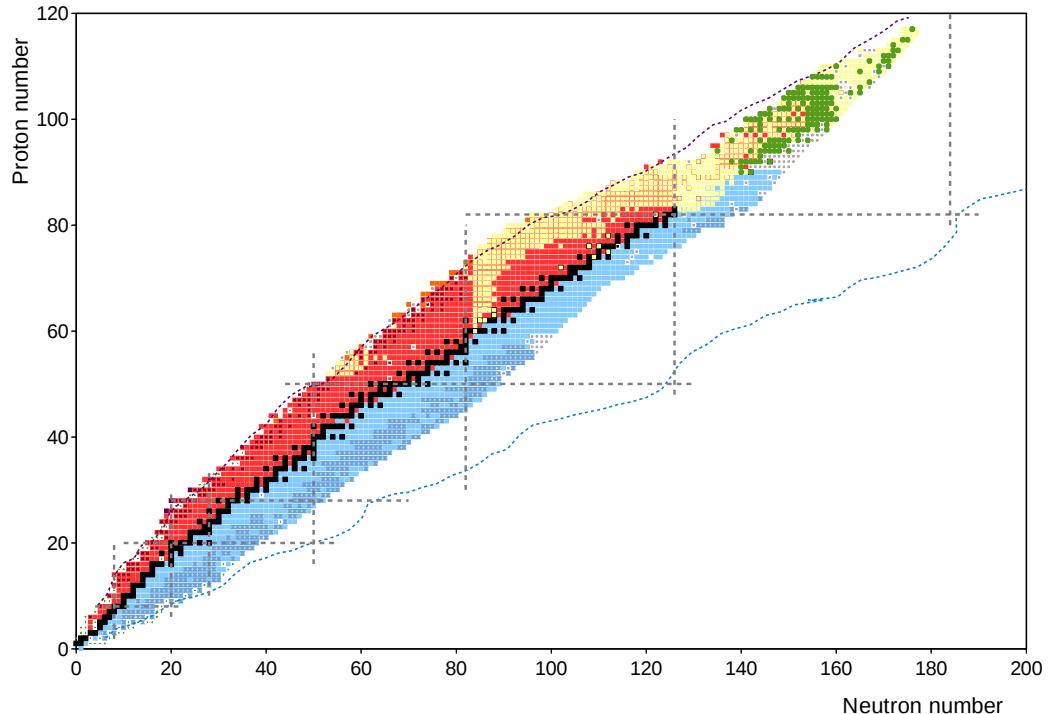
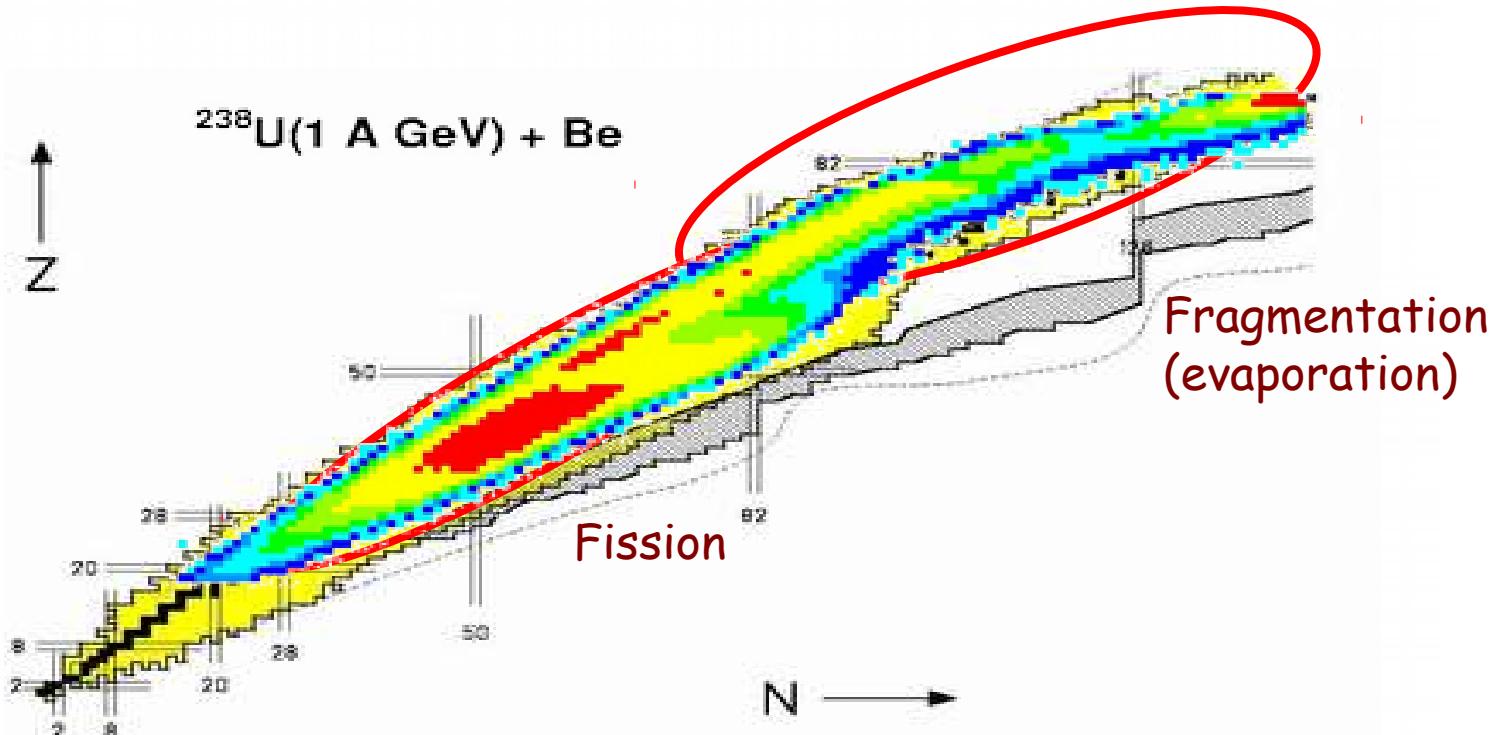


How to measure most exotic isotopes ?

- In-flight methods
(fragmentation, fusion-evaporation)
- ISOL
(spallation, fusion, DIC)



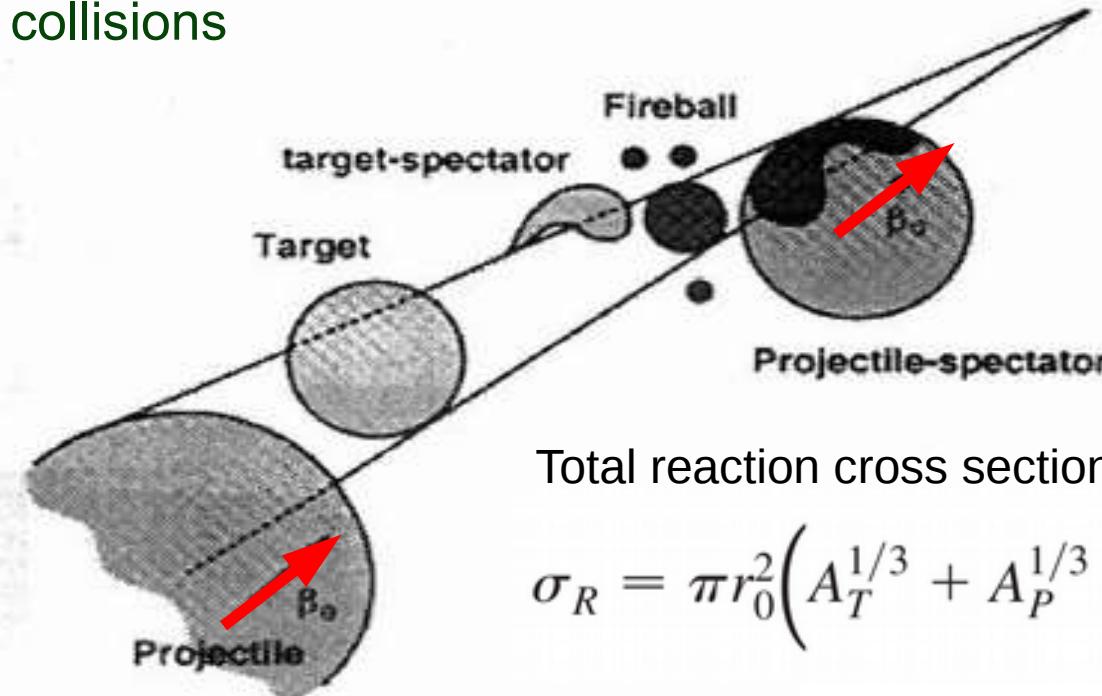
What if in one reaction one could produce all particle bound isotops and therefore provide us the means to see a clear separations between bound and unbound nuclei.



J. Benlliure
Surrey, June'05
NUSTAR minischool

Projectile fragmentation with high energy heavy ion beams !

Random removal of protons and neutrons from heavy projectile in peripheral collisions



Total reaction cross section

$$\sigma_R = \pi r_0^2 \left(A_T^{1/3} + A_P^{1/3} + a \frac{A_T^{1/3} A_P^{1/3}}{A_T^{1/3} + A_P^{1/3}} - c \right)^2$$

Geometric model of the fragmentation

Abrasion

Incomming projectile shears off a sector of the target

The non-overlapping regions of the target and projectile nuclei are assumed to be undisturbed and unheated. They are so called "spectators".

The hot overlap region forms a "fireball" that decays with release of nucleons and fragments.

Ablasion

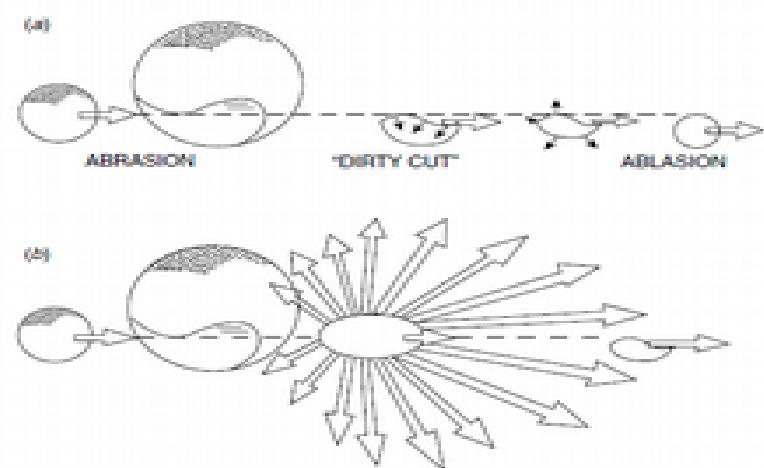
The target nucleus have a region of extra surface area, where the projectile cut.

Energy associated with the excess of surface is of about 1 MeV per excess fm^2 of surface area.

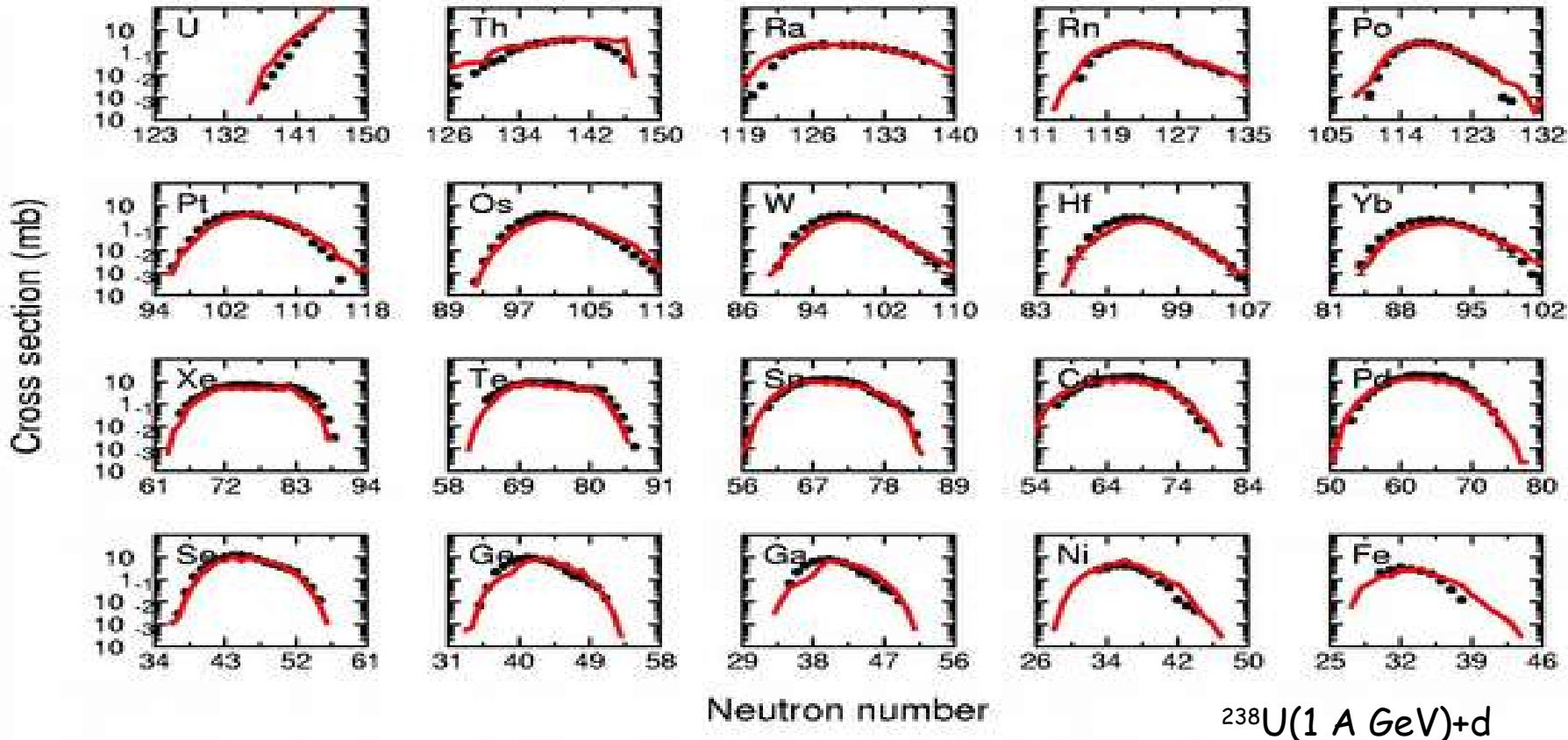
The excess of energy becomes available as excitation energy and results in emission of nucleons and fragments.

(Fission)

Extra excitation energy is released through fission.



Cross sections are smooth functions
which can be approximated by gaussian or exponentials in A-A_{projectile}



Model of projectile fragmentation

Momentum width of projectile fragments in the center
Of mass is isotropic and is derived from intrinsic momentum
(removal of the Fermi momentum from equilibrated system).

$$\sigma^2 = \sigma_0^2 \frac{A_f(A_p - A_f)}{A_p - 1}$$

$$\sigma_0^2 = \frac{p_F^2}{5}$$

A.S. Goldhaber Phys.Lett. B 53 (1974)

Longitudinal momentum width:

Transversal momentum width:
(includes corrections due to e.g.
Coulomb deflection).

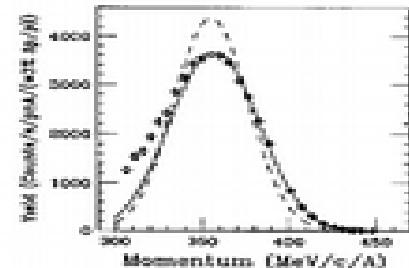


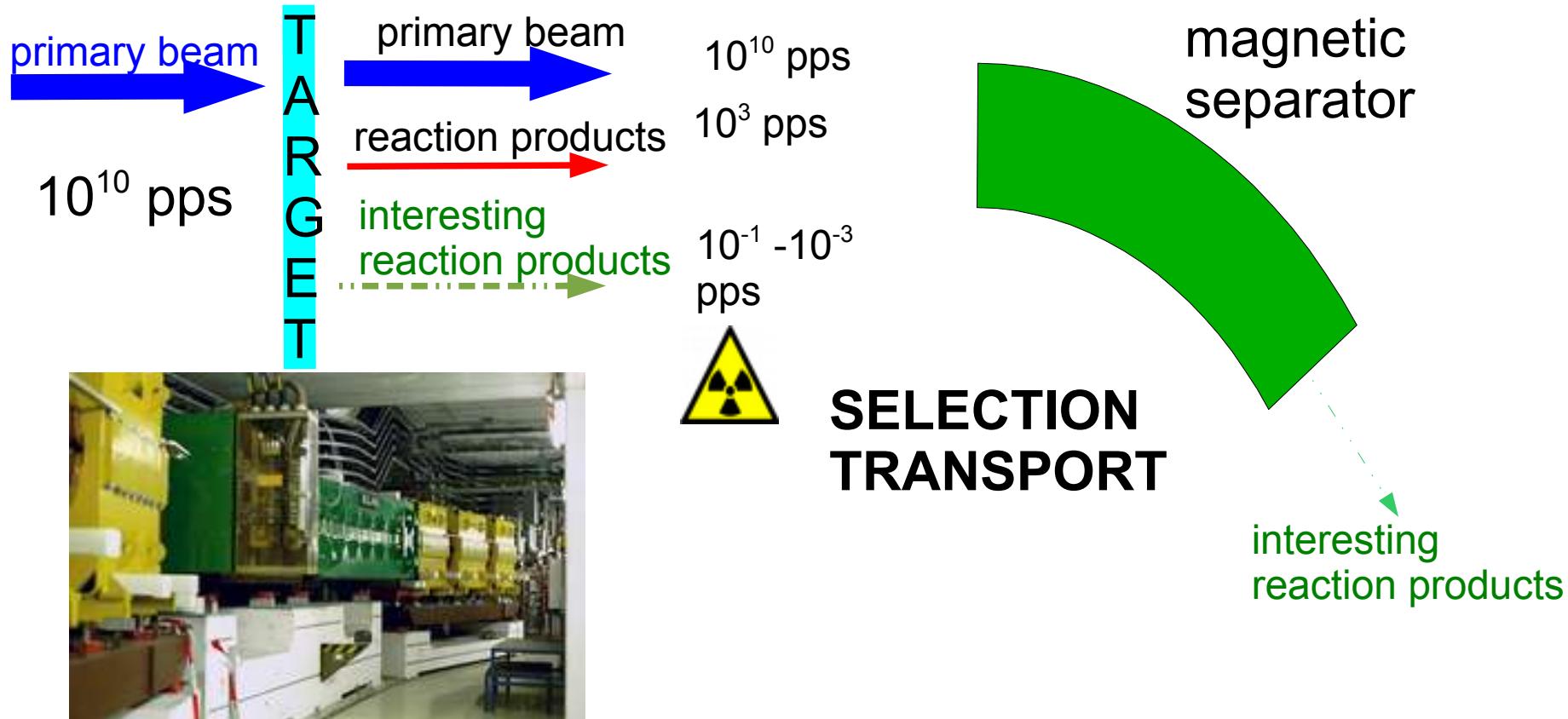
Fig. 2. Momentum distribution for ${}^7\text{Li}$ observed in the fragmentation of ${}^{16}\text{O}$ at 800 MeV/ c/A in a 700 mg/ cm^2 ${}^{9}\text{Be}$ target. The solid line comes from fitting the data, see caption fig. 1, over the range $p_F/\text{c} = 200$ to 500 MeV/ c . The dashed line is the corresponding Gaussian curve from fragmentation only, while the dotted line was obtained by adding this fitted σ_0 in quadrature with the approximate target effect width σ_2 from eq. (3). The low momentum tail is easily observed in this figure.

$$\sigma_{||}^2 = \frac{0.83 p_F}{\sqrt{5}} \sqrt{\frac{A_f(A_p - A_f)}{A_p - 1}}$$

$$\sigma_{\perp}^2 = \sigma_{||}^2 + \frac{A_f(A_f - 1)}{A_p(A_p - 1)} \sigma_0^2$$

$$\sigma_2 = 195 \frac{\text{MeV}}{c}$$

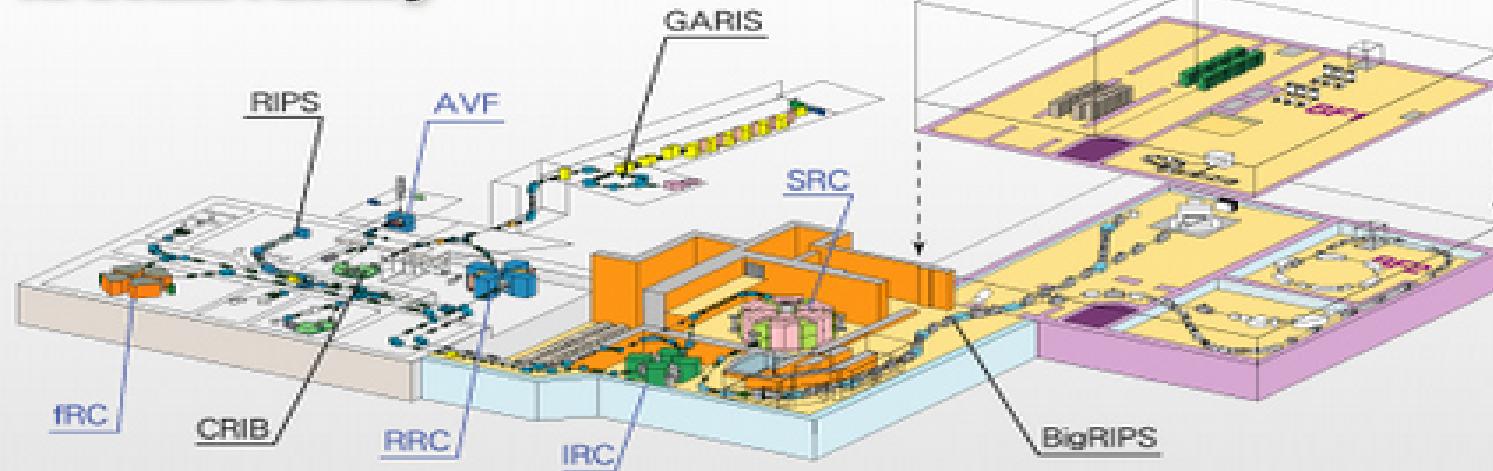
ROLE OF ELECTROMAGNETIC SEPARATORS – “IN-FLIGHT” METHODS



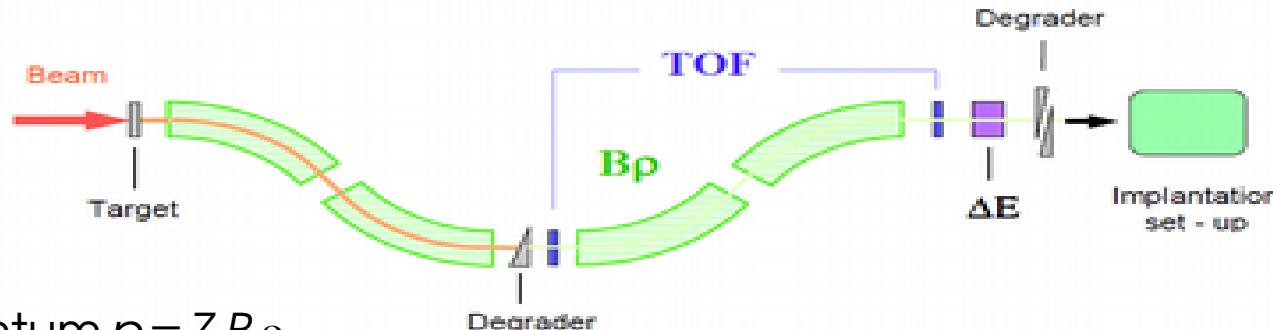
RIBF at RIKEN (JAPAN)

Primary beams of 350 MeV/nucl.

RI Beam Factory



Large acceptance separators ! Ion identification.



$$A\gamma v = \text{momentum } p = Z B \rho$$

$B\rho$ - magnetic rigidity (magnetic field times bending radius)

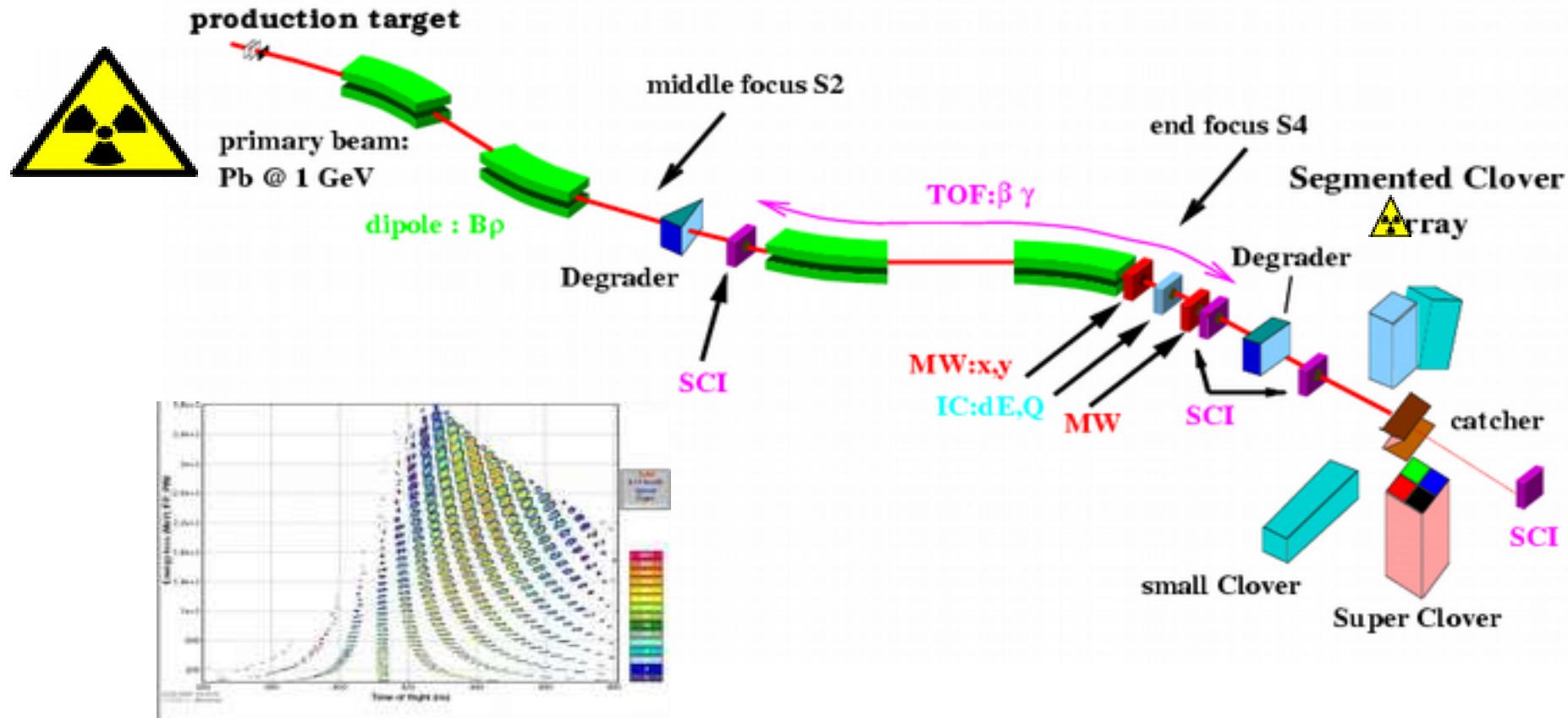
$$\frac{A}{Z} = \frac{B\rho}{v\gamma}$$

Measure: B , ρ , velocity (or time of flight)

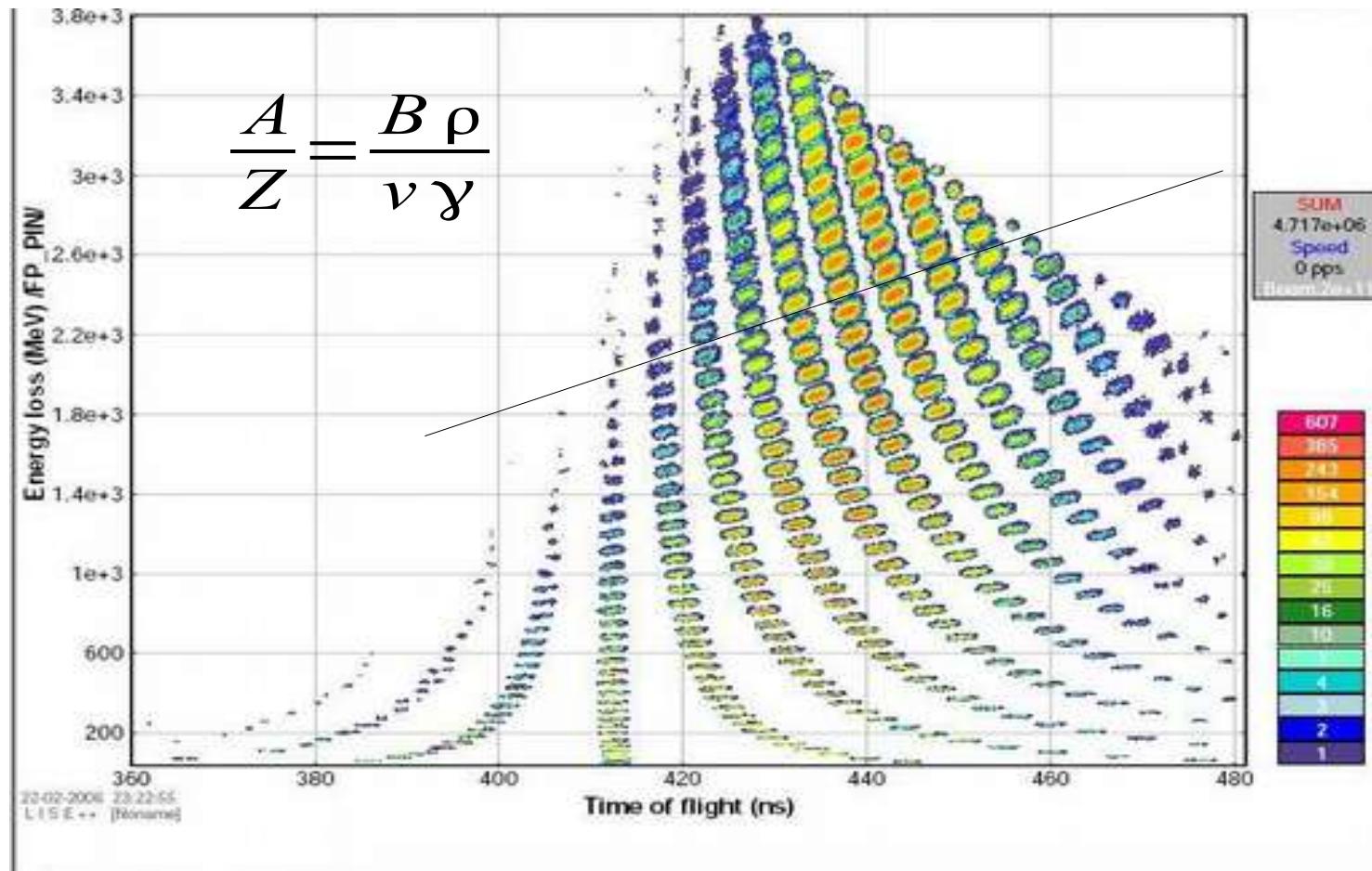
$$\Delta E \simeq Z^2$$

(Bethe–Bloch formula)

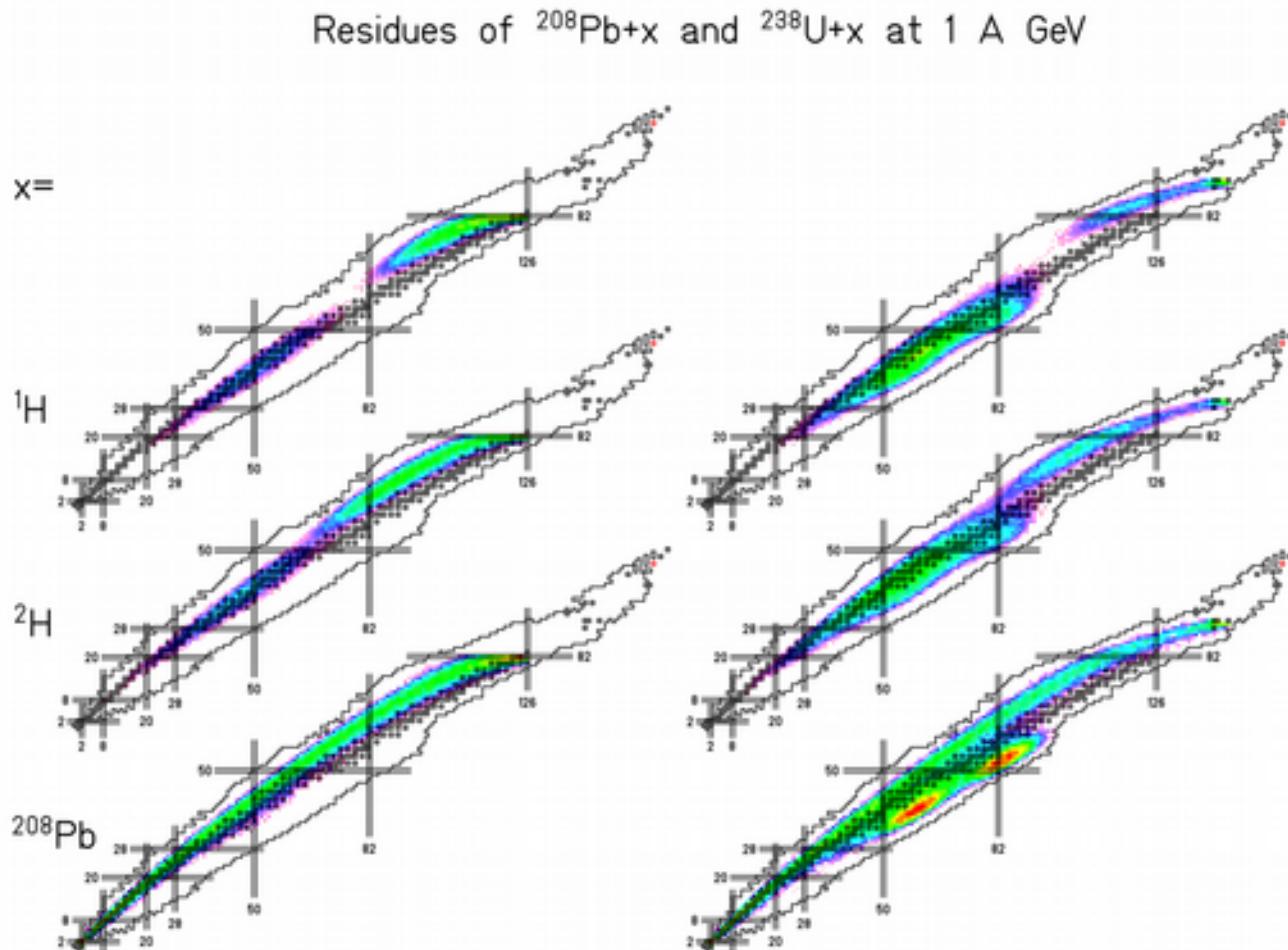
Relativistic heavy ion fragmentation



Ion identification plot

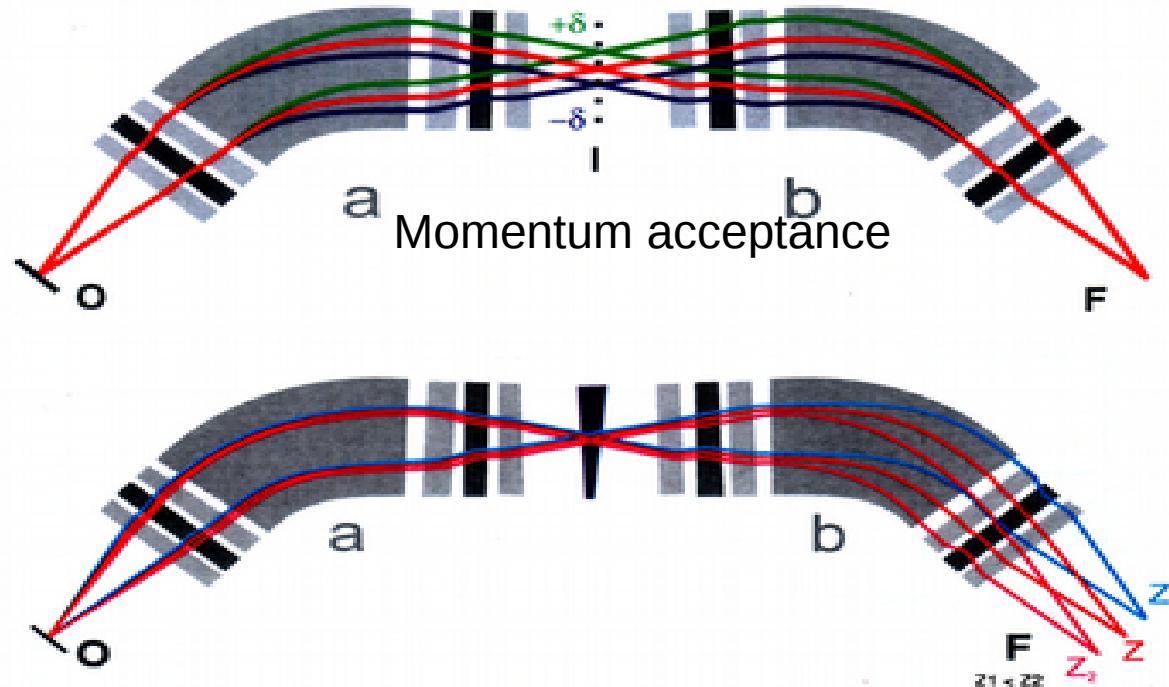


Fragmentation vs. fission



Fragment separator - doubly achromatic device

Focussing of ions independent of their velocity and angular spread

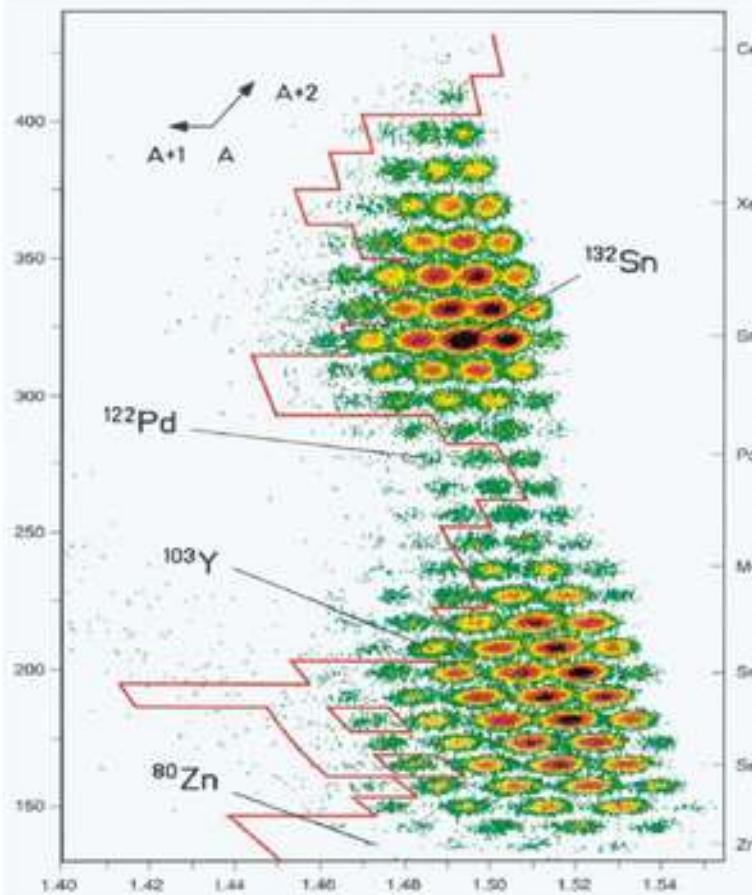


Currently operational:

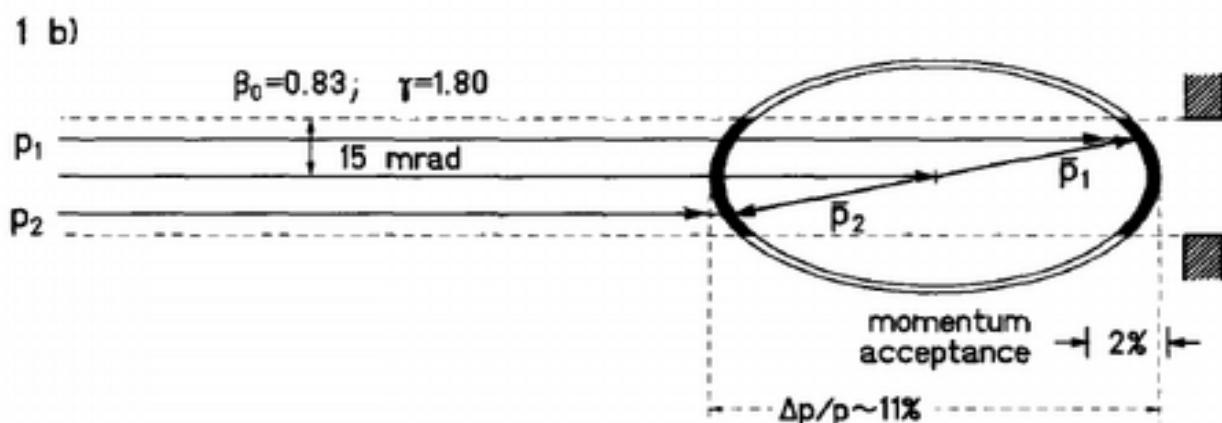
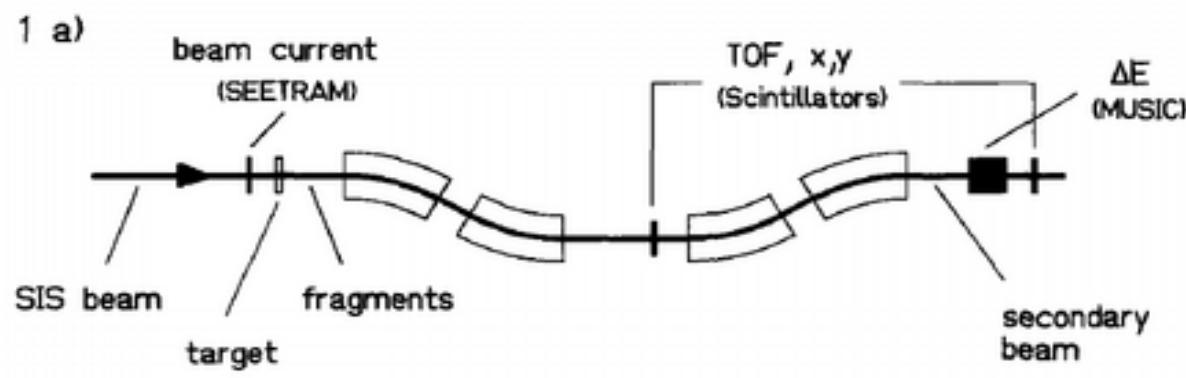
*FRS (GSI, Germany), LiSE (Ganil, France), A1900 (USA),
BIG RIPS (RIKEN, JAPAN) RIBLL (Lanzhou, China)*

Fission kinematics

M. Bernas et al. / Physics Letters B 331 (1994) 19–24

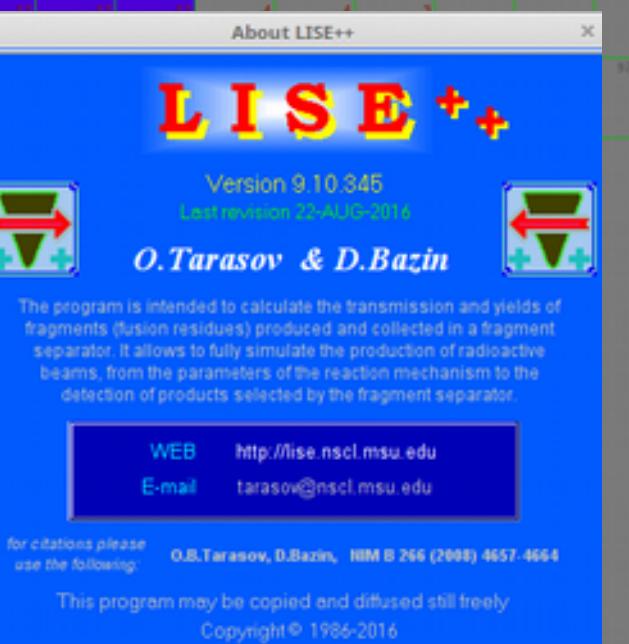


M. Bernas et al. / Physics Letters B 331 (1994) 19–24



PROJECTILE: FRAGMENT																84Rb	85Rb	86Rb	87Rb	88Rb	89Rb	90Rb	91Rb	92Rb	93Rb	94Rb	95Rb	96Rb	97Rb	98Rb	99Rb	100Rb	101Rb						
74Ba	75Br	76Br	77Br	78Br	79Br	80Br	81Br	82Br	83Br	84Br	85Br	86Br	87Br	88Br	89Br	90Br	91Br	92Br	93Br	94Br	95Br	96Br	97Br	98Br	99Br	100Br	101Br												
73Se	74Se	75Se	76Se	77Se	78Se	79Se	80Se	81Se	82Se	83Se	84Se	85Se	86Se	87Se	88Se	89Se	90Se	91Se	92Se	93Se	94Se	95Se	96Se	97Se	98Se	99Se	100Se	101Se											
72As	73As	74As	75As	76As	77As	78As	79As	80As	81As	82As	83As	84As	85As	86As	87As	88As	89As	90As	91As	92As	93As	94As	95As	96As	97As	98As	99As	100As	101As										
71Ge	72Ge	73Ge	74Ge	75Ge	76Ge	77Ge	78Ge	79Ge	80Ge	81Ge	82Ge	83Ge	84Ge	85Ge	86Ge	87Ge	88Ge	89Ge	90Ge	91Ge	92Ge	93Ge	94Ge	95Ge	96Ge	97Ge	98Ge	99Ge	100Ge	101Ge									
70Ga	71Ga	72Ga	73Ga	74Ga	75Ga	76Ga	77Ga	78Ga	79Ga	80Ga	81Ga	82Ga	83Ga	84Ga	85Ga	86Ga	87Ga	88Ga	89Ga	90Ga	91Ga	92Ga	93Ga	94Ga	95Ga	96Ga	97Ga	98Ga	99Ga	100Ga	101Ga								
69Zn	70Zn	71Zn	72Zn	73Zn	74Zn	75Zn	76Zn	77Zn	78Zn	79Zn	80Zn	81Zn	82Zn	83Zn	84Zn	85Zn	86Zn	87Zn	88Zn	89Zn	90Zn	91Zn	92Zn	93Zn	94Zn	95Zn	96Zn	97Zn	98Zn	99Zn	100Zn	101Zn							
68Cu	69Cu	70Cu	71Cu	72Cu	73Cu	74Cu	75Cu	76Cu	77Cu	78Cu	79Cu	80Cu	81Cu	82Cu	83Cu	84Cu	85Cu	86Cu	87Cu	88Cu	89Cu	90Cu	91Cu	92Cu	93Cu	94Cu	95Cu	96Cu	97Cu	98Cu	99Cu	100Cu	101Cu						
67Ni	68Ni	69Ni	70Ni	71Ni	72Ni	73Ni	74Ni	75Ni	76Ni	77Ni	78Ni	79Ni	80Ni	81Ni	82Ni	83Ni	84Ni	85Ni	86Ni	87Ni	88Ni	89Ni	90Ni	91Ni	92Ni	93Ni	94Ni	95Ni	96Ni	97Ni	98Ni	99Ni	100Ni	101Ni					
66Co	67Co	68Co	69Co	70Co	71Co	72Co	73Co	74Co	75Co	76Co	77Co	78Co	79Co	80Co	81Co	82Co	83Co	84Co	85Co	86Co	87Co	88Co	89Co	90Co	91Co	92Co	93Co	94Co	95Co	96Co	97Co	98Co	99Co	100Co	101Co				
65Fe	66Fe	67Fe	68Fe	69Fe	70Fe	71Fe	72Fe	73Fe	74Fe	75Fe	76Fe	77Fe	78Fe	79Fe	80Fe	81Fe	82Fe	83Fe	84Fe	85Fe	86Fe	87Fe	88Fe	89Fe	90Fe	91Fe	92Fe	93Fe	94Fe	95Fe	96Fe	97Fe	98Fe	99Fe	100Fe	101Fe			
64Mn	65Mn	66Mn	67Mn	68Mn	69Mn	70Mn	71Mn	72Mn	73Mn	74Mn	75Mn	76Mn	77Mn	78Mn	79Mn	80Mn	81Mn	82Mn	83Mn	84Mn	85Mn	86Mn	87Mn	88Mn	89Mn	90Mn	91Mn	92Mn	93Mn	94Mn	95Mn	96Mn	97Mn	98Mn	99Mn	100Mn	101Mn		
63Cr	64Cr	65Cr	66Cr	67Cr	68Cr	69Cr	70Cr	71Cr	72Cr	73Cr	74Cr	75Cr	76Cr	77Cr	78Cr	79Cr	80Cr	81Cr	82Cr	83Cr	84Cr	85Cr	86Cr	87Cr	88Cr	89Cr	90Cr	91Cr	92Cr	93Cr	94Cr	95Cr	96Cr	97Cr	98Cr	99Cr	100Cr	101Cr	
62V	63V	64V	65V	66V	67V	68V	69V	70V	71V	72V	73V	74V	75V	76V	77V	78V	79V	80V	81V	82V	83V	84V	85V	86V	87V	88V	89V	90V	91V	92V	93V	94V	95V	96V	97V	98V	99V	100V	101V

4 events
in 10 days
at 50 pA



The program is intended to calculate the transmission and yields of fragments (fusion residues) produced and collected in a fragment separator. It allows to fully simulate the production of radioactive beams, from the parameters of the reaction mechanism to the detection of products selected by the fragment separator.

WEB <http://lise.nscl.msu.edu>
E-mail tarasow@nscl.msu.edu

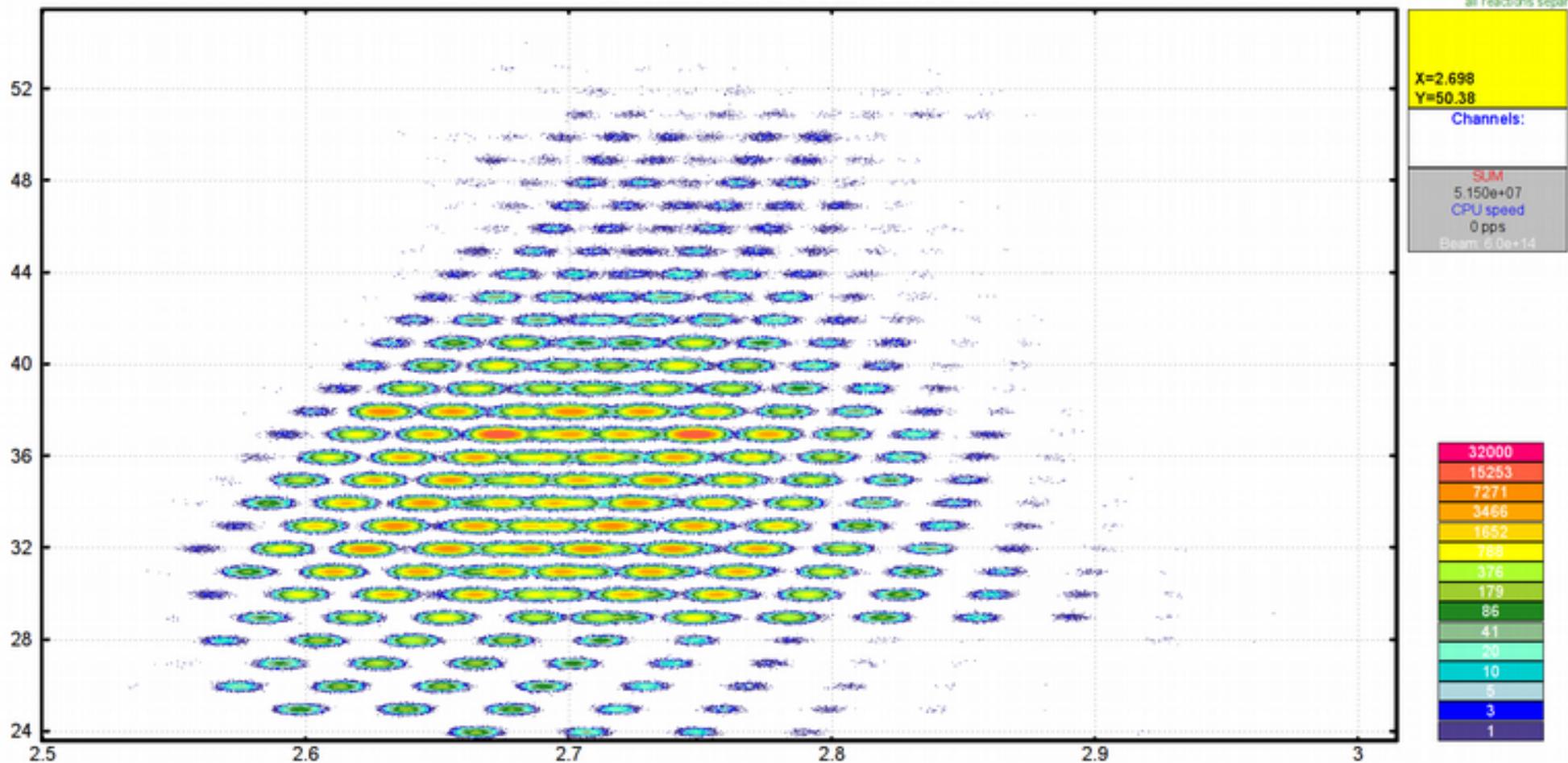
for citations please use the following: O.B.Tarasov, D.Bazin, NIM B 266 (2008) 4657-4664

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Z-A/Q

^{238}U (345 MeV/u) + Be (4 mm); Settings on $^{76}\text{Fe}^{26+, 28+}$; Config: DSSWSDSSMMMDMMWSMDDMMMMMSM...
 $\text{dp/p}=5.99\%$; Wedges: 0, 0; Brho(Tm): 8.0276, 8.0276, 8.0129, 8.0129, 8.0075....
 constructed from TOF and dE1 measurements **

all charge states separ
all reactions separ



X=2.698
Y=50.38

Channels:

SUM

5.150e+07

CPU speed

0 pps

Beam: 6.0e+14

32000

15253

7271

3466

1652

788

376

86

41

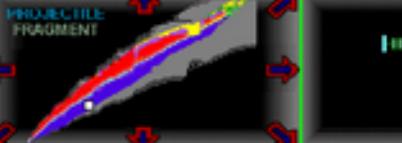
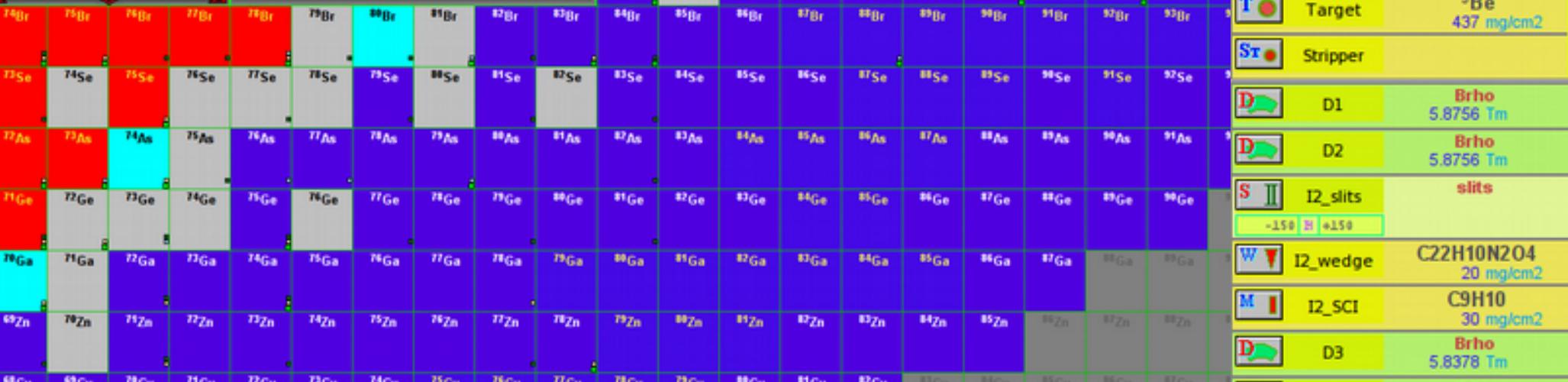
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10

5

3

1

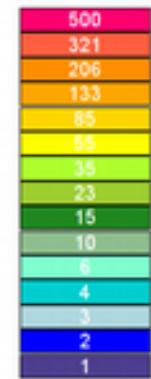
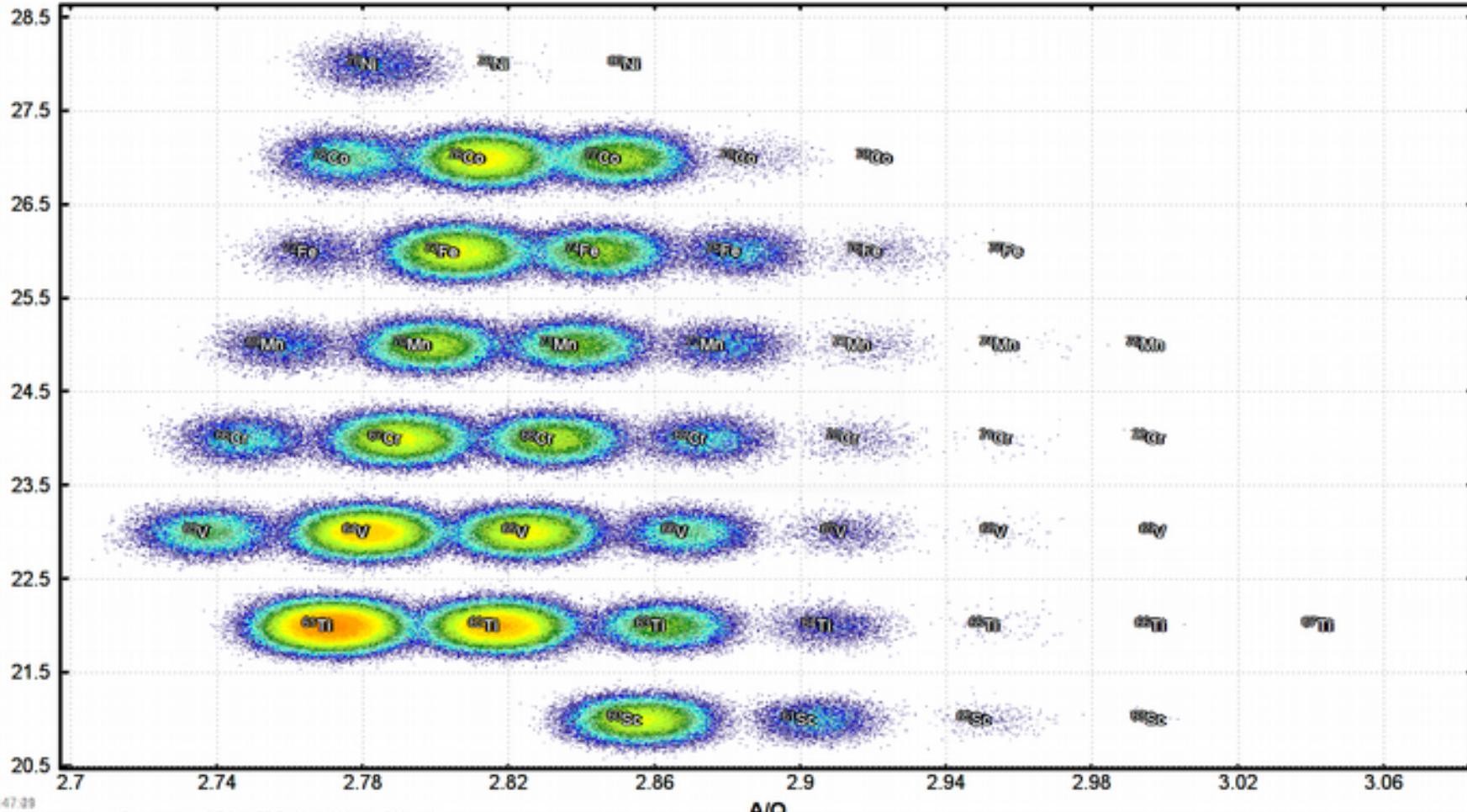
																85Rb	87Rb	88Rb	89Rb	90Rb	91Rb	92Rb	93Rb	94Rb	95Rb	96Rb	97Rb	98Rb	99Rb	100Rb								
PROJECTILE FRAGMENT																		85Kr	86Kr	87Kr	88Kr	89Kr	90Kr	91Kr	92Kr	93Kr	94Kr	95Kr	96Kr	97Kr	98Kr	99Kr	100Kr					
74Br	75Br	76Br	77Br	78Br	79Br	80Br	81Br	82Br	83Br	84Br	85Br	86Br	87Br	88Br	89Br	90Br	91Br	92Br	93Br	94Br	95Br	96Br	97Br	98Br	99Br	100Br												
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72As	73As	74As	75As	76As	77As	78As	79As	80As	81As	82As	83As	84As	85As	86As	87As	88As	89As	90As	91As	92As	93As	94As	95As	96As	97As	98As	99As	100As										
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66Co	67Co	68Co	69Co	70Co	71Co	72Co	73Co	74Co	75Co	76Co	77Co	78Co	79Co	80Co	81Co	82Co	83Co	84Co	85Co	86Co	87Co	88Co	89Co	90Co	91Co	92Co	93Co	94Co	95Co	96Co	97Co	98Co	99Co	100Co				
65Fe	66Fe	67Fe	68Fe	69Fe	70Fe	71Fe	72Fe	73Fe	74Fe	75Fe	76Fe	77Fe	78Fe	79Fe	80Fe	81Fe	82Fe	83Fe	84Fe	85Fe	86Fe	87Fe	88Fe	89Fe	90Fe	91Fe	92Fe	93Fe	94Fe	95Fe	96Fe	97Fe	98Fe	99Fe	100Fe			
64Mn	65Mn	66Mn	67Mn	68Mn	69Mn	70Mn	71Mn	72Mn	73Mn	74Mn	75Mn	76Mn	77Mn	78Mn	79Mn	80Mn	81Mn	82Mn	83Mn	84Mn	85Mn	86Mn	87Mn	88Mn	89Mn	90Mn	91Mn	92Mn	93Mn	94Mn	95Mn	96Mn	97Mn	98Mn	99Mn	100Mn		
63Cr	64Cr	65Cr	66Cr	67Cr	68Cr	69Cr	70Cr	71Cr	72Cr	73Cr	74Cr	75Cr	76Cr	77Cr	78Cr	79Cr	80Cr	81Cr	82Cr	83Cr	84Cr	85Cr	86Cr	87Cr	88Cr	89Cr	90Cr	91Cr	92Cr	93Cr	94Cr	95Cr	96Cr	97Cr	98Cr	99Cr	100Cr	
62V	63V	64V	65V	66V	67V	68V	69V	70V	71V	72V	73V	74V	75V	76V	77V	78V	79V	80V	81V	82V	83V	84V	85V	86V	87V	88V	89V	90V	91V	92V	93V	94V	95V	96V	97V	98V	99V	100V
																	Projectile 86Kr36+ 200 MeV/u 10 kW	Fragment 76Fe26+	Target 9Be 437 mg/cm ²	Stripper	D1 Brho 5.8756 Tm	D2 Brho 5.8756 Tm	I2_slits slits -150 & +150	I2_wedge <chem>C22H10N2O4</chem> 20 mg/cm ²	I2_SCI C9H10 30 mg/cm ²	D3 Brho 5.8378 Tm	D4 Brho 5.8378 Tm	FP_slits slits -3 & +3	degrader Al 2200 micron	pin1 Si 488 micron	pin2 Si 503 micron	pin3 Si 996 micron	dssd Si 995 micron	ssd Si 1000 micron				

Z-A/Q

Continue

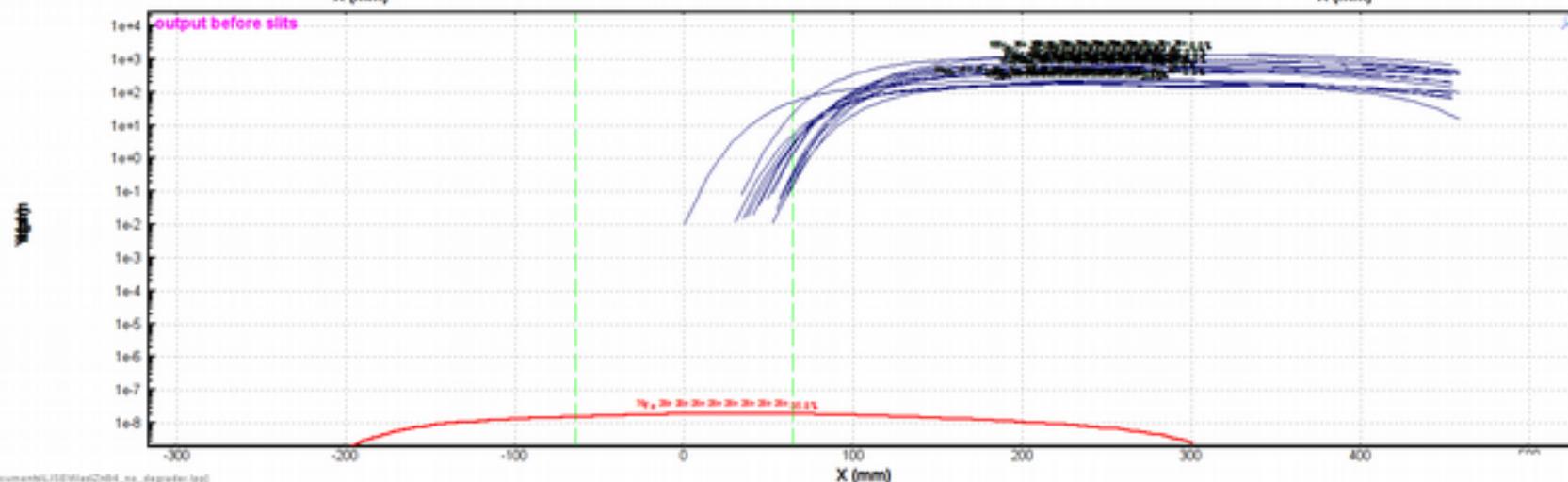
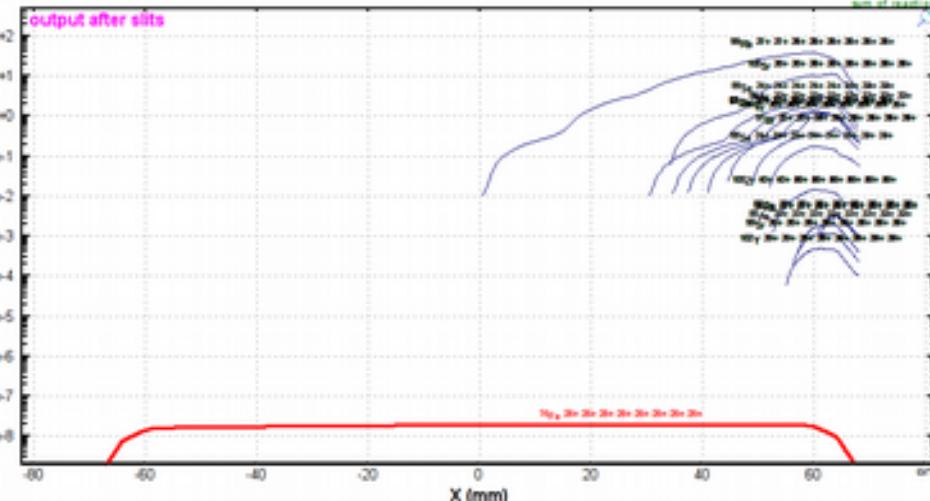
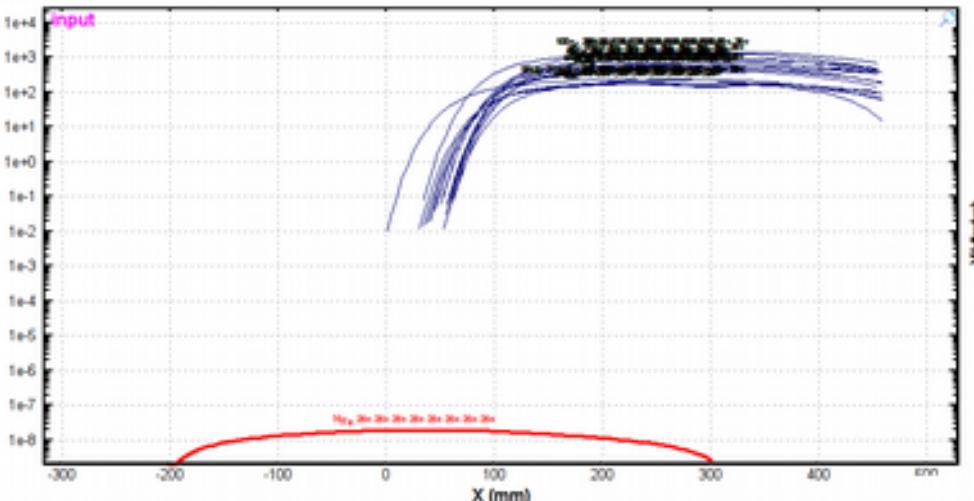
^{86}Kr (200 MeV/u) + Be (437 mg/cm²); Settings on ^{76}Fe ; Config: DDSWMDDSM^{MM}MM
 $d\text{p}/\text{p} = 5.07\%$; Wedges: 0; Brho(Tm): 5.8756, 5.8756, 5.8748, 5.8748
 constructed from TOF and dE1 measurements **

without charge states
 all reactions separ.



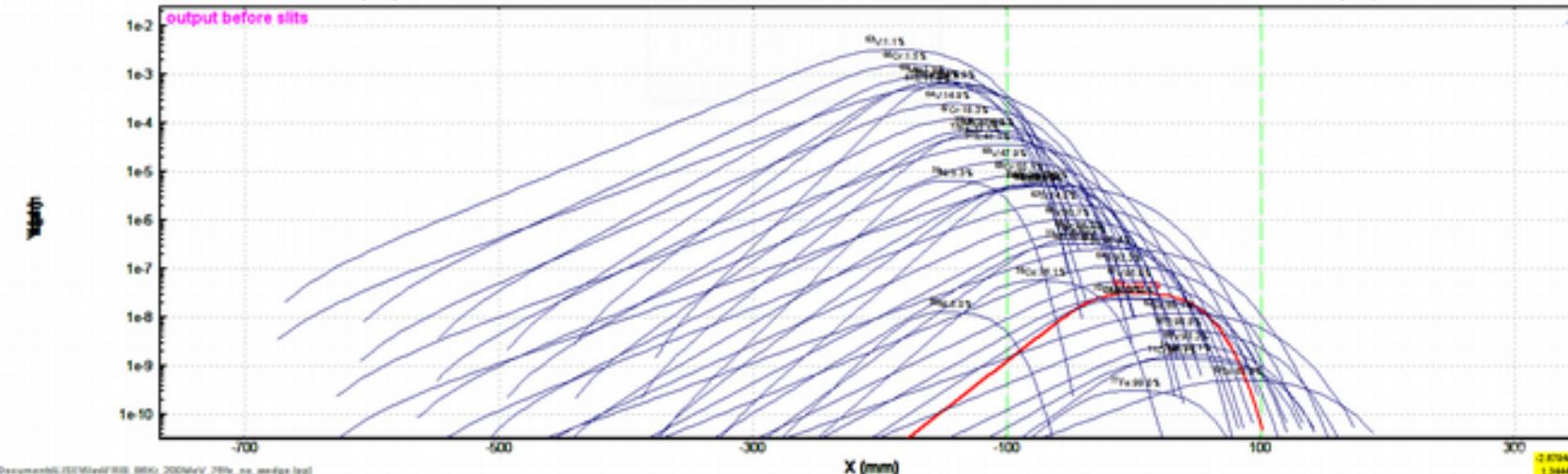
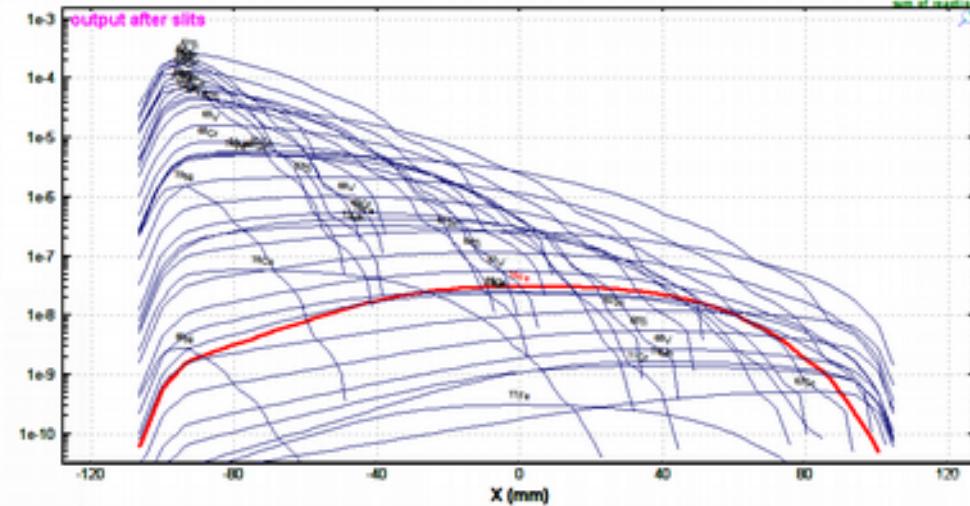
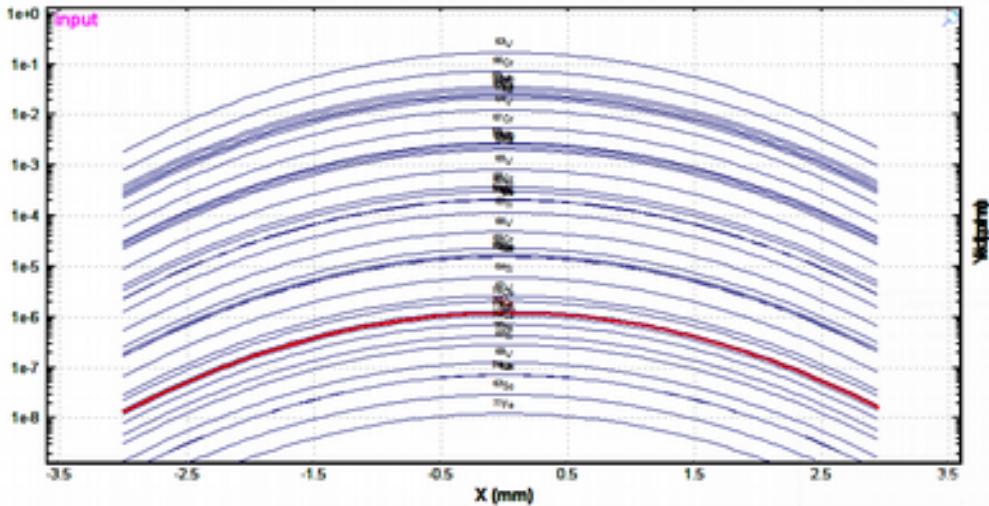
F1 slit-Xspace

^{238}U (345 MeV/u) + Be (4 mm); Settings on $^{76}\text{Fe}^{26+..26+}$; Config: DSSWSDSSMMMDMMWSMDDMMMMMSM...
 $\text{dp/p}=5.99\%$; Wedges: 0, 0; Biho(Tm): 8.0276, 8.0276, 8.0129, 8.0129, 8.0075....



D1-Xspace

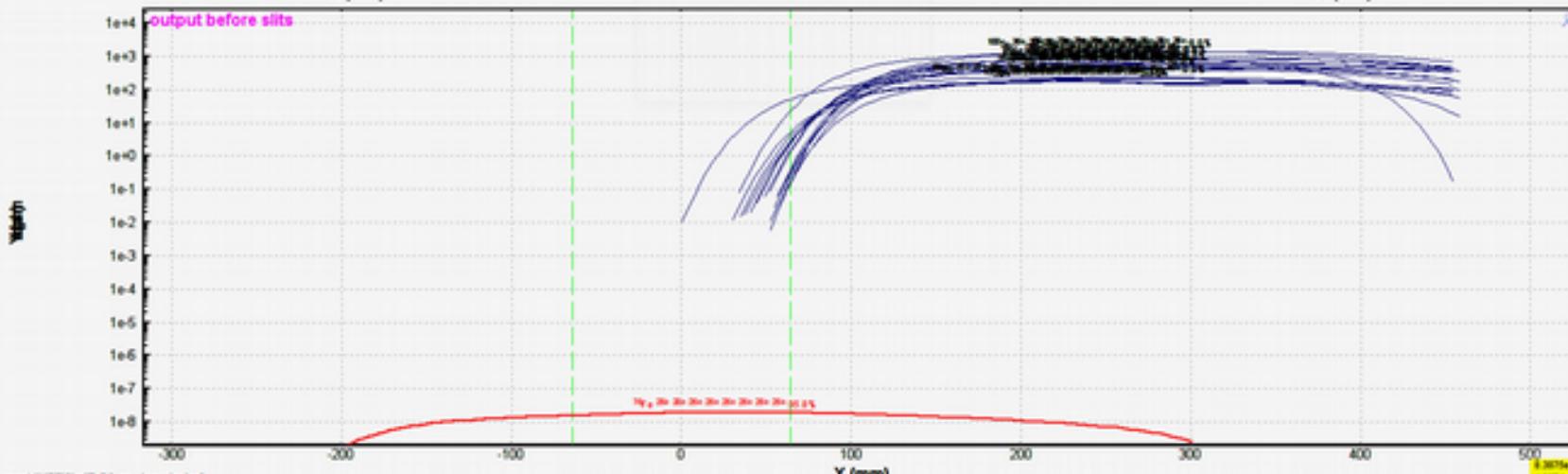
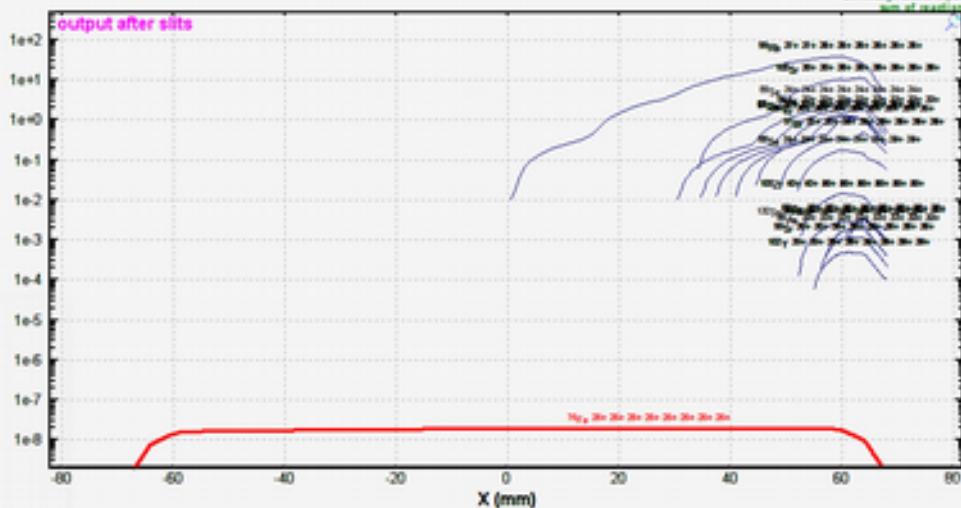
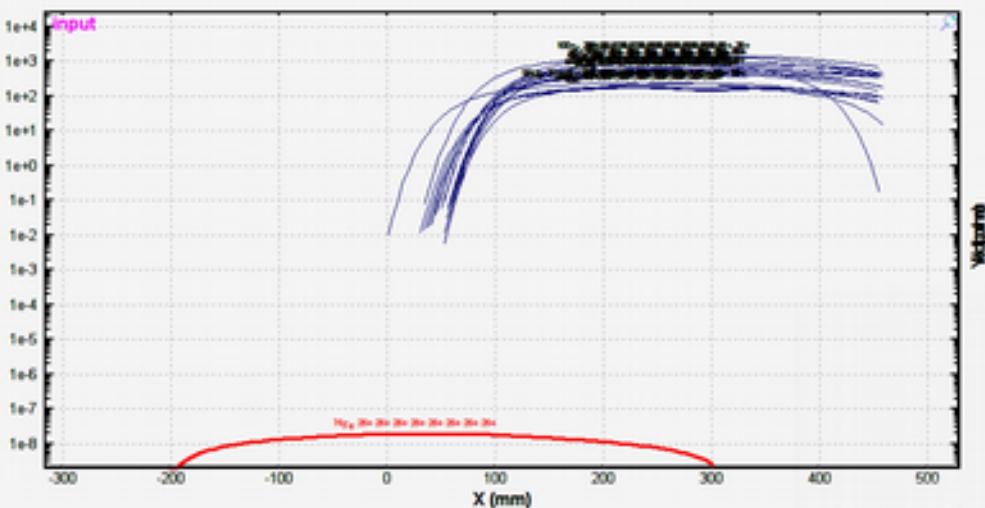
^{88}Kr (200 MeV/u) + Be (437 mg/cm²): Settings on ^{56}Fe ; Config: DDSWMDDSM~~MM~~MM
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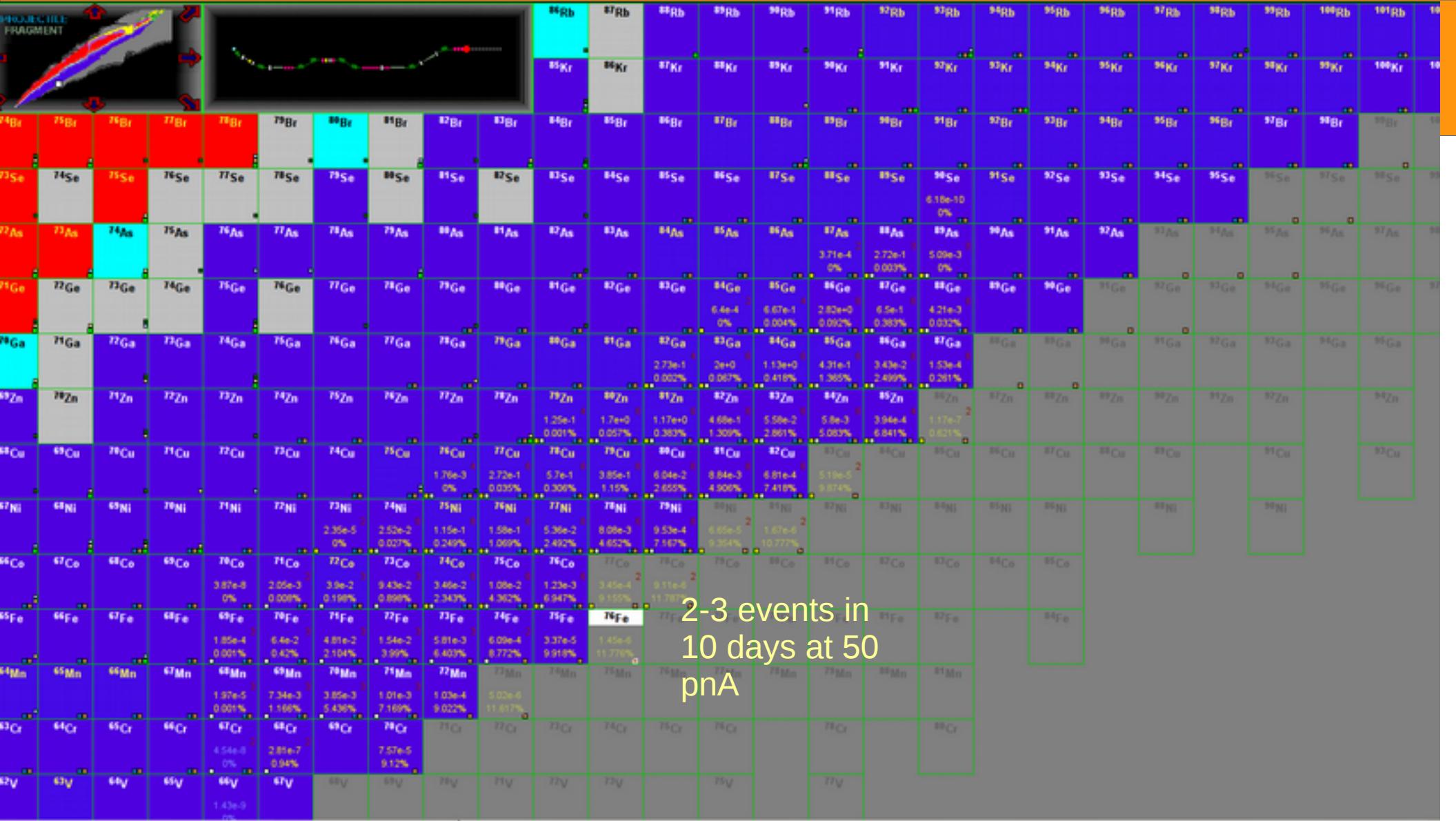


F1 slit-Xspace

^{238}U (345 MeV/u) + Be (4 mm); Settings on $^{76}\text{Fe}^{26+}, 26+$; Config: DSSWSDDSSMMMDMWMSDDMMMMMSM...
dp/p=5.99% ; Wedges: 0, 0; Brho(Tm): 8.0276, 8.0276, 8.0129, 8.0129, 8.0075....

all charge states separated
out of existing





Z-A/Q

^{238}U (345 MeV/u) + Be (4 mm); Settings on $^{76}\text{Fe}^{26+}, 26+$; Config: DSSWSDSSMMMDMWMSMDDMMMMMSM...
 $\phi/p = 5.99\%$; Wedges: 0, 0; Brho(Tm): 8.0276, 8.0276, 8.0129, 8.0129, 8.0075....
 constructed from TOF and dE1 measurements **

all charge states separ
all reactions separ

X=2.698
Y=50.38

Channels:

SUM

5.150e+07

CPU speed

0 pps

Beam: 6.0e+14

32000

15253

7271

3466

1652

788

376

179

86

41

20

10

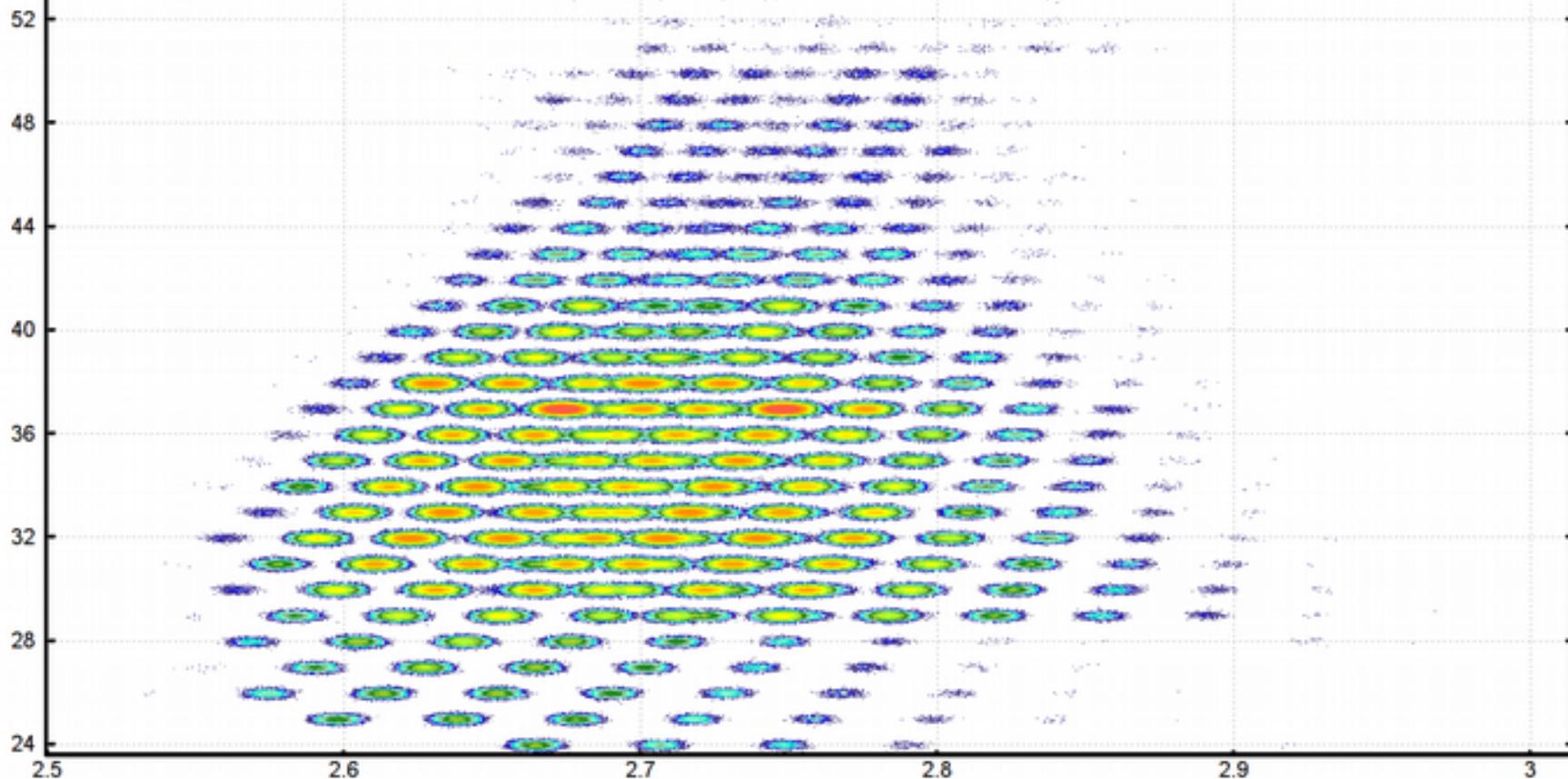
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3

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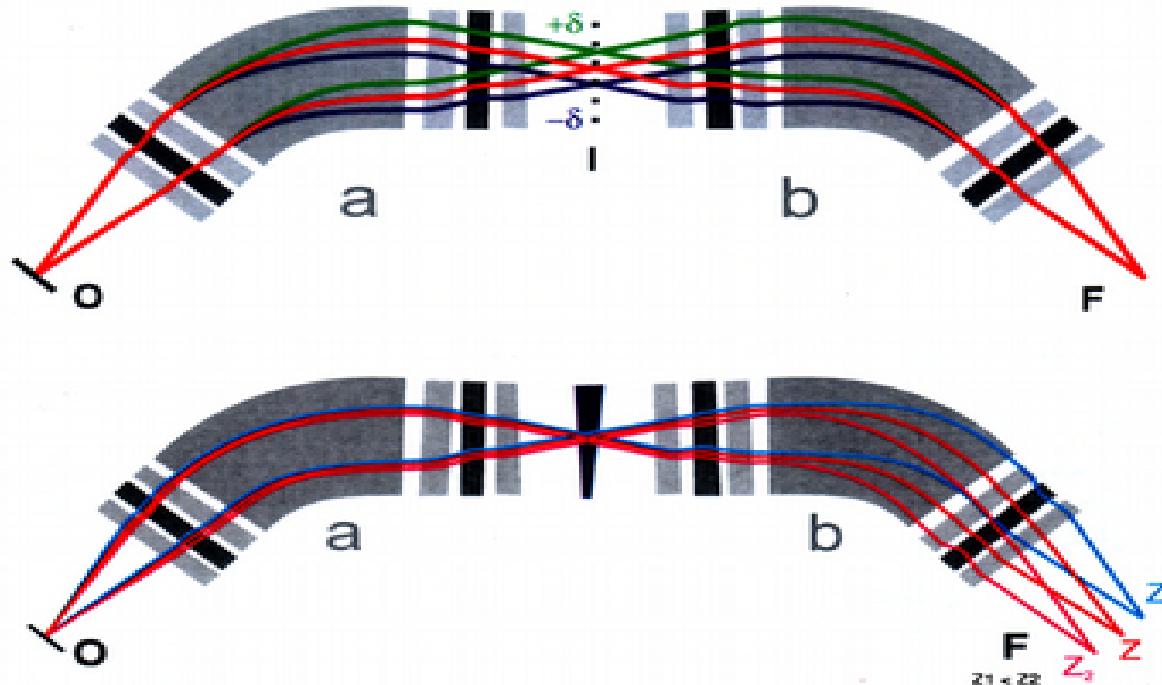


N



Fragment separator - doubly achromatic device

Focussing of ions independent of their velocity and angular spread



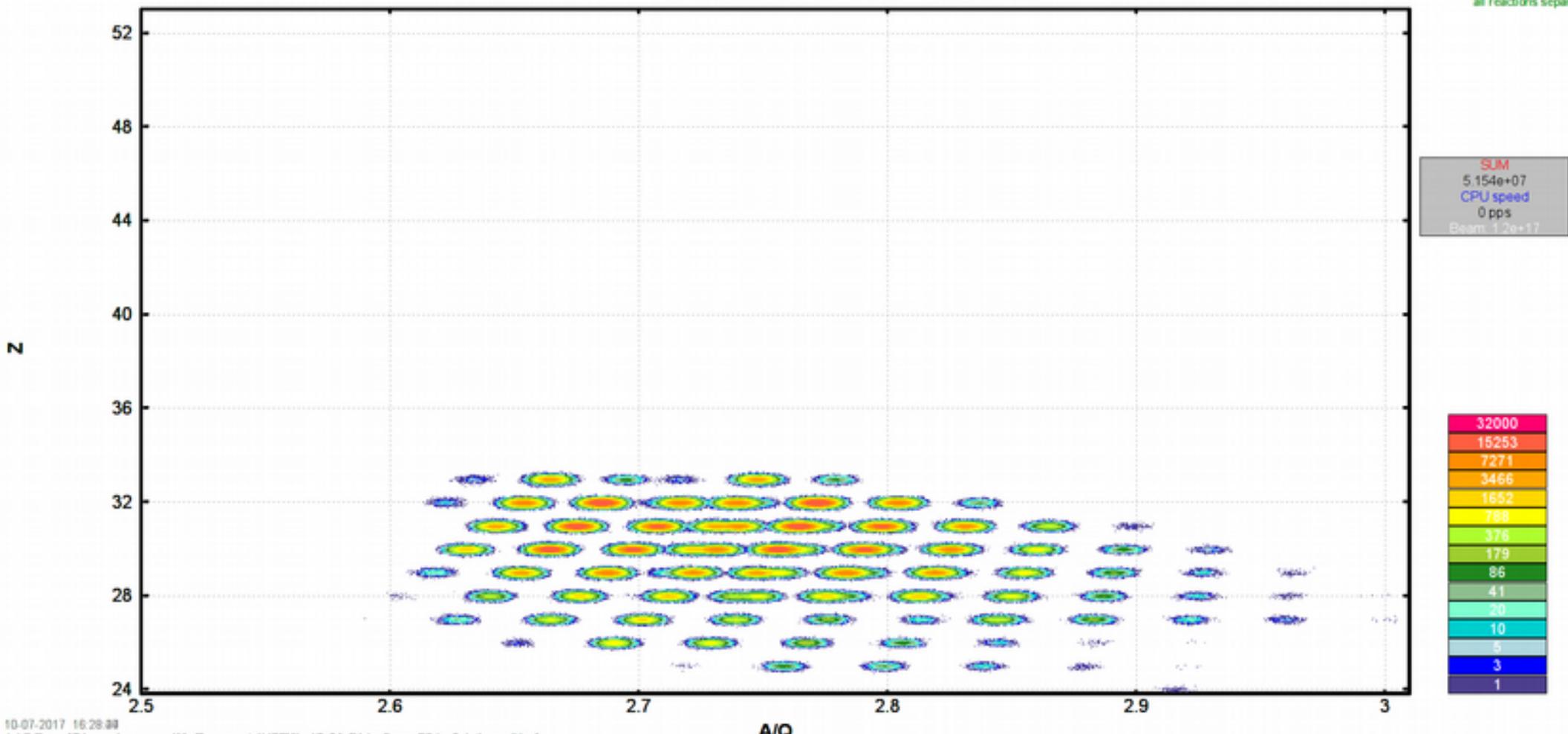
Currently operational:

*FRS (GSI, Germany), LiSE (Ganil, France), A1900 (USA),
BIG RIPS (RIKEN, JAPAN), RIBLL (Lanzhou, China)*

Z-A/Q

^{238}U (345 MeV/u) + Be (4 mm); Settings on $^{76}\text{Fe}^{26+}, 26^+$; Config: DSSWSDSSMMMDMMWSMDDMMMMMSM...
 $\text{dp/p}=4.64\%$; Wedges: Al (5 mm), Al (3.5 mm); Brho(Tm): 8.1000, 7.5940, 7.5779, 7.5779, 7.1823....
 constructed from TOF and dE1 measurements **

all charge states separ
all reactions separ



Z-A/Q

^{86}Kr (200 MeV/u) + Be (437 mg/cm²); Settings on ^{76}Fe ; Config: DDSWMDDSMmmmmmm
 dp/p=5.07% ; Wedges: C22H10N2O4 (20 mg/cm²); Brho(Tm): 5.8756, 5.8756, 5.8378, 5.8378
 constructed from TOF and dE1 measurements **

without charge states
 all reactions separ.

