \delta = \Delta B\rho / B\rho_0$$

$$B\rho = c_0 \beta\gamma\ \ m/q = \nu\ m/q$$

$$\delta_m = \Delta m/m\ ,\ \delta_q = \Delta q/q\ ,\ \delta_\nu = \Delta\nu/\nu_0$$

Separator stage, D

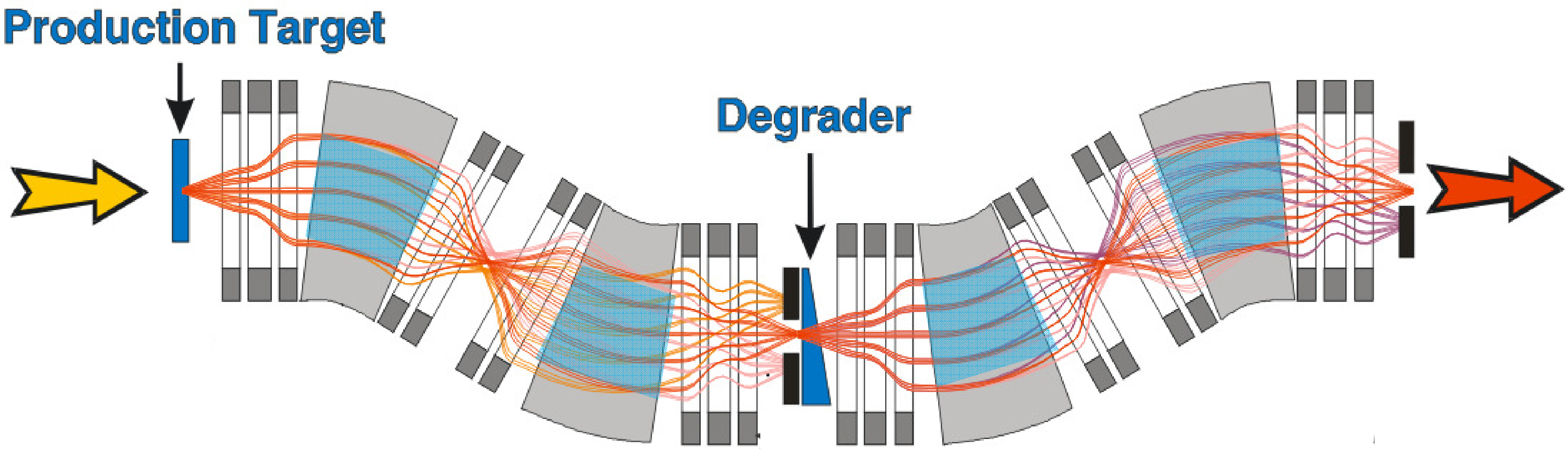
$$\begin{pmatrix} x \\ a \\ \delta_m \\ \delta_q \\ \delta_\nu \end{pmatrix}_f = \begin{pmatrix} (x|x) & \cancel{(x|a)} & (x|\delta) & -(x|\delta) & (x|\delta) \\ (a|x) & (a|a) & (a|\delta) & -(a|\delta) & (a|\delta) \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ a \\ \delta_m \\ \delta_q \\ \delta_\nu \end{pmatrix}_i$$

Degrader wedge W

$$\begin{pmatrix} x \\ a \\ \delta_m \\ \delta_q \\ \delta_\nu \end{pmatrix}_f = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ (\delta_\nu|x) & (\delta_\nu|a) & (\delta_\nu|\delta_m) & (\delta_\nu|\delta_q) & (\delta_\nu|\delta_\nu) \end{pmatrix} \begin{pmatrix} x \\ a \\ \delta_m \\ \delta_q \\ \delta_\nu \end{pmatrix}_i$$

Full system $= \mathbf{D_2 \,.\, W \,.\, D_1}$

Resolution



Resolving power R

$$R = \frac{1}{x_0\, a_0} \int \frac{\vec{B}(s)}{B\rho}\, d\vec{f}$$

For given emittance $x_0\, a_0$ the B-field area covered by the beam defines R.

R is limited by momentum spread

1^{st} half: $\Delta p/p_{\text{nucl. reaction}} \sim 0.4 - 8\ \%$

2^{nd} half: $\Delta p/p_{\text{E-loss fluct.}} \sim 0.05 - 0.3\ \%$

statistical energy-loss fluctuation

Transfer Matrix Description

Geissel, Weick, Winkler, Münzenberg, Yavor, NIM B 247 (2006) 368.

Momentum resolving power of one half

$$R = \frac{(x|\delta)}{\Delta x_f} \quad \sim 1000\text{-}2000$$

Energy-loss straggling

$$\delta_{v,str} \sim 1/1000$$

Resolution in mass, charge

$$R_m = \frac{(x|\delta_m)}{\Delta x_f} \qquad R_q = \frac{(x|\delta_q)}{\Delta x_f}$$

for achromatic separator $(x|\delta_v)_{tot} = 0$

$$R_q = \frac{[(\delta_v|\delta_q) - 1 + (\delta_v|\delta_v)] \,/ (\delta_v|\delta_v)}{\sqrt{1/R^2 + (\delta_{v,str}/(\delta_v|\delta_v))^2}} = R\,\frac{[(\delta_v|\delta_q) - 1 + (\delta_v|\delta_v)]}{(\delta_v|\delta_v)}$$

for $\delta_{v\,str} \rightarrow 0$ $\quad \sim 0 - 100$

$$R_m = \frac{[(\delta_v|\delta_m) + 1 - (\delta_v|\delta_v)] \,/ (\delta_v|\delta_v)}{\sqrt{1/R^2 + (\delta_{v,str}/(\delta_v|\delta_v))^2}} = R\,\frac{[(\delta_v|\delta_m) + 1 - (\delta_v|\delta_v)]}{(\delta_v|\delta_v)}$$

Effect of degrader at different velocity

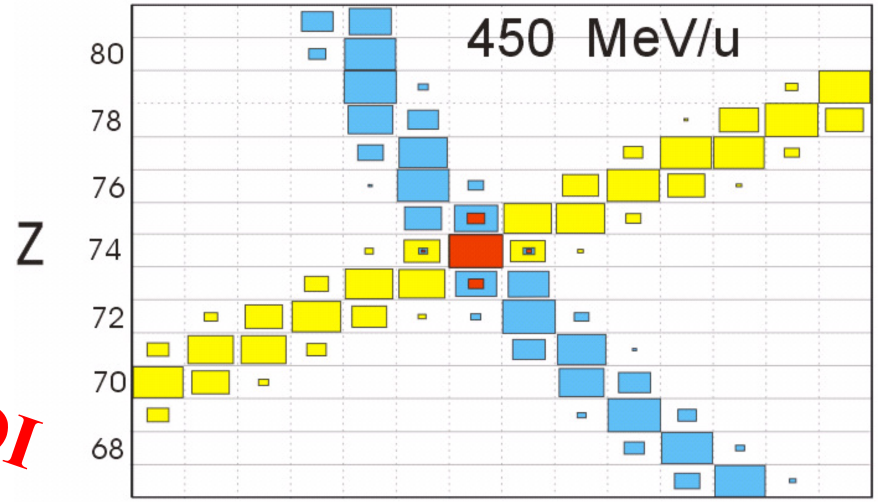
fragment ^{190}W in achromatic FRS
with Al degrader d/r=0.5
transmission

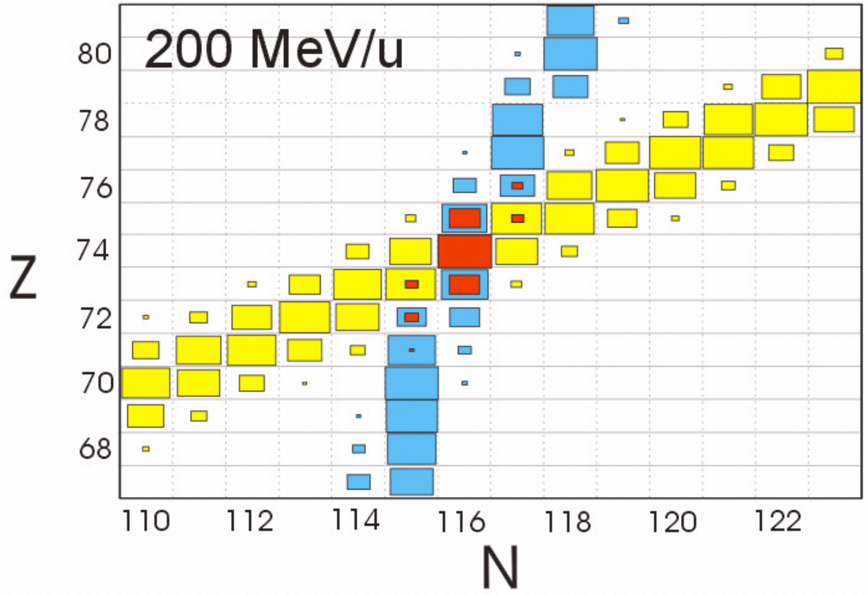
1st slits at $\pm 2\sigma_x$

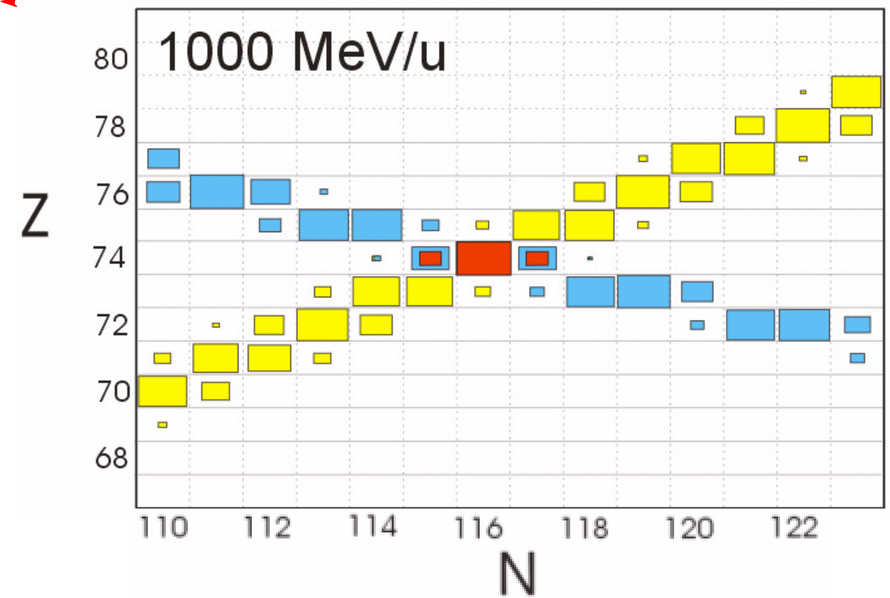
2nd slits at $\pm 2\sigma_x$

both slits at $\pm 2\sigma_x$

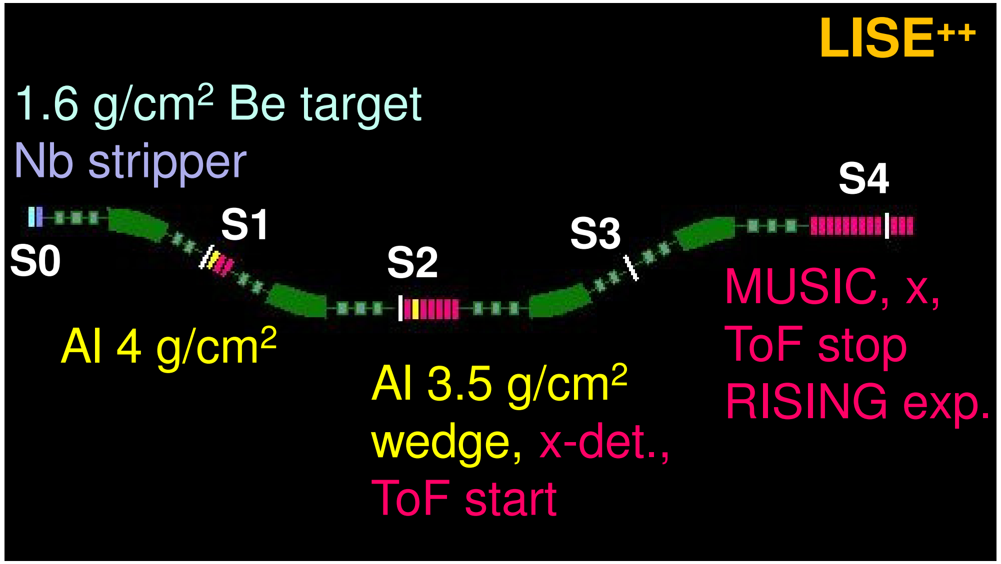
MOCADI simulation

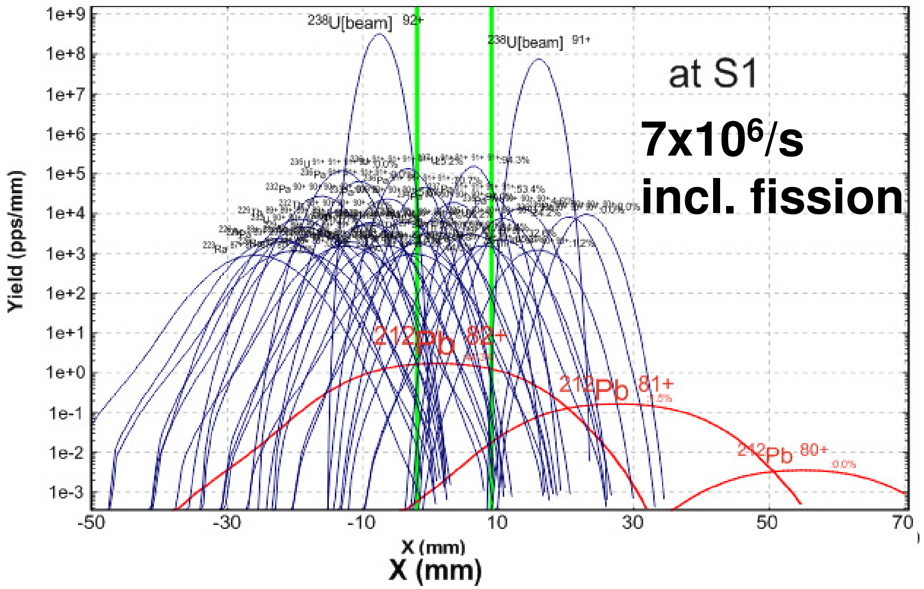


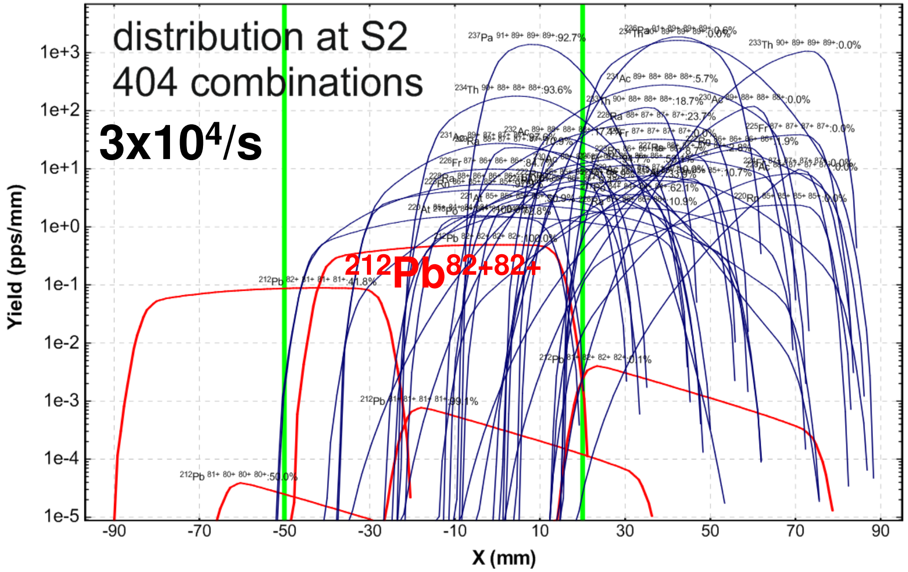


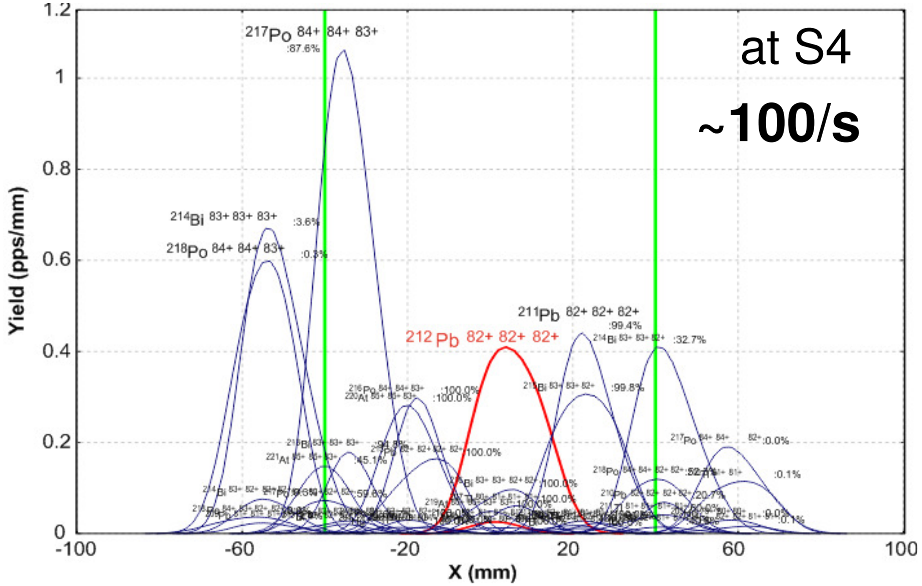


Separator Setting for ^{212}Pb
(exp. S350 in 2009)

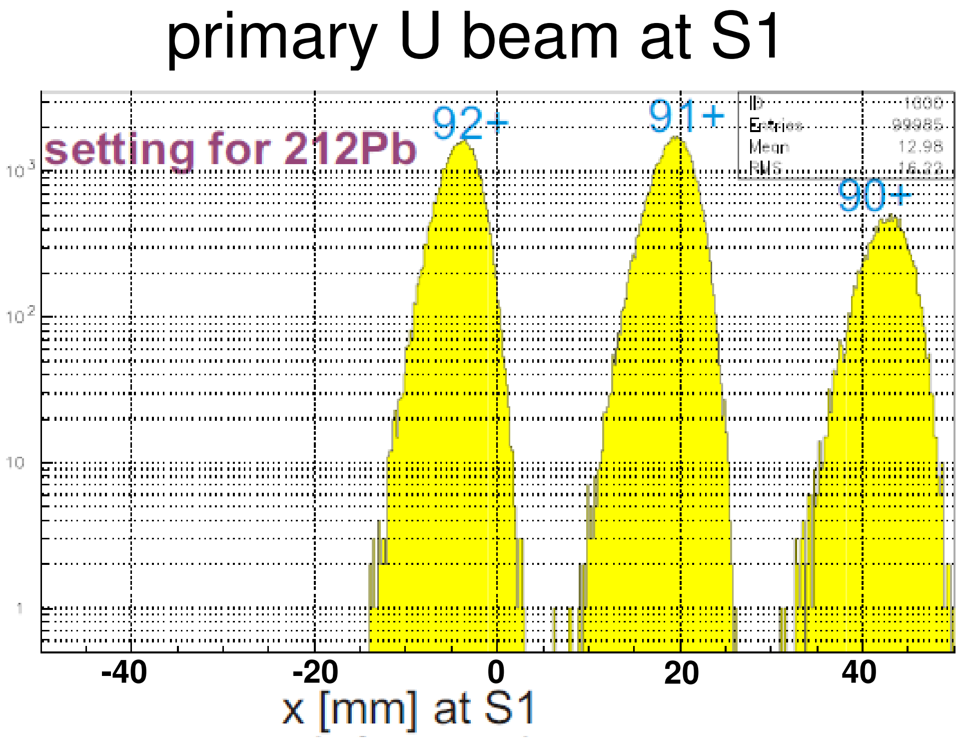


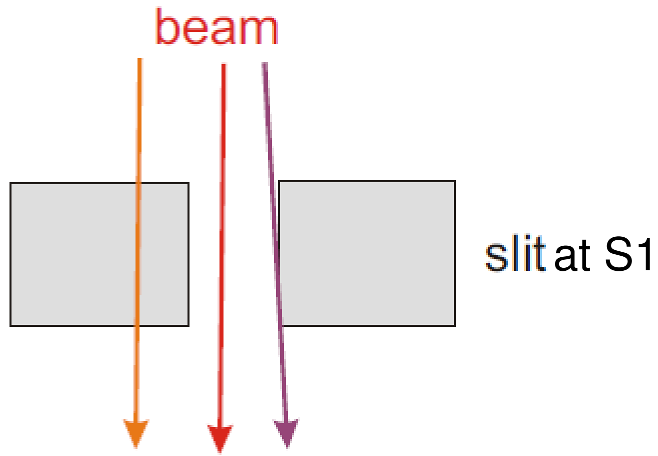




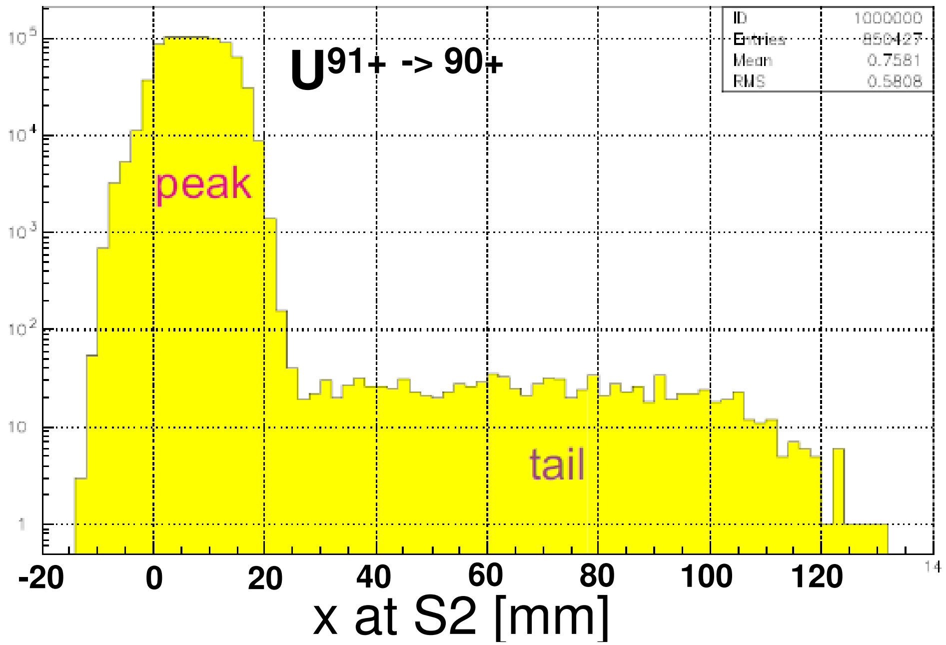


Details with Monte-Carlo





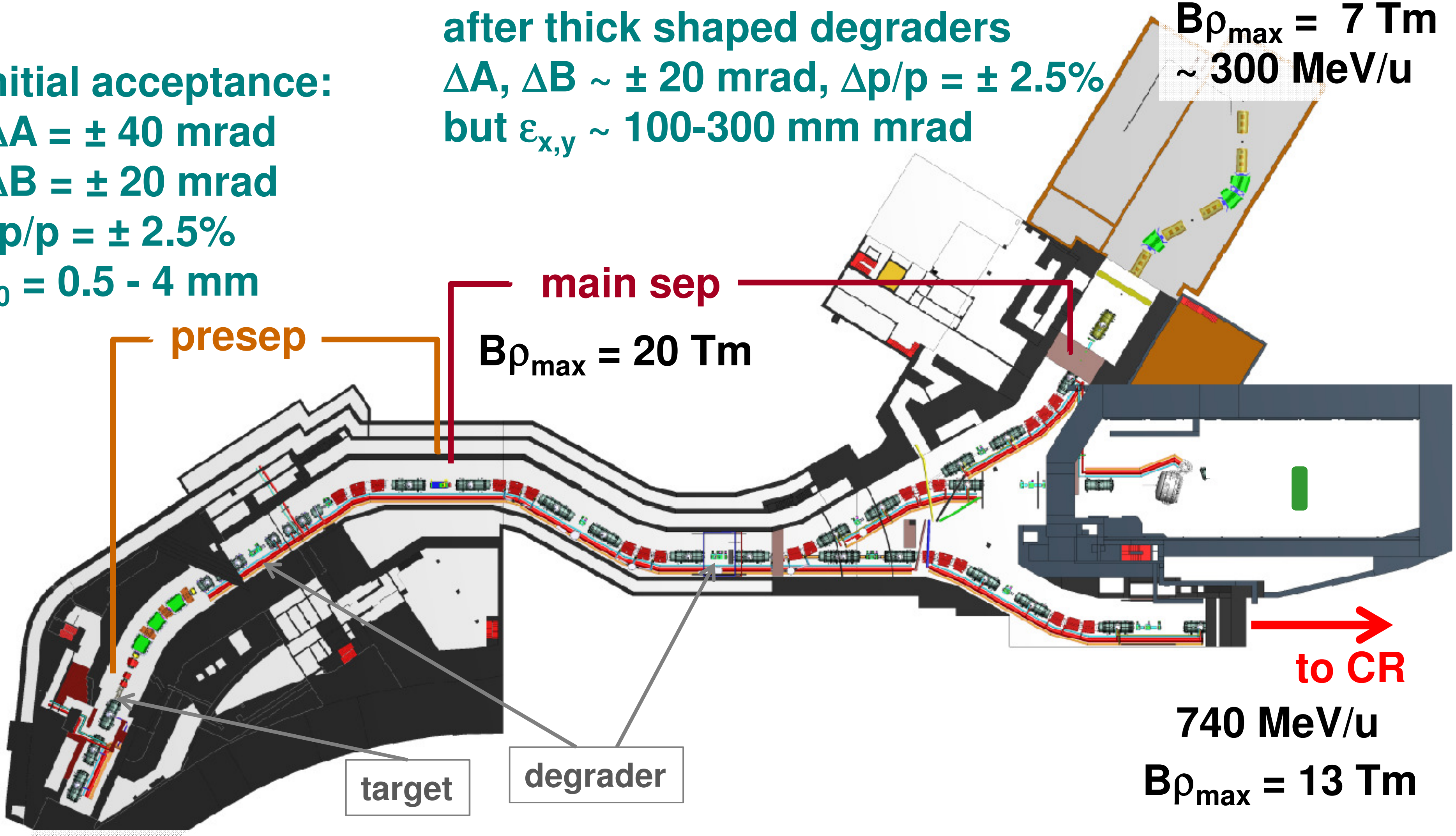
MOCADI



Super-FRS

Initial acceptance:
$\Delta A = \pm 40$ mrad
$\Delta B = \pm 20$ mrad
$\Delta p/p = \pm 2.5\%$
$x_0 = 0.5 - 4$ mm

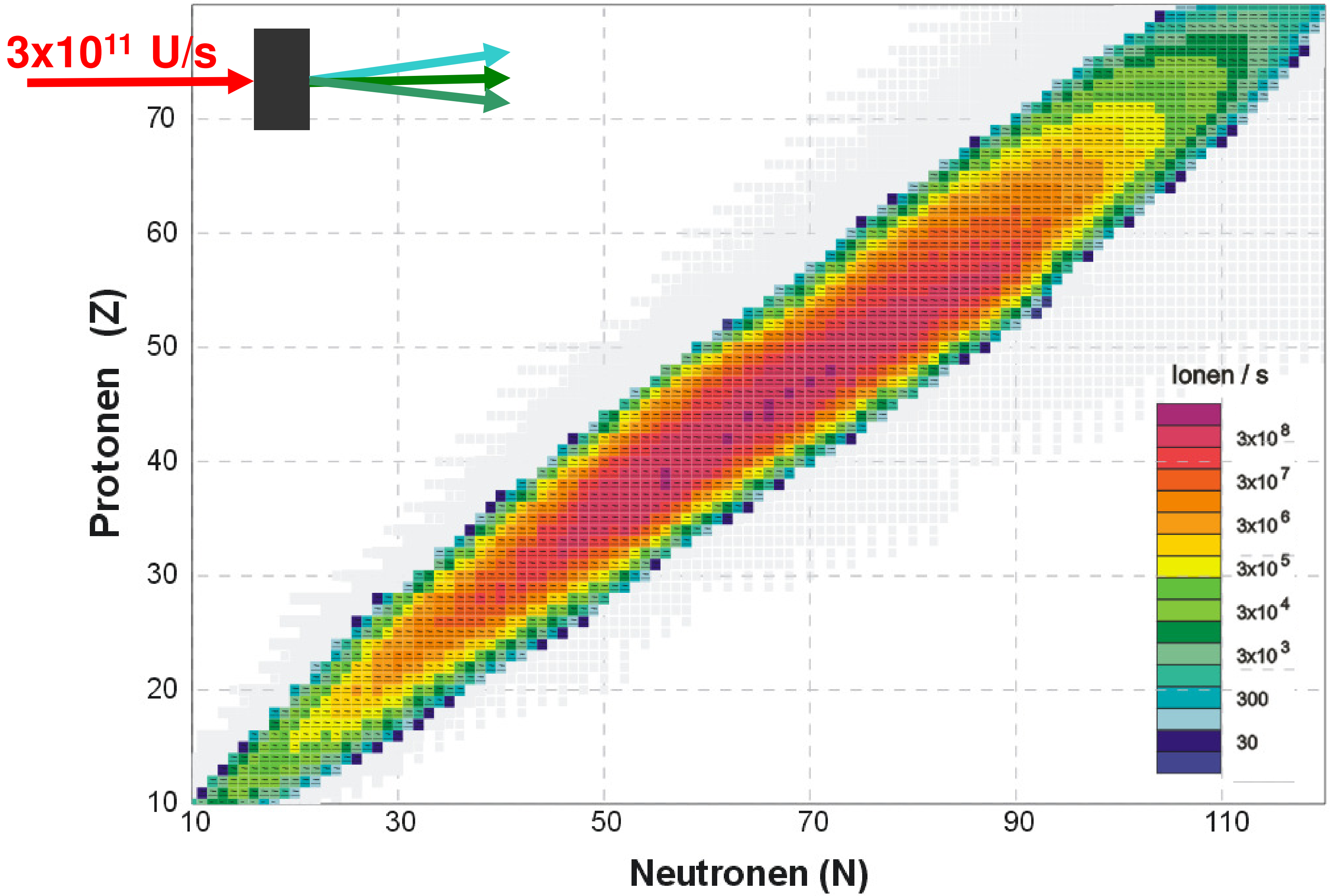
after thick shaped degraders
$\Delta A, \Delta B \sim \pm 20$ mrad, $\Delta p/p = \pm 2.5\%$
but $\varepsilon_{x,y} \sim 100\text{-}300$ mm mrad



$^{238}U^{28+}$ 0.4 – 2.7 GeV/u

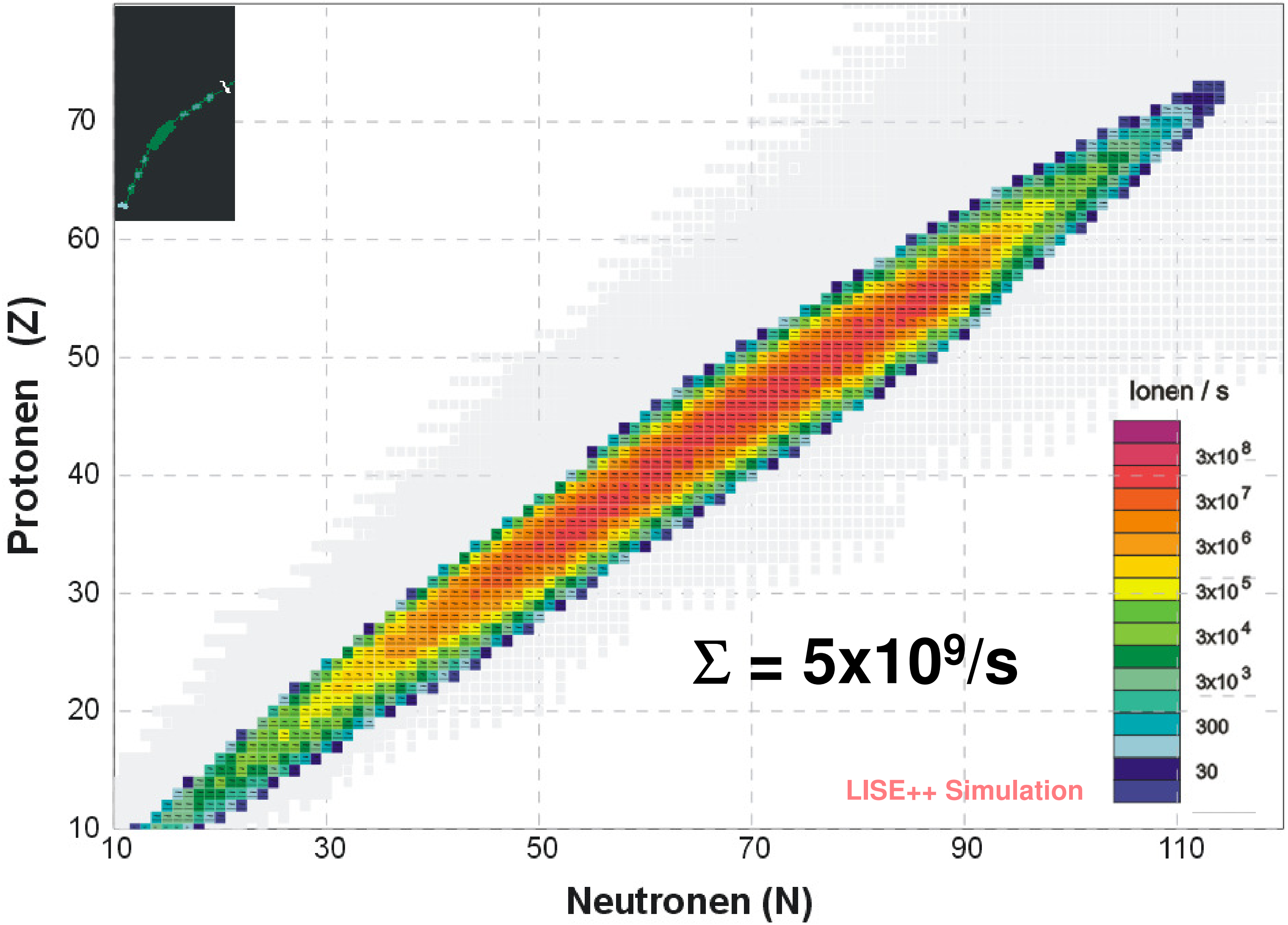
Separation

All fission fragments after target, 1.5 GeV/u ^{238}U --> 4 g/cm^2 ^{12}C



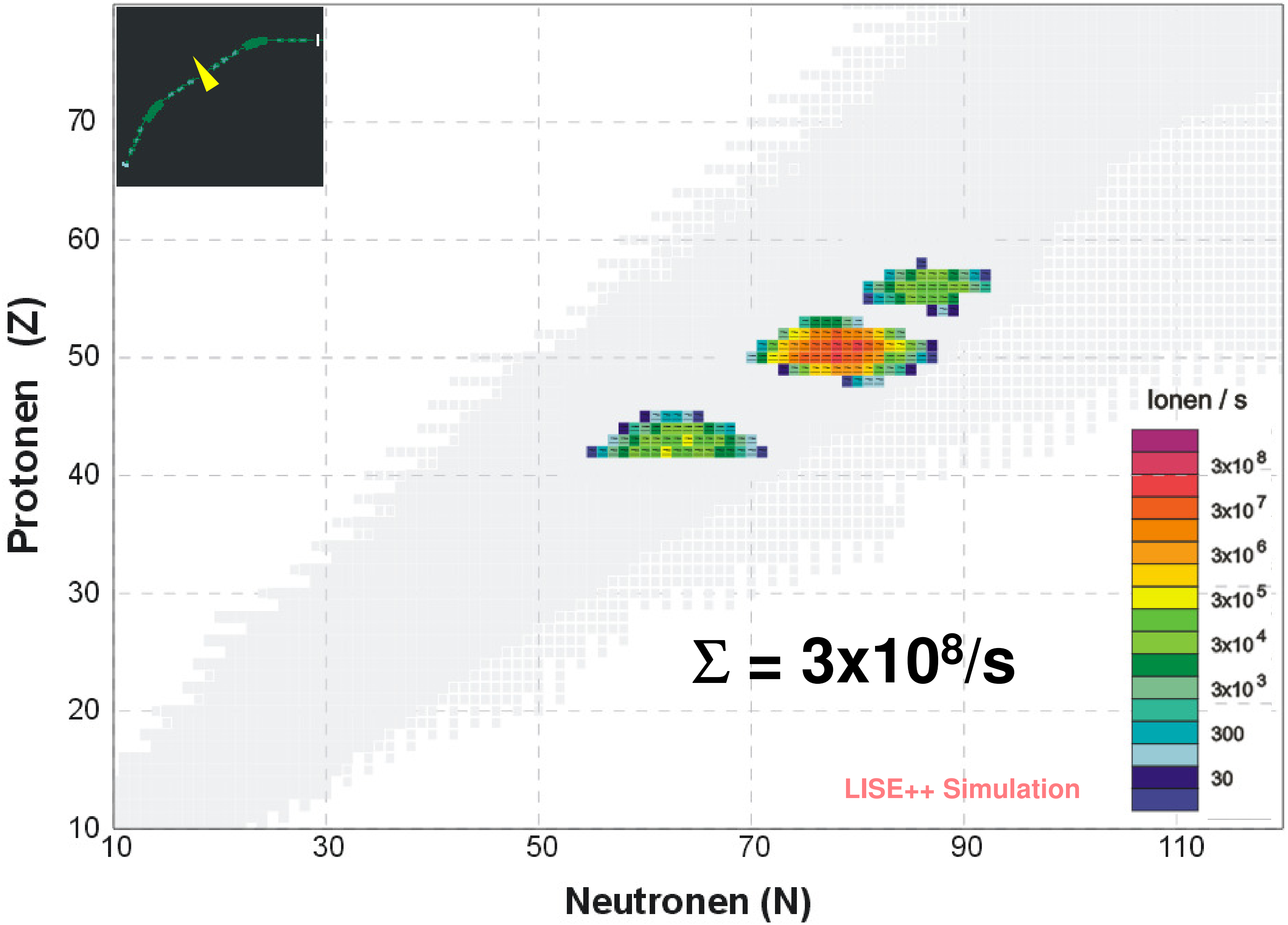
Separation

Separation only by Bρ



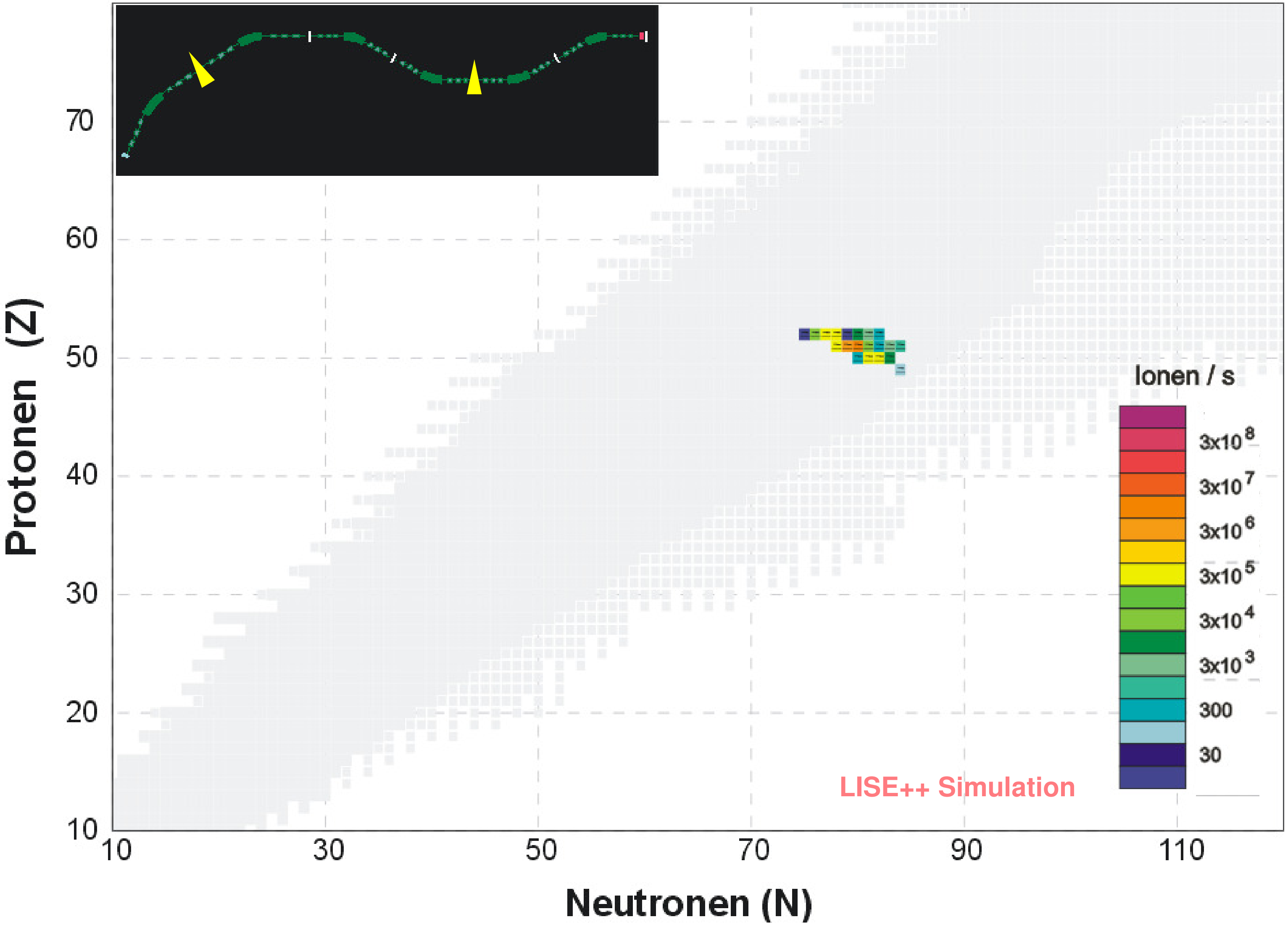
Separation

Separation after pre-separator (Bρ-ΔE-Bρ)



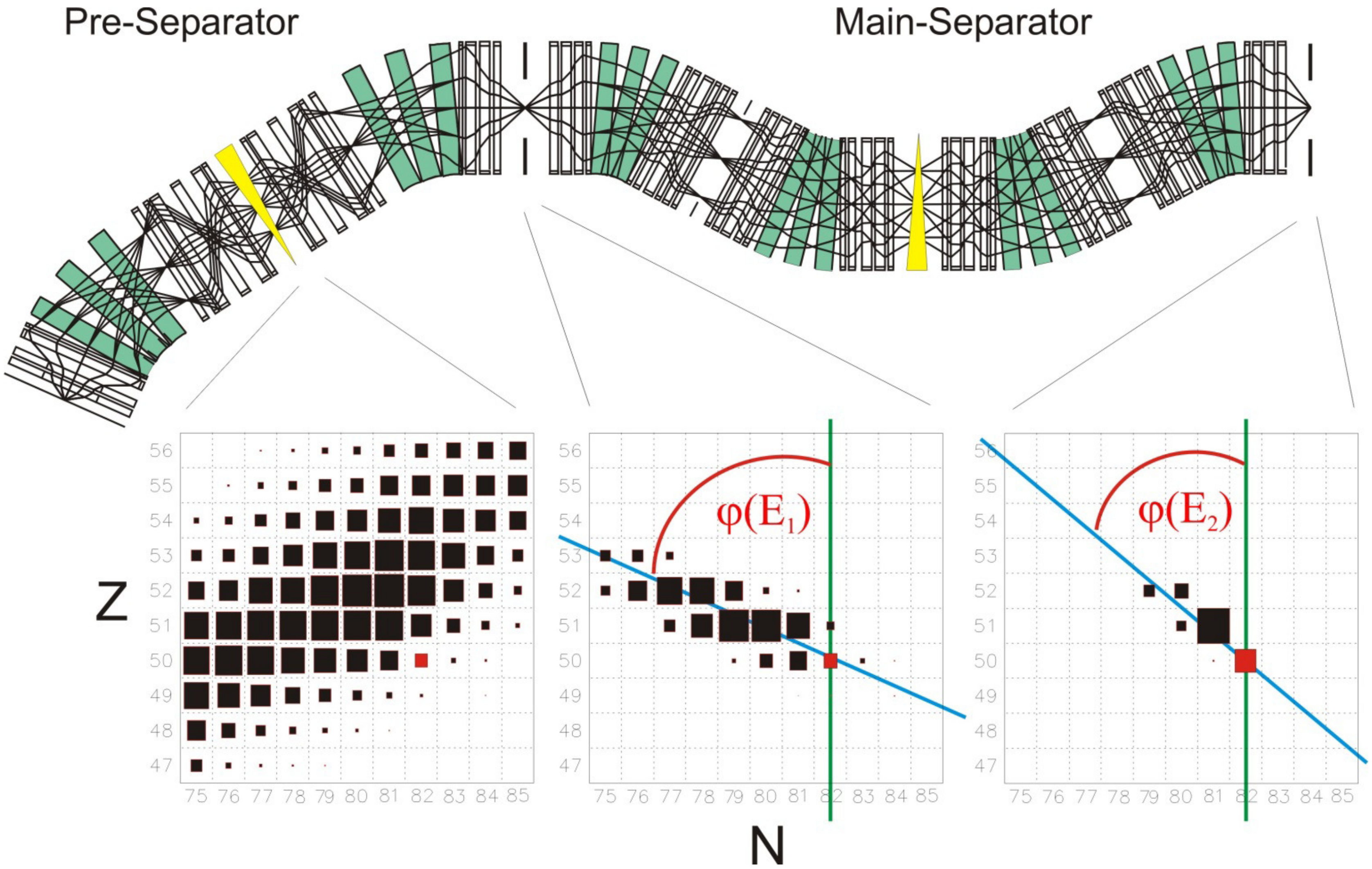
Separation

Separation after main separator (Bρ-ΔE-Bρ) x (Bρ-ΔE-Bρ)



Separation Performance

1.1 A GeV ^{238}U on 4 g/cm^2 C target, two Al degraders d/R=0.3, d/R=0.7

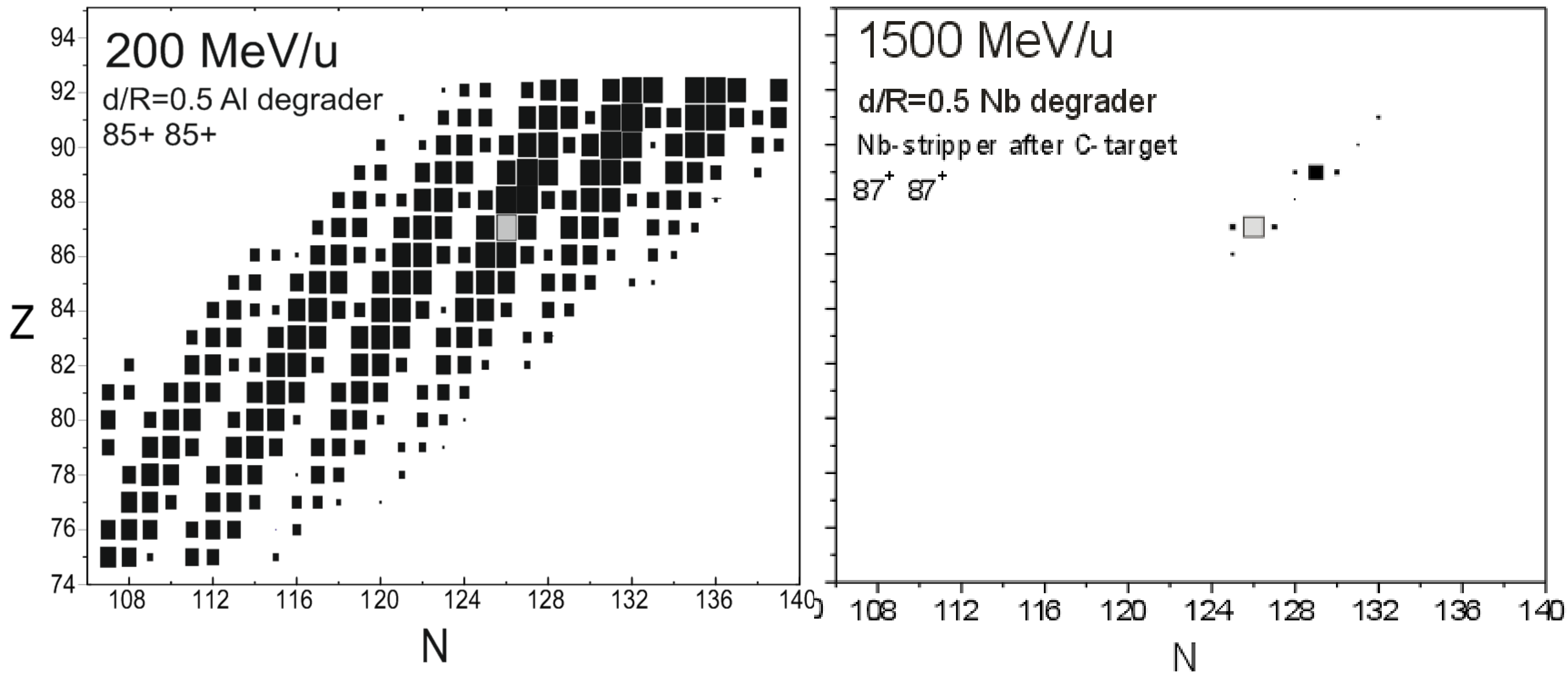


For fission fragments separation is difficult, other beams more pure.

Q-State Effect on Separator

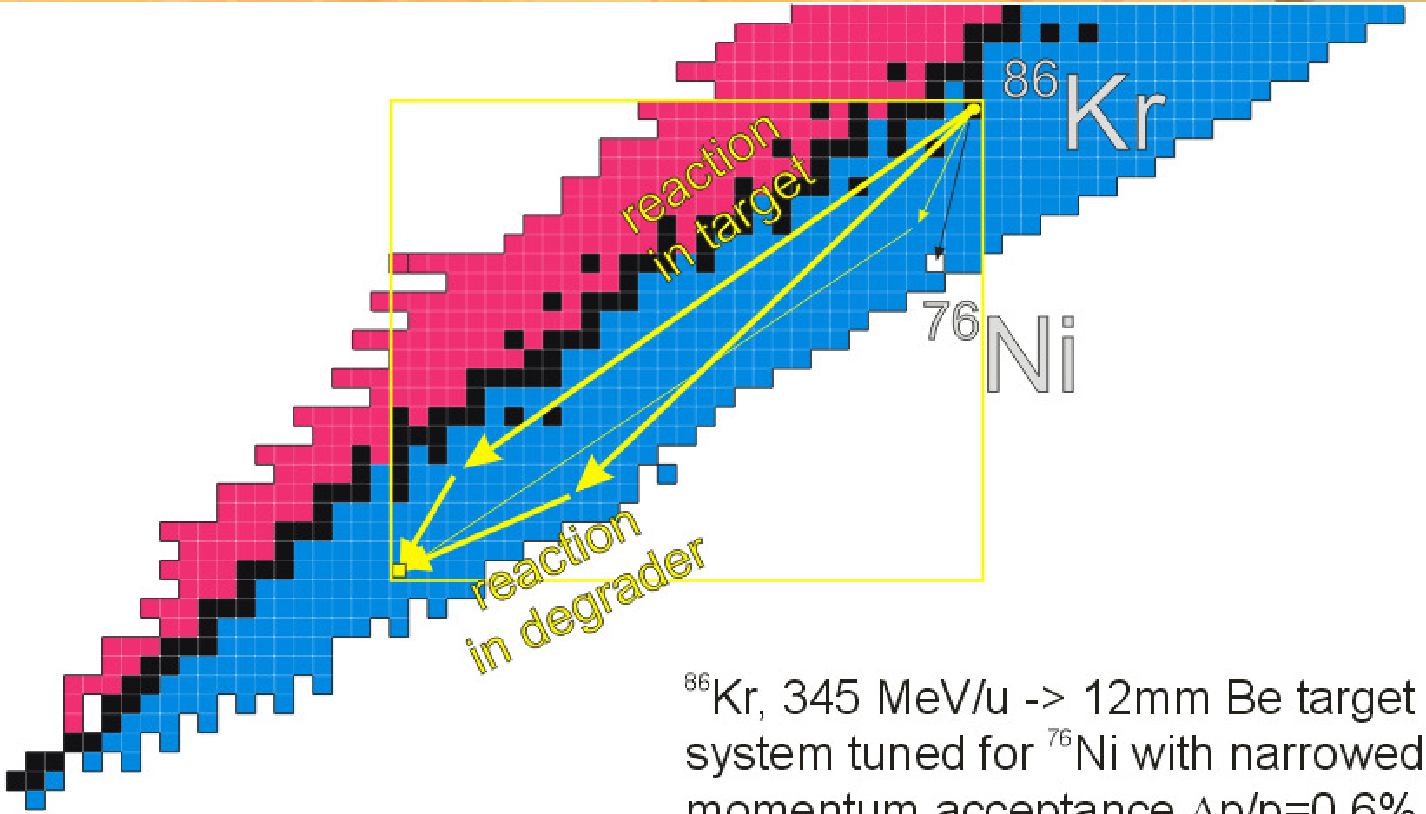
Separation of ^{213}Fr

optimal combination of q-states and stripper materials at different energy, FRS with achromatic S2 degrader in LISE++

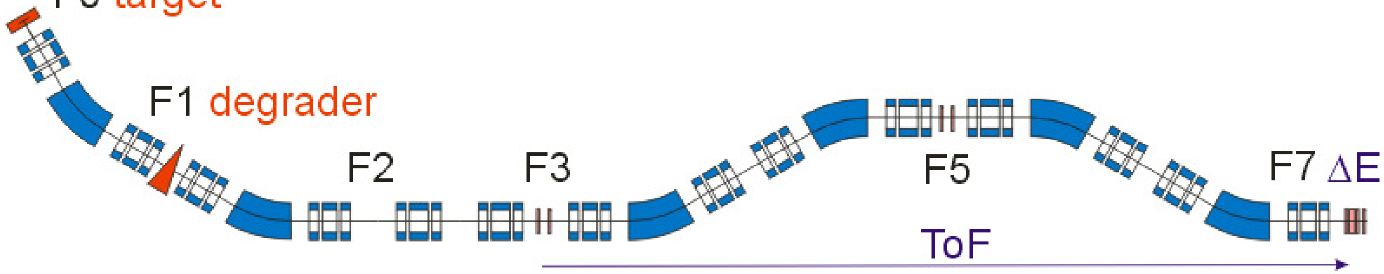


Change in q in degrader fools the Bρ-ΔE-Bρ separation

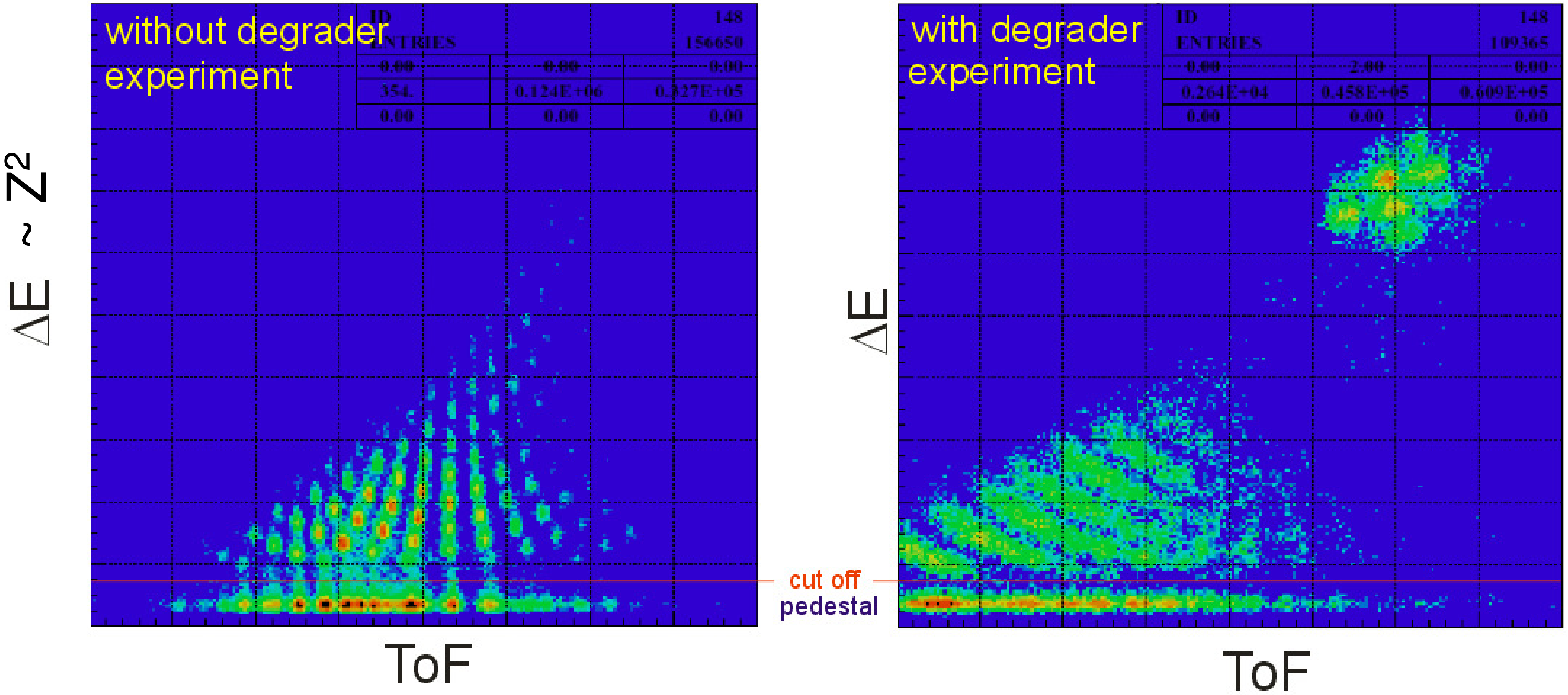
Fragments from Degrader
BigRIPS Comissioning at RIKEN



^{86}Kr, 345 MeV/u -> 12mm Be target system tuned for ^{76}Ni with narrowed momentum acceptance $\Delta p/p$=0.6%, a **6mm Al** degrader at F1 was used.

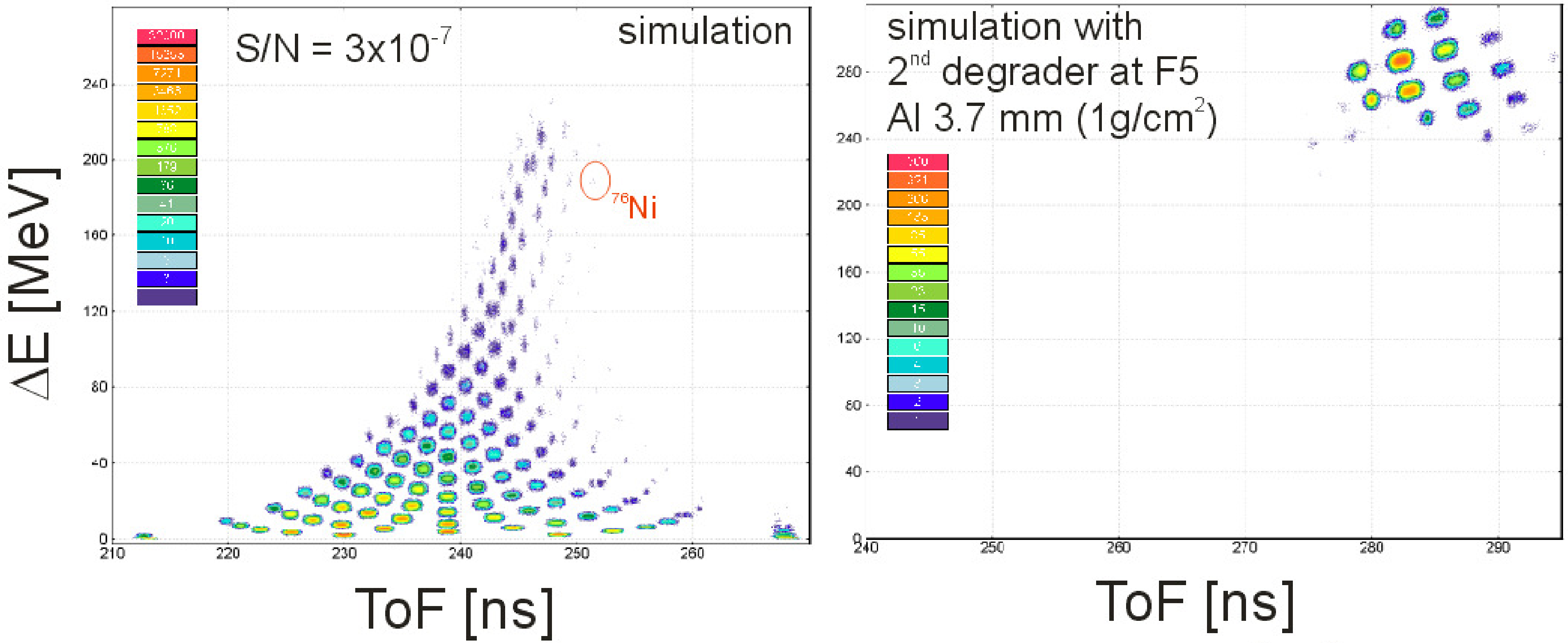


BigRIPS Commissioning in 2006
Setting ^{86}Kr -> ^{76}Ni



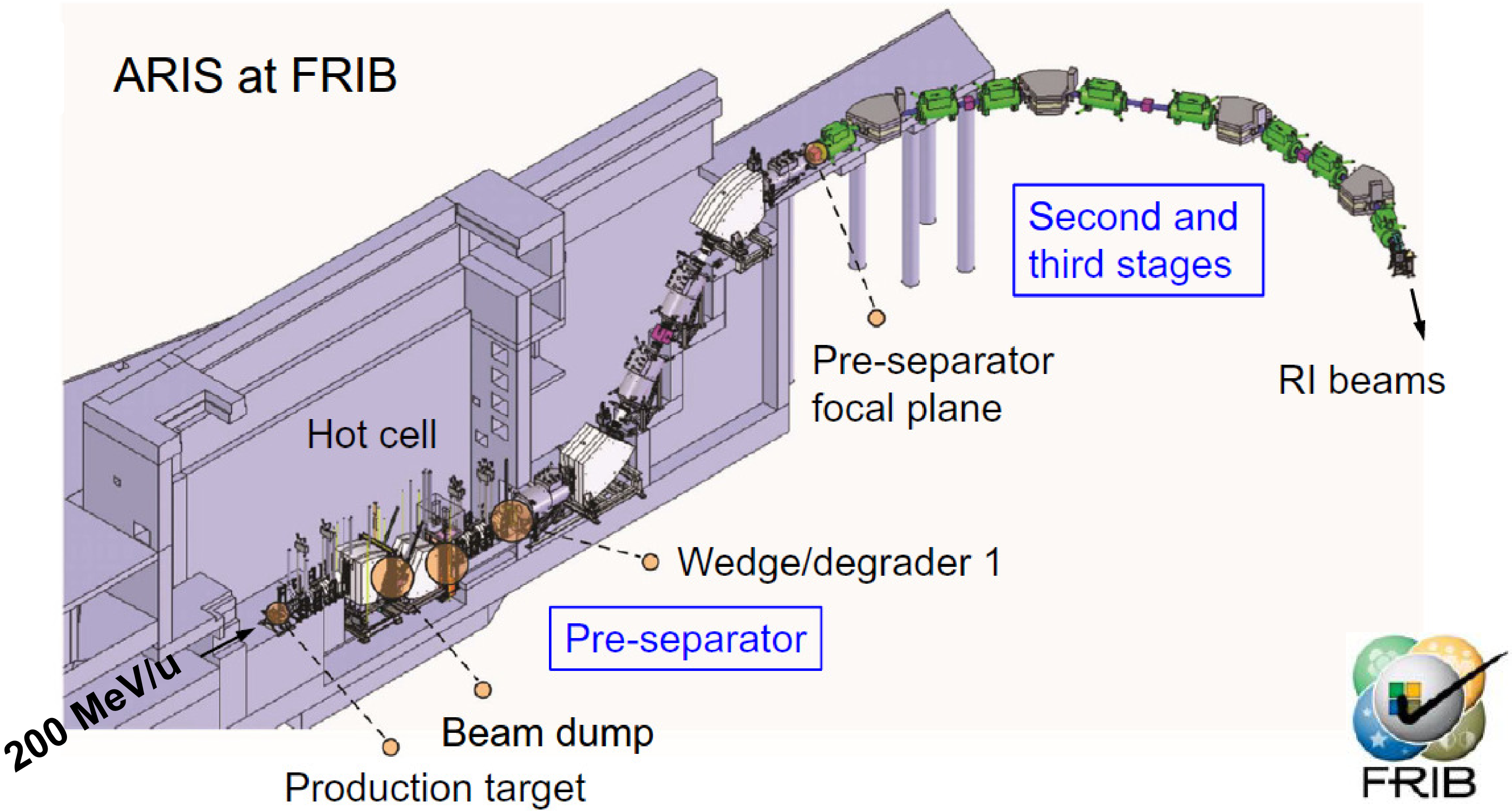
Without degrader ^{76}Ni region not visible,
with degrader still lots of lighter fragments.

BigRIPS $^{86}Kr \rightarrow {}^{76}Ni$
Simulation with LISE^{++}



Ratio: total rate / ^{76}Ni rate (=S/N).

FRIB Separator



- **Asymmetric pre-separator to compress Bρ spread by factor 3**
- **Pre and main separator in different planes**

M. Hausmann, M. Portillo, C. Wilson et al.

Separator Comparison

			in LAB			normalized to Bρ =18 Tm for m/q = 2.56		
		[Tm]	[mrad]	[mrad]	[%]	[mrad]	[mrad]	[%]
	stages	Brho	A	B	dp/p	A	B	dp/p
FRS	1	18	11	17	1.2	11.0	17.0	1.2
A1900-MSU	1	6	30	50	2.9	10.0	16.7	1.7
BigRIPS	2	9	55	40	3.0	27.5	20.0	2.2
Super-FRS	2	20	40	20	2.5	44.4	22.2	2.2
ARIS-FRIB	3	7	40	40	4.5	15.6	15.6	2.9

Forward focusing (symmetric in projectile system, Lorentz transformation)

transverse: $A = p'_x / p_0$

longitudinal: $\Delta p_z/p = \gamma\, p'_z / p_0$

	[mm] x0	$R=\frac{(x\|\delta)}{2(x\|x)x_0}$	[m^2] dipole area*
FRS	1.2	3385	2.36
A1900-MSU	1.0	1480	0.68
BigRIPS	0.5	2850	1.28
Super-FRS	1.0	2900	4.08
ARIS-FRIB	0.5	1300	0.96

* for 2 dipoles

Resolution limit by energy-loss straggling in half range thickness degrader, R ~ 800.

→ Use large area Super-FRS dipoles for high-resolution physics experiments

Summary

Most production reactions require large acceptance.
Fragments more forward focused at higher energies.
Hunt for very rare cases covered by much more intense species.

Simulation must include ion optics, atomic, nuclear physics.
Many orders of magnitude rate difference, many paths to follow.

Simplified convolution method for fast rate calculation and optimisation,
Monte Carlo for precision and details. → LISE^{++}, MOCADI.

$B\rho$-ΔE-$B\rho$ method works well, but is limited in resolution,
has problems with many atomic charge states.

Problem of too high rates for particle tracking
requires many stage separators like Super-FRS, BigRIPS, ARIS.