# Spectrometers and Separators

## *(a biased review)*

- Some Basics
  - Selectivity versus Transmission
  - Selection technics
  - Transmission technics
- Tools
- Practical examples
  - A large Acceptance magnetic spectrometer: Vamos (Ganil)
  - A gas filled separator: RITU (Jyvaskyla)
  - A high energy fragment separator: BigRIPS

# Selectivity *versus* Transmission

## Selectivity/Rejection

= Nb of BAD particle produced/Nb of BAD particle transmitted

-depends on the type of particle (beam like, target like, adjacent channels…)

-hard (physical separation) vs soft (identification by detection)

*O.N. Malyshev et al. / Nuclear Instruments and Methods in Physics Research A 440 (2000) 86–94*

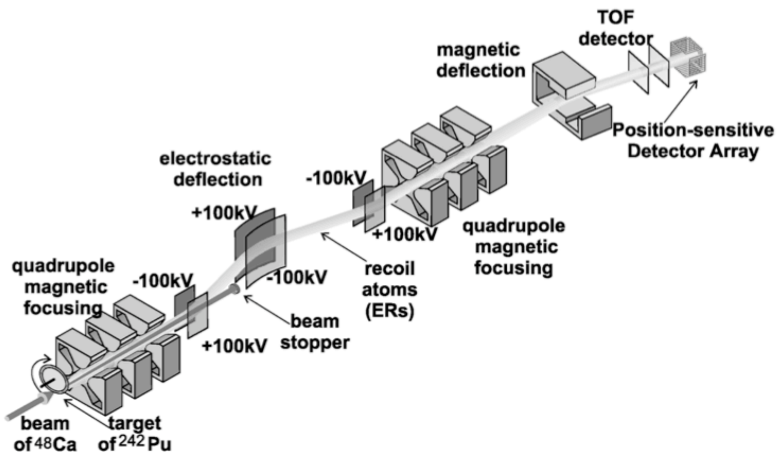


Fig. 1. Schematic view of the VASSILISSA separator.

Rejection by separator :

-of full energy beam particles: $10^9$-$10^{11}$

-of target like: $10^5$

E-ToF discrimination : x100

Alpha/fission decay : x$10^6$

Total selectivity > $10^{19}$ for beam

## Transmission

= Nb of GOOD particles transmitted / Nb of GOOD particles produced

-depends on :

- angular acceptance
- momentum acceptance
- charge state acceptance

Magnetic rigidity Bρ = mv/Q

Electric rigidity Eρ = $mv^2/Q$

Acceptance:

-Angle: ± 70mrad (15msr)

-Energy: ± 15%

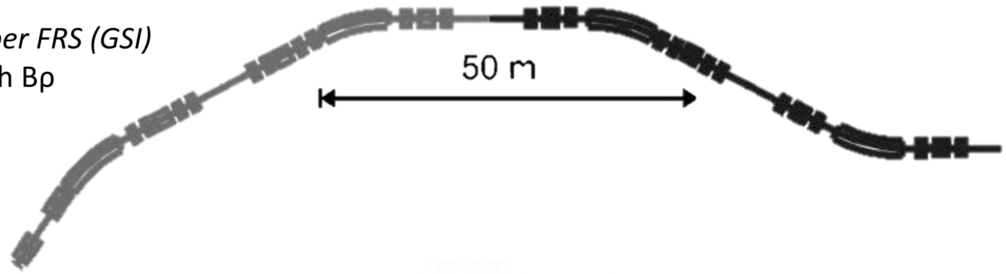
Transmission

-3% for Ne+Actinides

-40% for Ca+Actinides

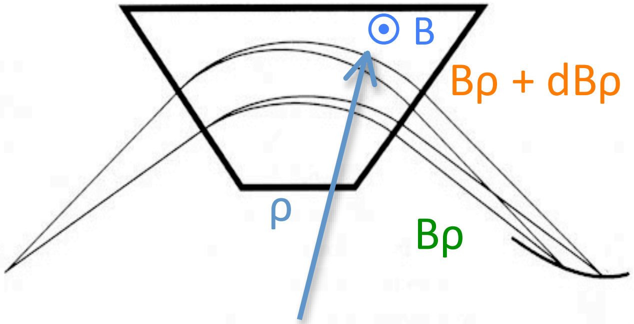
# How to select ?

*Super FRS (GSI)*
High Bρ

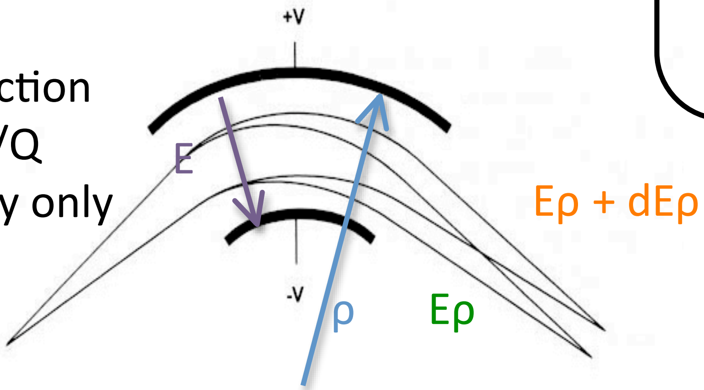



*Magnex (INFN Catania)*
High acceptance

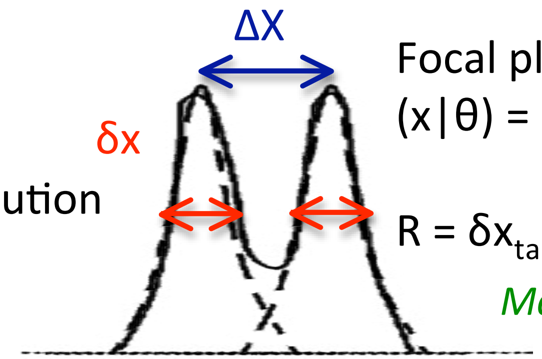
Magnetic selection
$B\rho = mv/Q$



Electric selection
$E\rho = mv^2/Q$
➔ low Energy only



Resolution



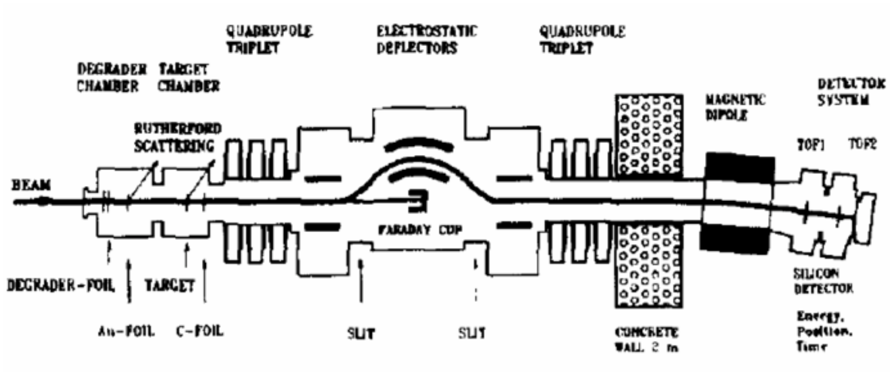
Focal plane:
$(x|\theta) = 0$

*Dispersion*

$R = \delta x_{target} \cdot (x|x)/(x|B\rho)$

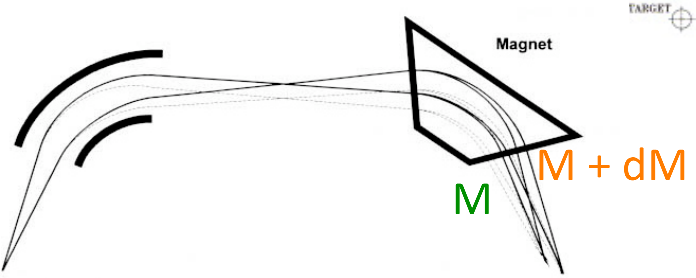
*Magnification*

*Vassilissa (Dubna)* Separator

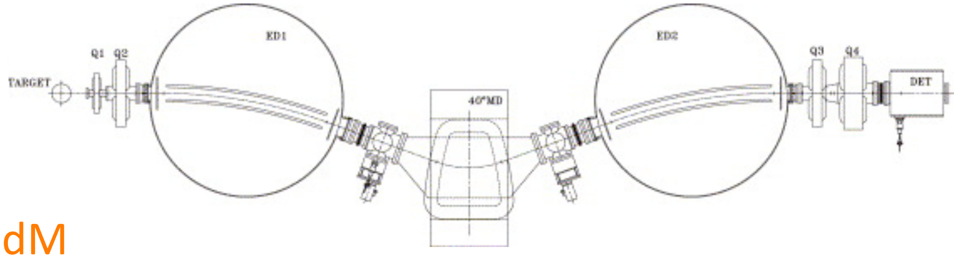


# Other selections

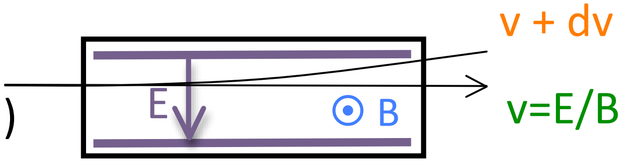
Mass selection

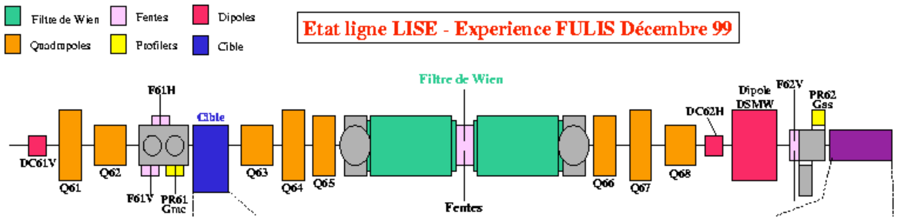


*EMMA (Triumf)*
Recoil Mass Spectrometer



Velocity filter
(poor resolution)





*LISE (Ganil)* Wien Filter

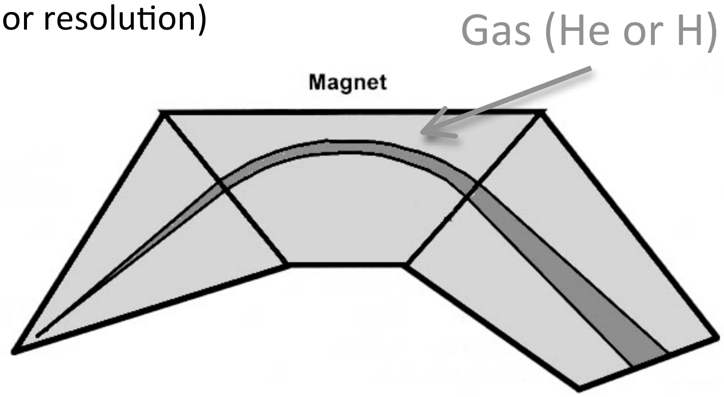
Gas Filled magnetic dipole

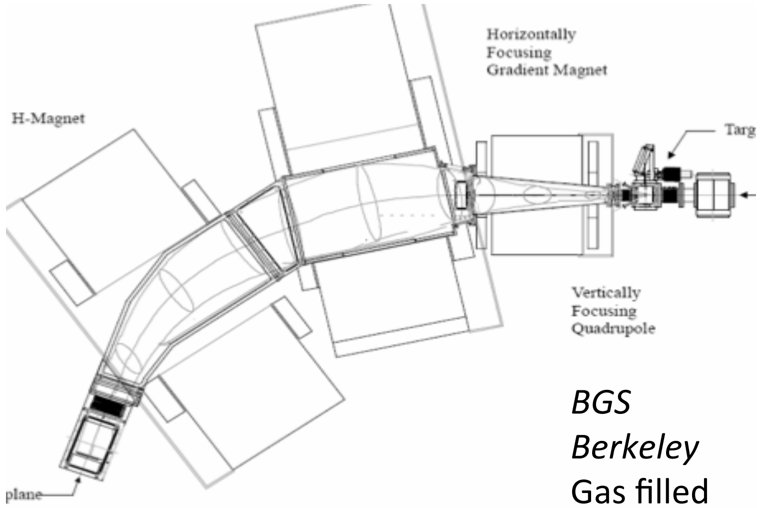
$B\rho = mv/Q_{ave} = mv/[(ev/v_0)Z^{1/3}]$

$= 0.0227\ A/Z^{1/3}$ Tm

➔No Q dependance

➔straggling in gas
(poor resolution)

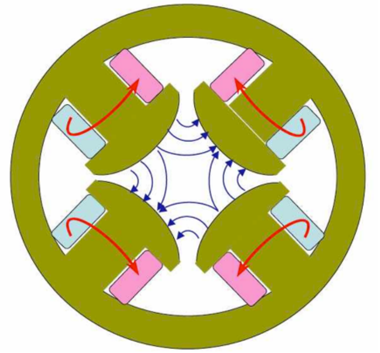




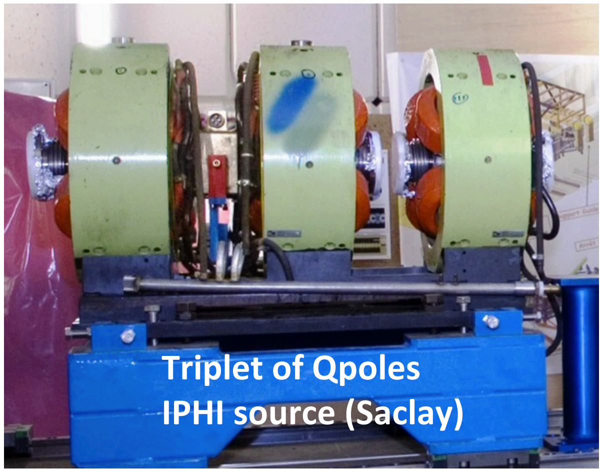
*BGS*
*Berkeley*
Gas filled
Separator

# How to transmit ?

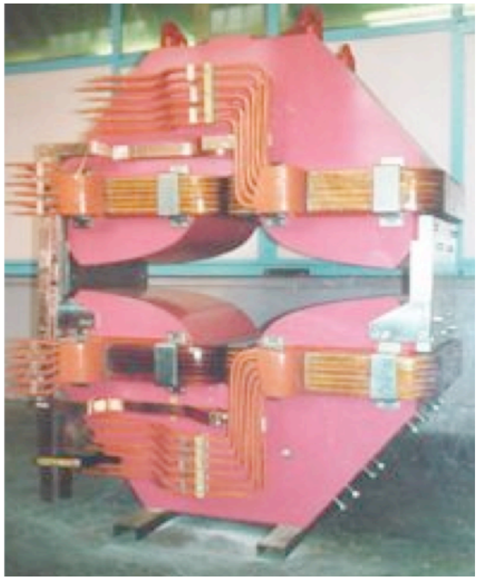
Quadrupoles to focus the beam



X : focus
Y : defocus

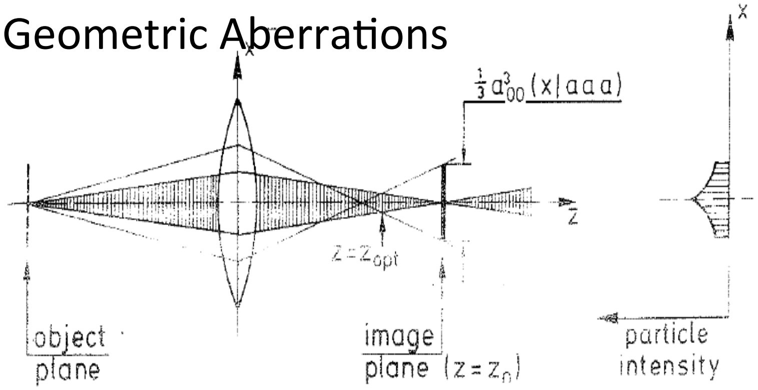


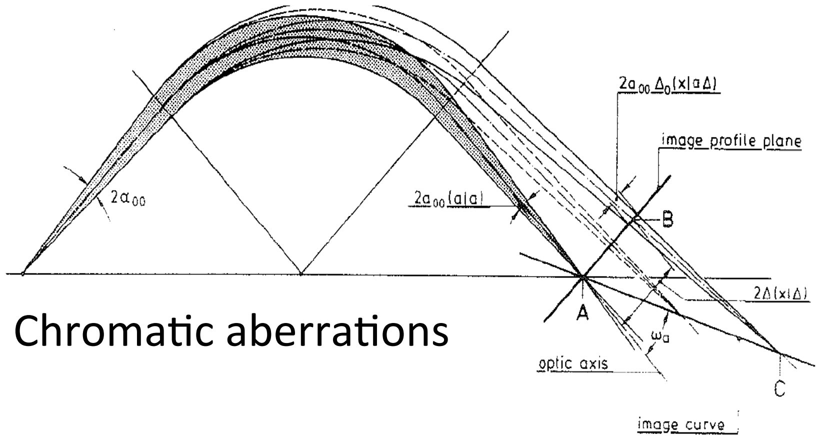
**Triplet of Qpoles**
**IPHI source (Saclay)**



Elliptical 2nd Qpole of Vamos (Ganil)
➔ Pole shaping to correct aberrations

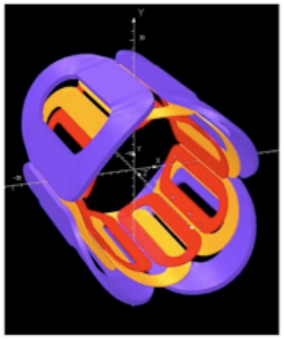
Geometric Aberrations

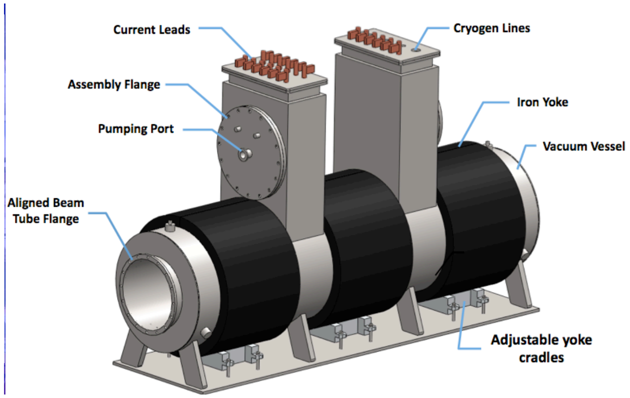




Chromatic aberrations

Superconducting multipoles of $S^3$ (Spiral2)





➔ superposition of coils to correct aberrations

# Simulation Tools

## Matrix formalism

After the element

Optical element(s)
(dipole, multipole, drift…)

Before the element

$$\begin{array}{r} \text{horizontal position} \\ \text{horizontal angle} \\ \text{vertical position} \\ \text{vertical angle} \\ \text{path of flight} \\ \text{relative momentum} \end{array} \begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix}_B = \begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{31} & R_{31} & R_{36} \\ R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\ R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{66} & R_{66} \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix}_A$$

$$l = v0(t - t_0)$$

$$\delta = \frac{p - p_0}{p_0}$$

➔ first order is the minimum, but higher orders can be treated

➔ used for the preliminary design an optical line, “light” at low order (< 3)

➔ for realistic elements, the matrix must be constructed accordingly from ray tracing

e.g. : Beta (1$^{st}$ order), Transport (1$^{st}$ to 3$^{rd}$ order), Cosy[infinity] (all orders)

## Ray tracing

Step by step integration of the trajectories in the 3D field maps

➔Requires full field maps for realisic sim.

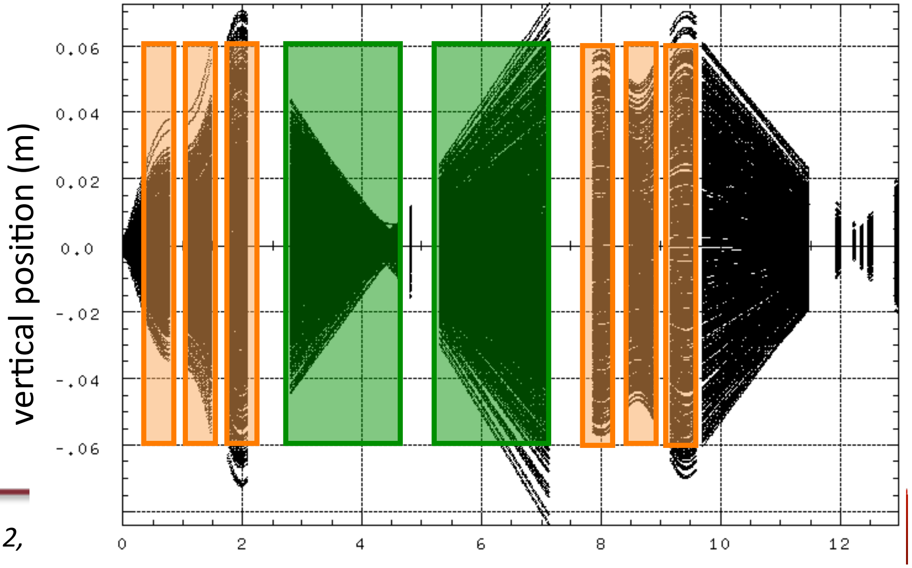
➔“all orders” included, no approximation

➔Calculations are very “heavy”

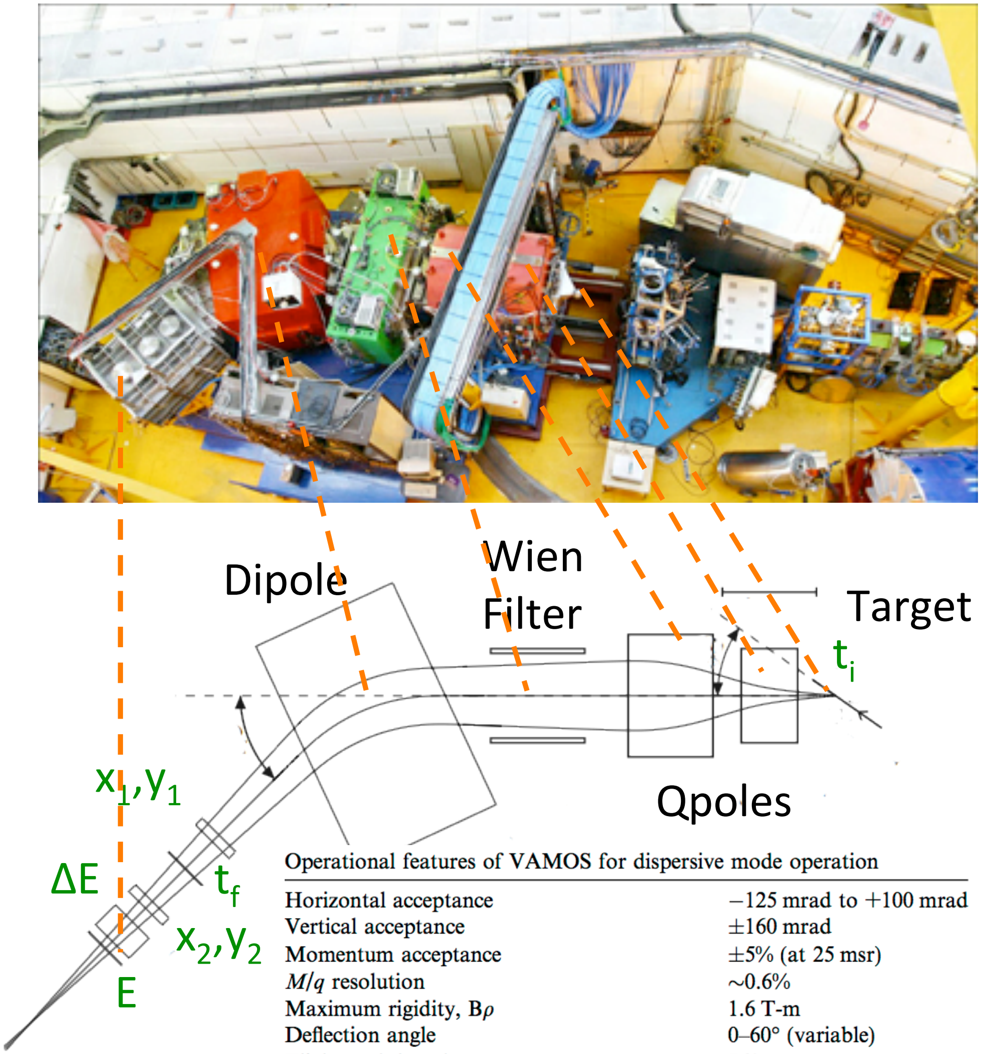
e.g. : Zgoubi, Opera 3D, Tracewin

➔ *S3 simulations: talk by F. Déchery*

Zgoubi simulation of LISE Wien filter



# High Acceptance Spectrometer : Vamos (Ganil)

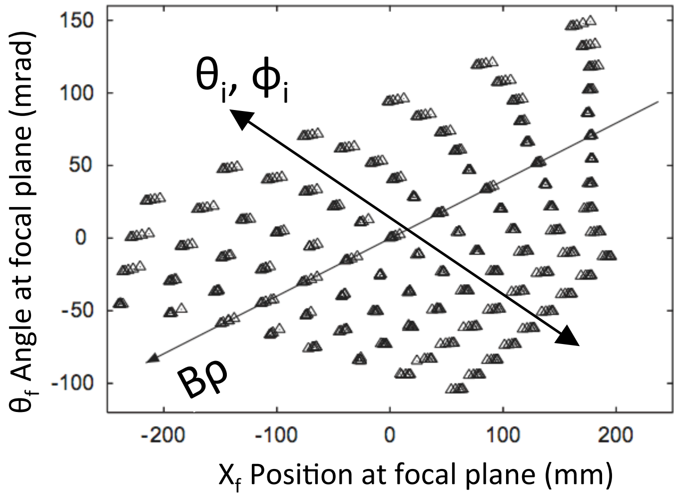


Operational features of VAMOS for dispersive mode operation

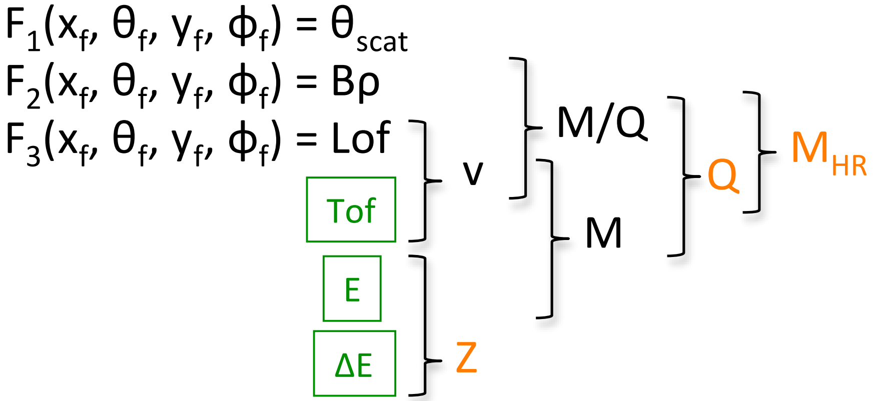
| | |
|---|---|
| Horizontal acceptance | −125 mrad to +100 mrad |
| Vertical acceptance | ±160 mrad |
| Momentum acceptance | ±5% (at 25 msr) |
| *M*/*q* resolution | ~0.6% |
| Maximum rigidity, B*ρ* | 1.6 T-m |
| Deflection angle | 0–60° (variable) |
| Flight path length | 760 cm |
| Linear translation | 40–120 cm |
| Angular rotation | 0–60° |

*S. Pullanhiotan & al. NIMB 266 (2008) 4148*
*NIMA 593 (2008) 343*

Large acceptance ➔ Large aberrations



Trajectories are simulated (e.g. Zgoubi)
➔ Phenomenological set of functions

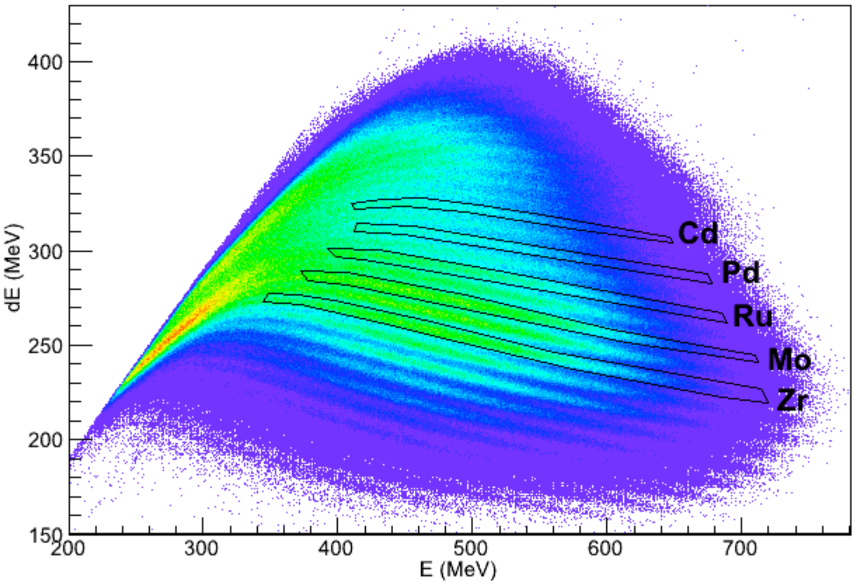


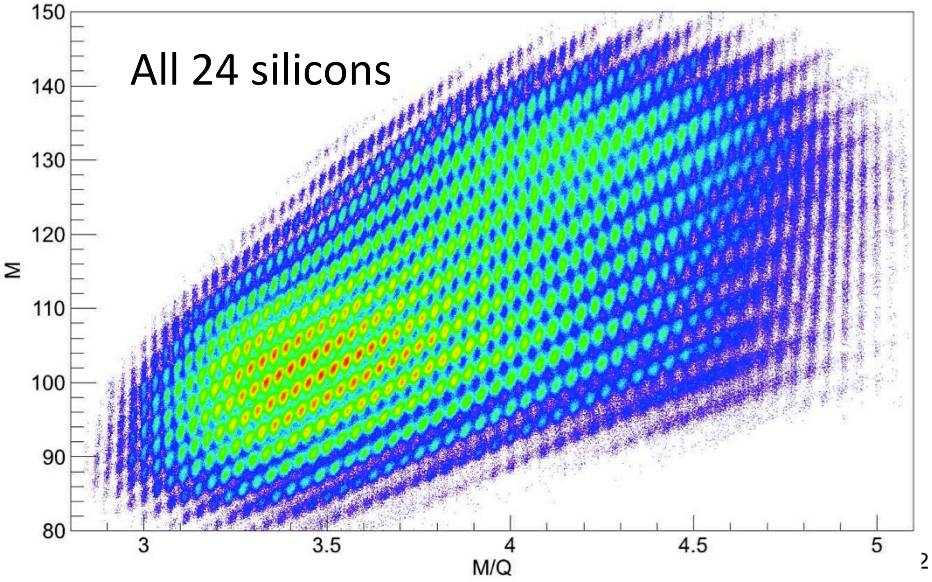
$F_1(x_f, \theta_f, y_f, \phi_f) = \theta_{scat}$
$F_2(x_f, \theta_f, y_f, \phi_f) = B\rho$
$F_3(x_f, \theta_f, y_f, \phi_f) = Lof$

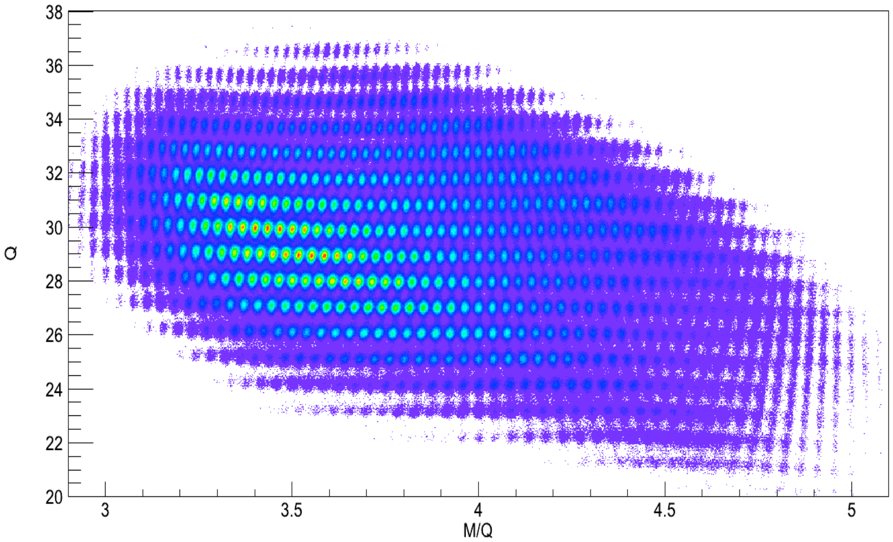
**$\delta Z/Z = 66$** **$\delta M/M = 220$**

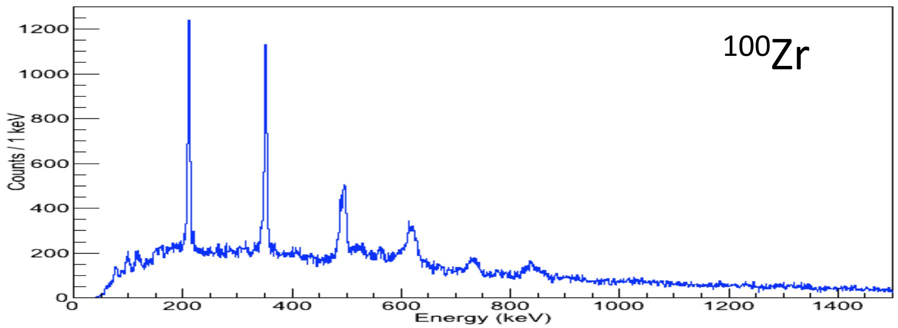
# Vamos: Practical case $^{238}$U+Be

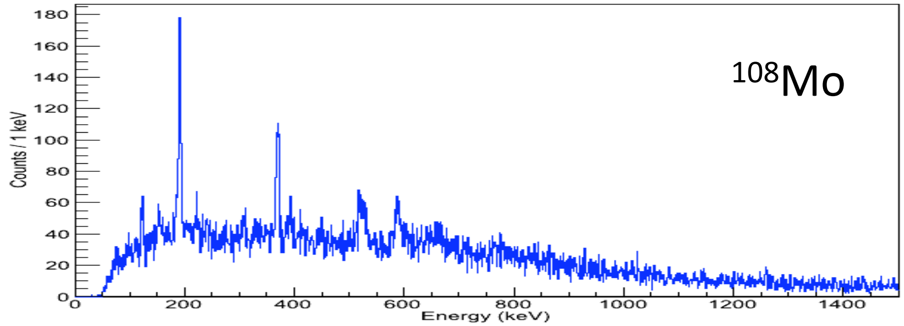
*L. Grente (Irfu/SPhN)* ➔ *Poster*





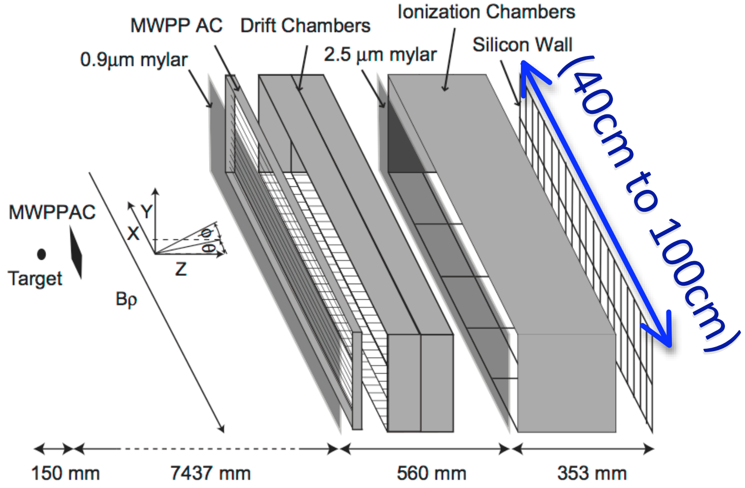


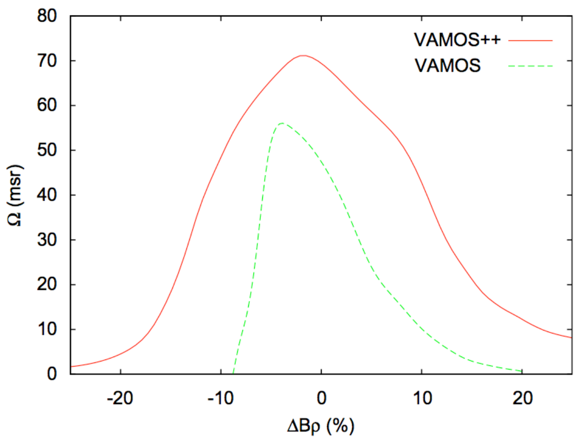




# Vamos++ : new focal plane

*M. Rejmund & al., NIMA 646 (2011) 184*

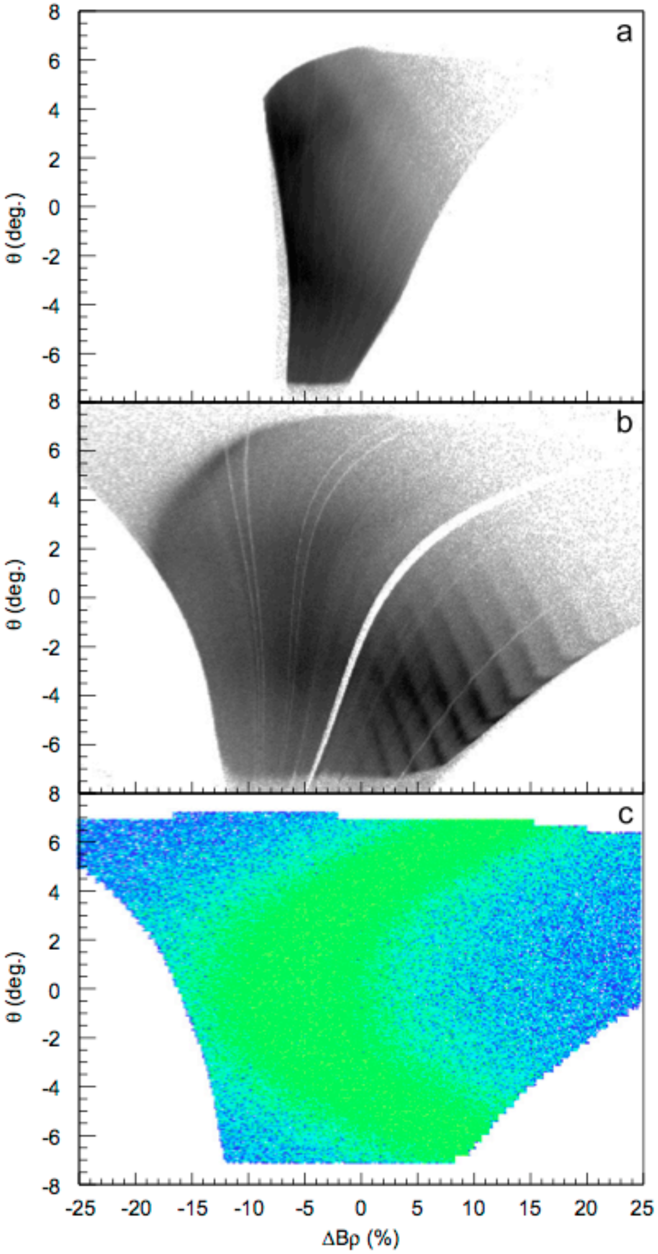




Focal plane detection is critical ➔ J. Uusitalo

*VAMOS in gas-filled mode ➔ Ch. Theisen*

$^{129}$Xe (967MeV)+$^{197}$Au(170μg/cm$^2$)



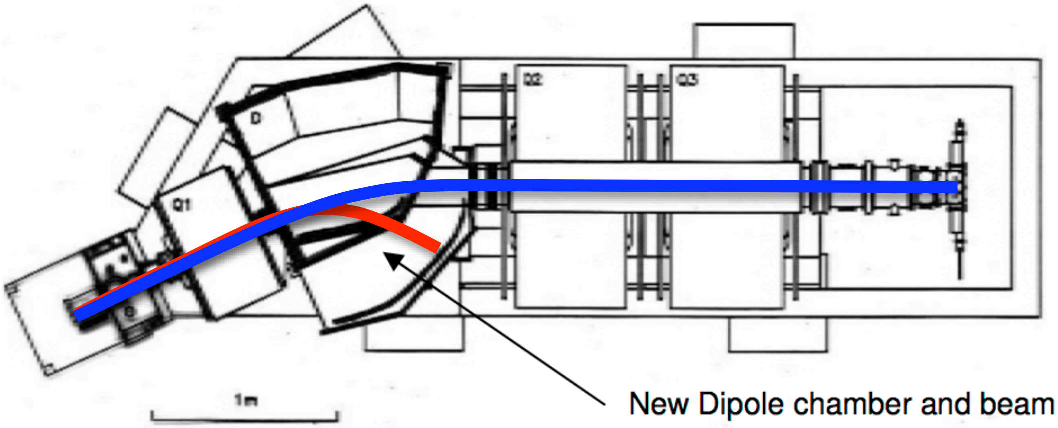
Old
Detection
400x110mm$^2$

New
Detection
1000x150mm$^2$

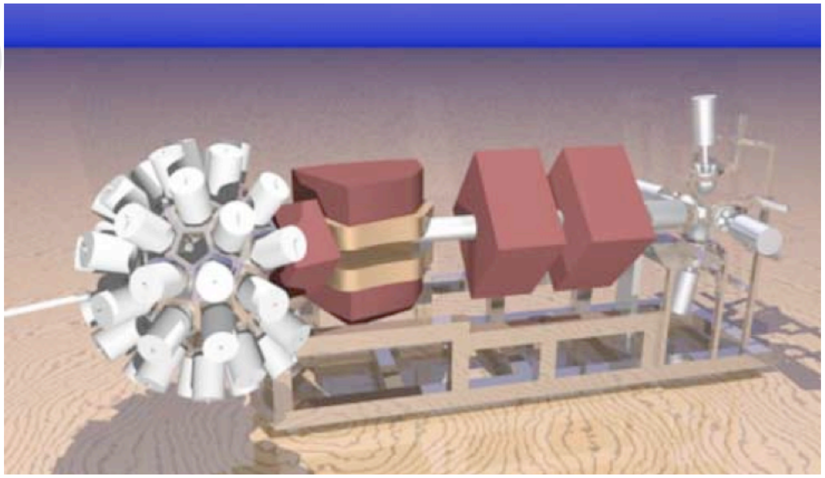
Simulation
(isotropic
distribution)

# RITU Gas filled separator (Jyväskylä Univ.)

*(from P. Greenlees)*

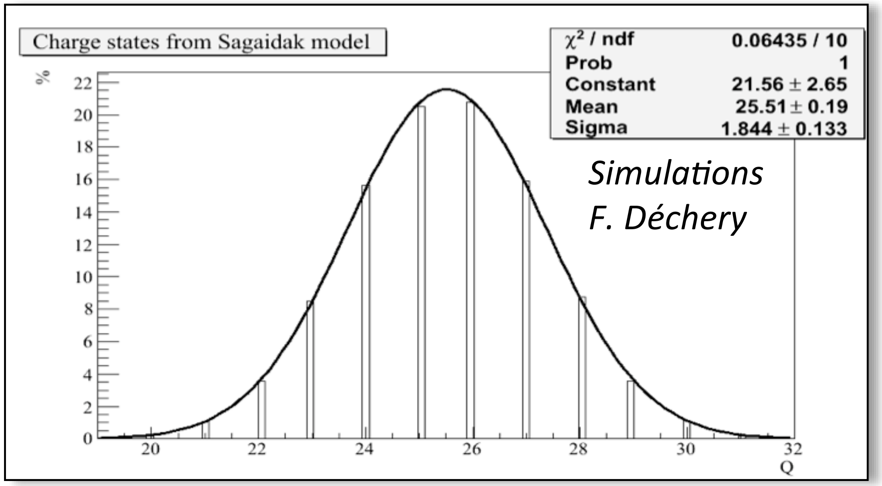


New Dipole chamber and beam stopper



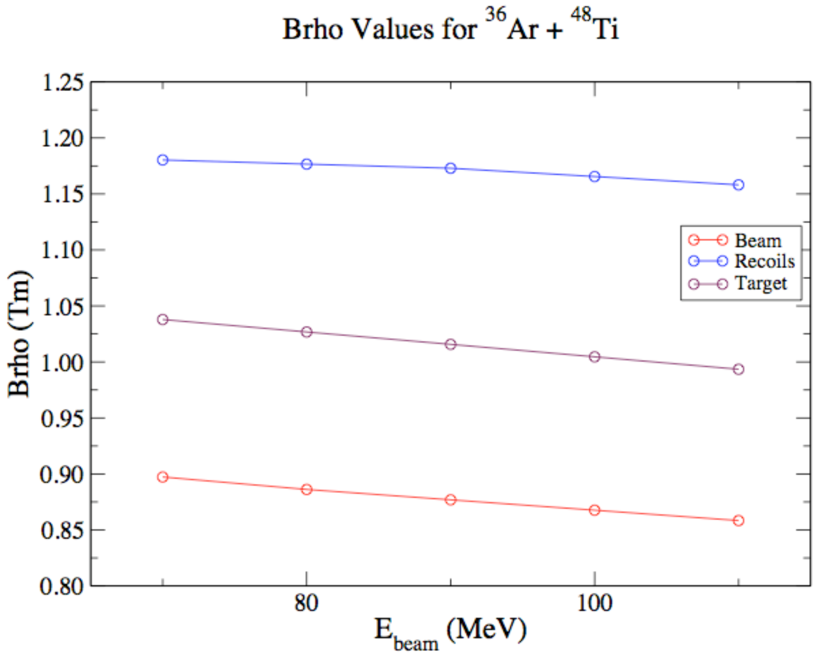
Exchange of electrons with the gaz ➔ “average” trajectories of the ions ➔ no Q dependance

$$B\rho = mv/Q_{ave} = mv/[(ev/v_0)Z^{1/3}]$$
$$= 0.0227\ A/Z^{1/3}\ \text{Tm}$$

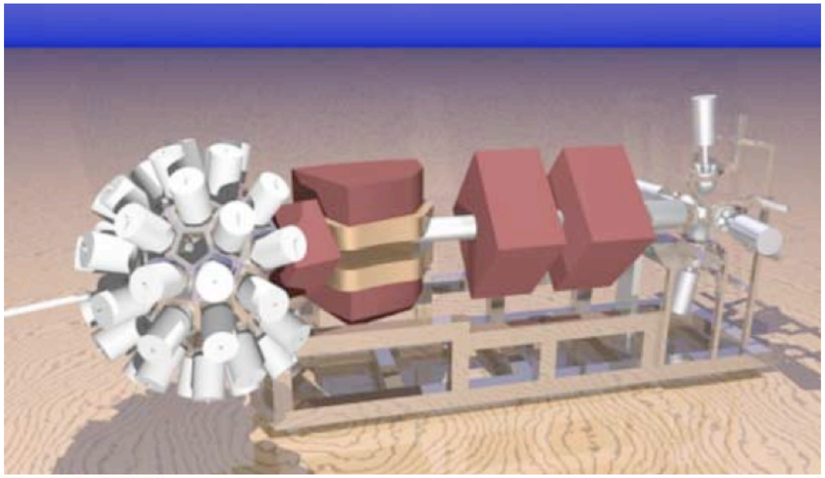


*Simulations*
*F. Déchery*

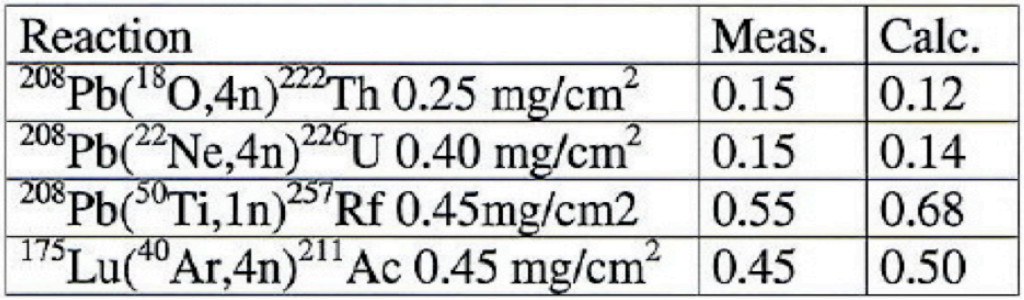
$^{100}$Sn@1MeV/u : Equilibrated Q distribution in the vacuum



# RITU: Performances



Gas: Helium @ 1bar with differential pumping
Length : 4.8m ➔ Must be short
Angular acceptance: ±80 mrad (V); ±30 mrad (H)
Solid angle: 10msr ➔ Very good



| Reaction | Meas. | Calc. |
|---|---|---|
| $^{208}Pb(^{18}O,4n)^{222}Th$ 0.25 mg/cm$^2$ | 0.15 | 0.12 |
| $^{208}Pb(^{22}Ne,4n)^{226}U$ 0.40 mg/cm$^2$ | 0.15 | 0.14 |
| $^{208}Pb(^{50}Ti,1n)^{257}Rf$ 0.45mg/cm2 | 0.55 | 0.68 |
| $^{175}Lu(^{40}Ar,4n)^{211}Ac$ 0.45 mg/cm$^2$ | 0.45 | 0.50 |

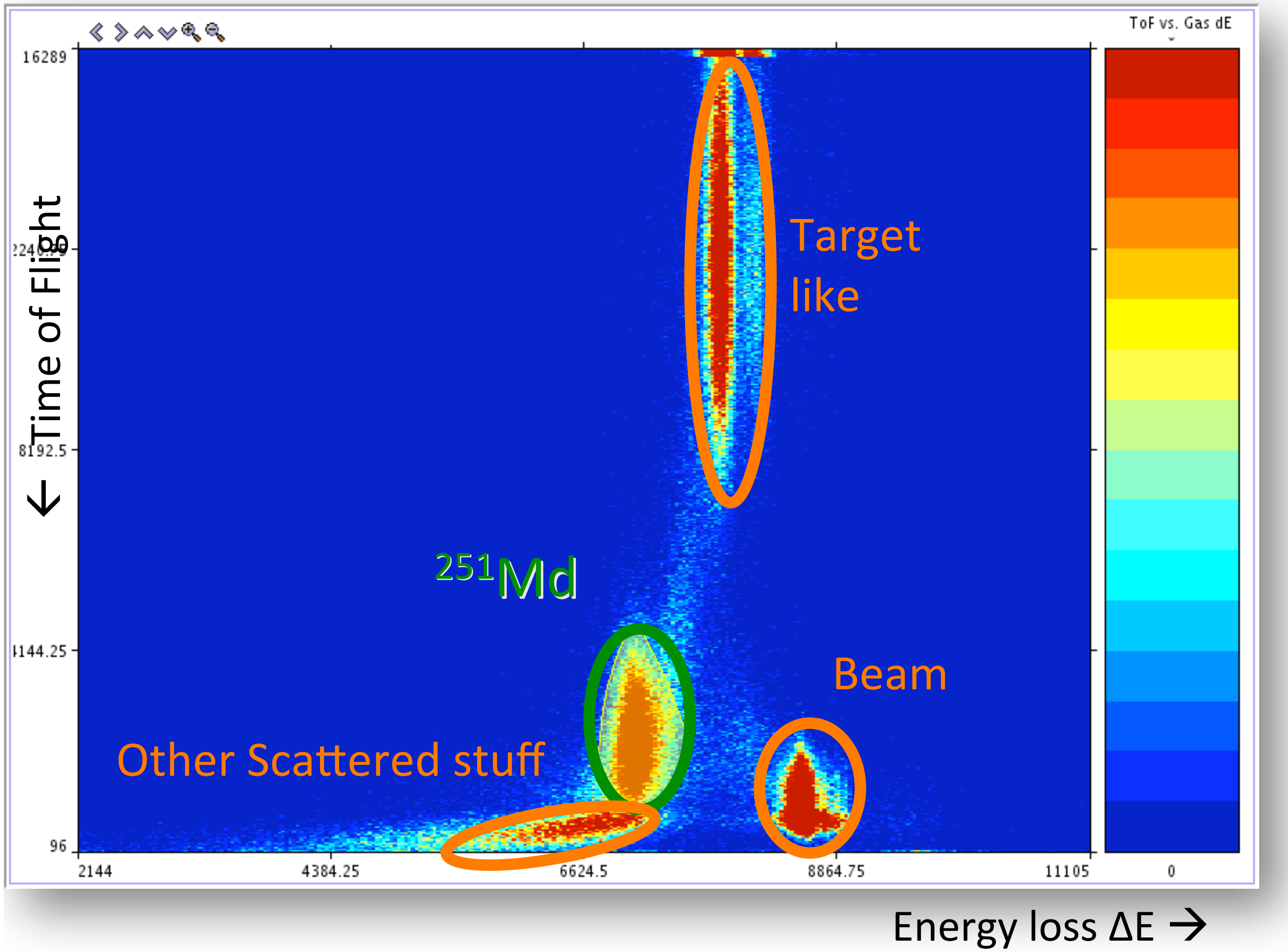
Mass resolution: 50 ➔ poor due to straggling in gas
- no selection of adjacent mass channels
- discrimination by the focal plane detection ➔ *e. g. Beta-tagging, P. Ruotsalainen*

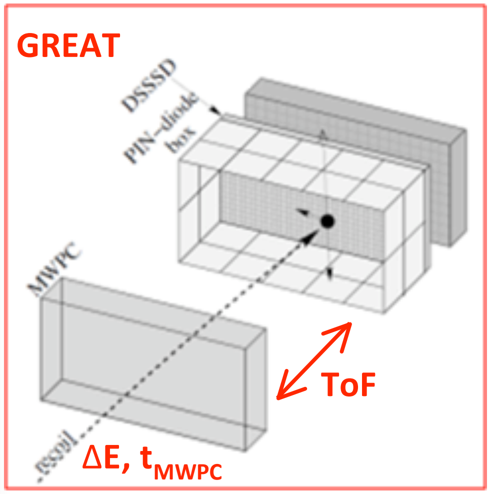
Magnetic rigidity: 2.2 Tm

## *Rejection*

~$10^{13}$ for reactions like $^{35}Cl$ + $^{181}Ta$
~ $5.10^{11}$ for reactions with $^{56}Fe$ beam

# RITU: Practical case $^{48}$Ca + $^{205}$Tl → $^{251}$Md + 2n



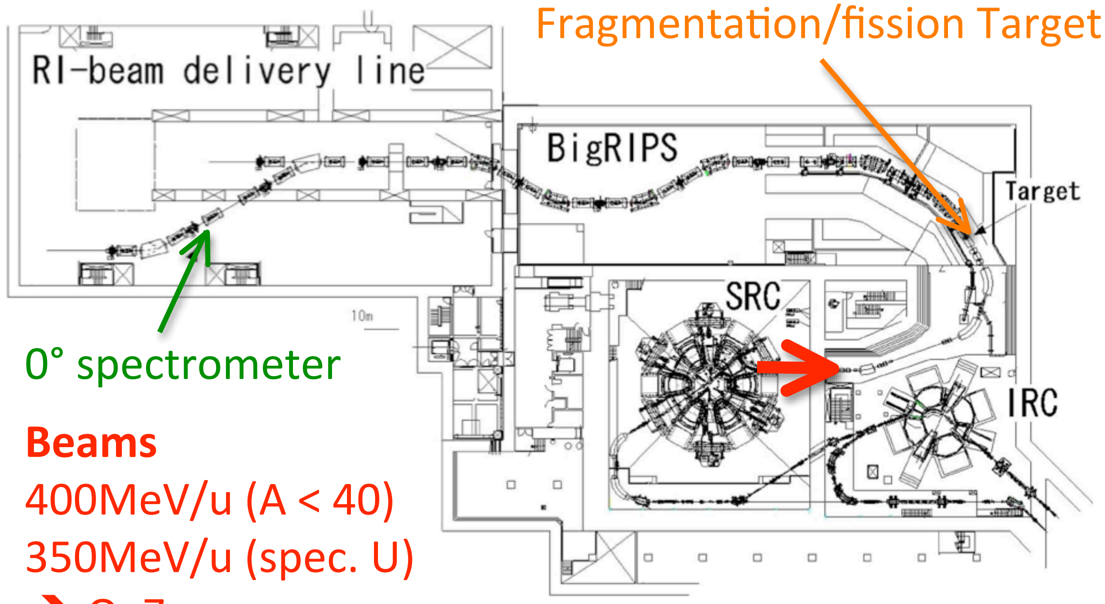


Tagging of $^{251}$Md allows the γ/e$^-$ spectroscopy around target ➔ *spectra from F. Déchery*

Importance of focal plane detection ➔ *J. Uusitalo*

# High energy fragment separator : BigRIPS at RIBF (Japan)

*T. Kubo IEEE Trans. on App. Superc. 17 (2007) 1069*



Fragmentation/fission Target

0° spectrometer

**Beams**

400MeV/u (A < 40)

350MeV/u (spec. U)

➔ Q=Z

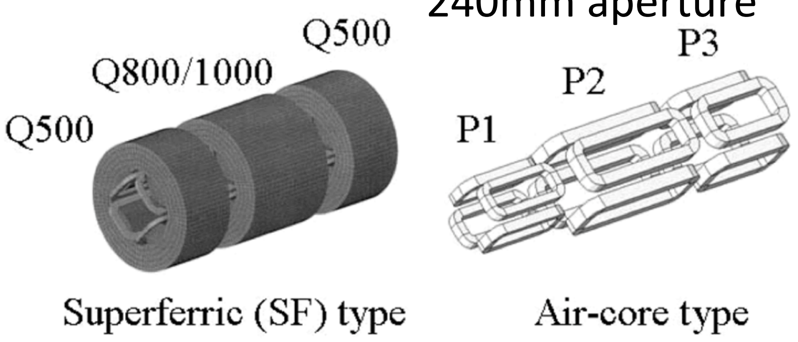
Angular acceptance: 10msr

Momentum acceptance : ±3%

$B\rho_{max}$ = 7 Tm

Length = 77m

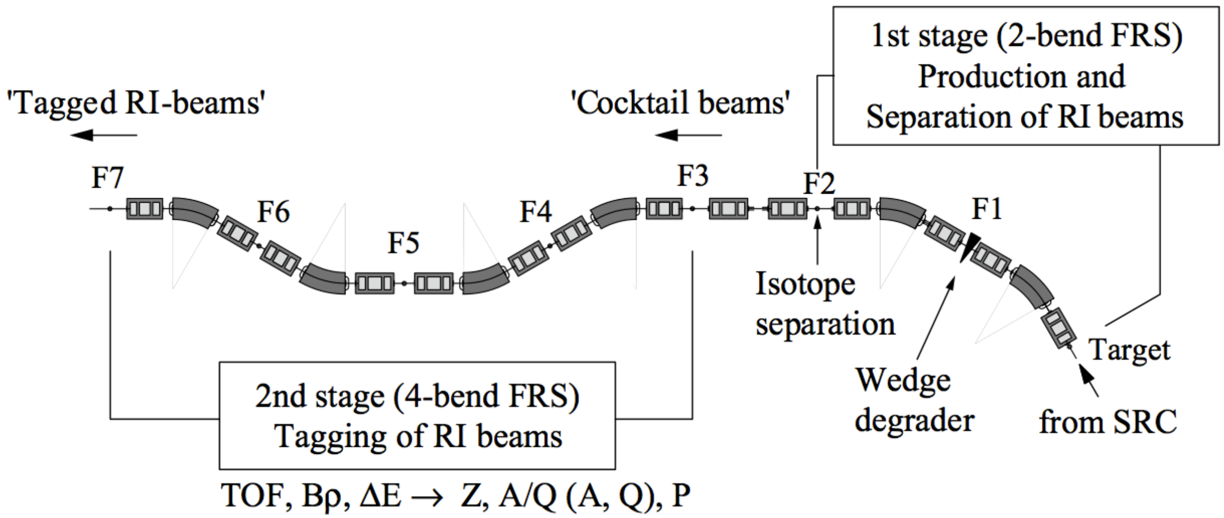
240mm aperture



Superferric (SF) type

Air-core type

BigRIPS : Tandem (Two-stage) Separator



TOF, Bρ, ΔE → Z, A/Q (A, Q), P

High beam power : 90kW

➔High radioactivity

+ high neutron fluxes

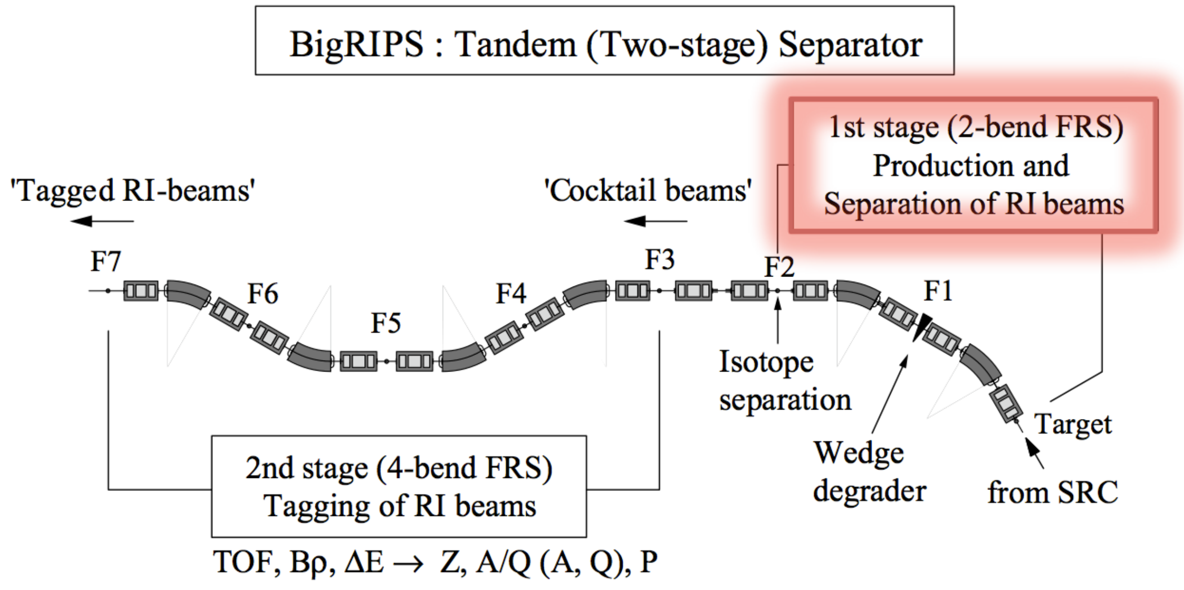
➔7000t of shielding

around the beam dump

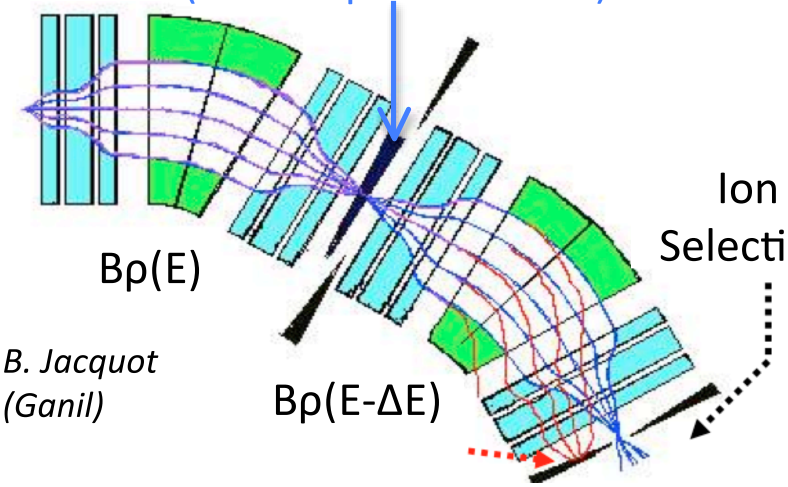
➔ Air core SC magnets

(with limited lifetime)

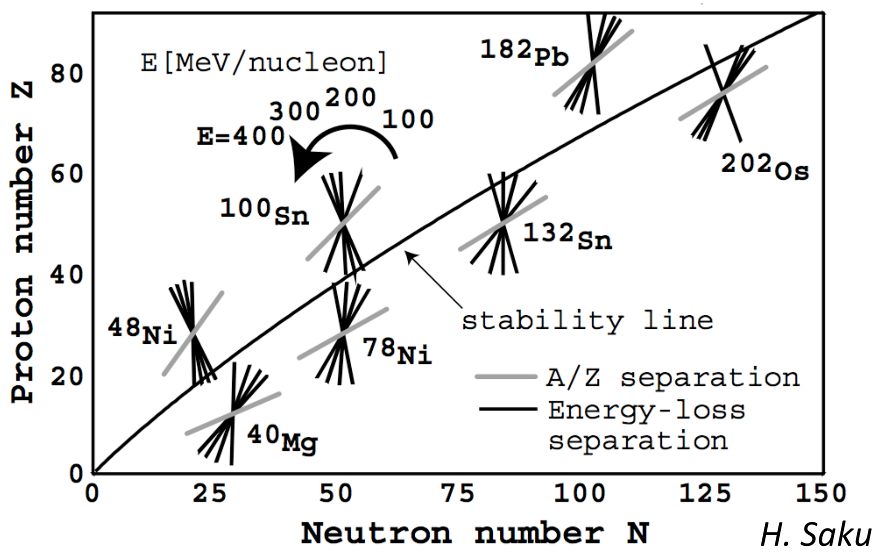
# BigRIPS 1st stage : production & separation



Wedge shape degrader
(ΔE independent of E)

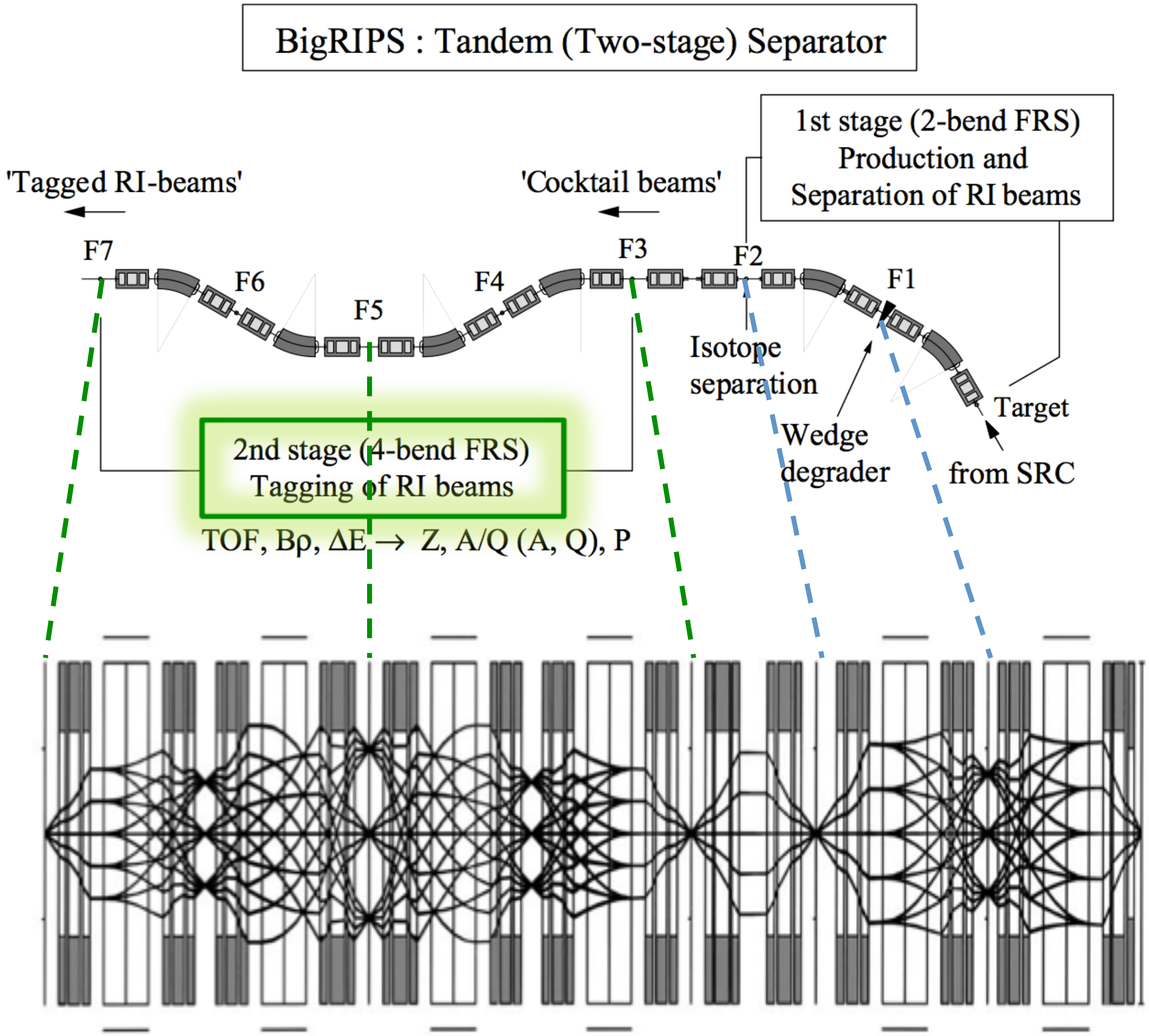


*B. Jacquot*
*(Ganil)*



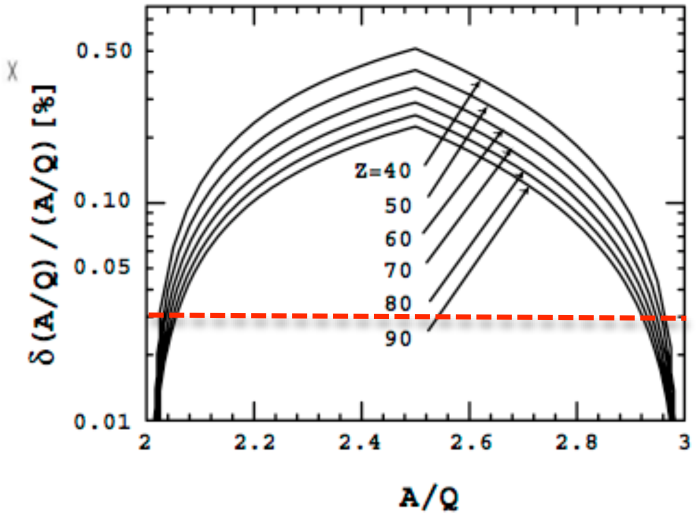
*H. Sakurai*
*(U. of Tokyo)*

# BigRIPS 2nd stage : Event by event tagging of the "cocktail beam"



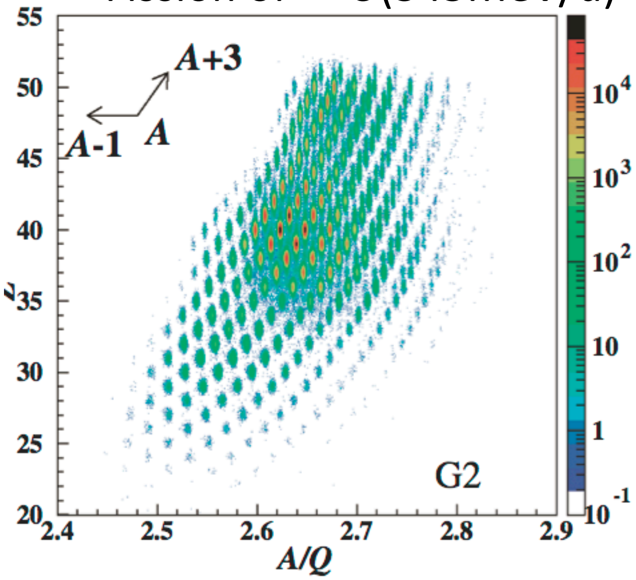
Detectors :
PPAC F5 ➔ x,y, ToF ➔ Bρ
Fast scintillators F3,F7 ➔ ΔE,ToF

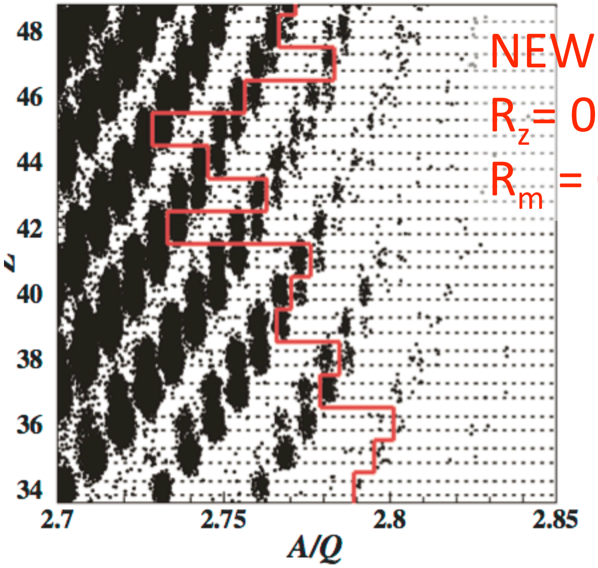
Counting rate ≈ $10^6$pps
Required resolution



# BigRIPS : Practical cases

Fission of $^{235}$U(345MeV/u)



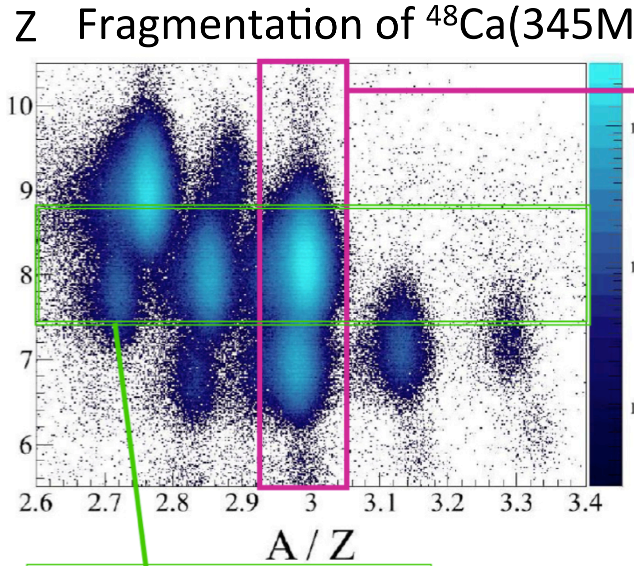


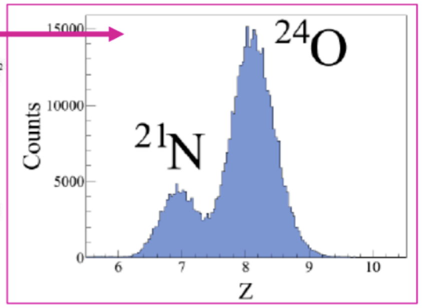
NEW nuclei !

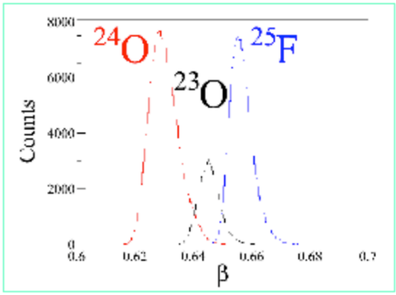
$R_z$ = 0.57%

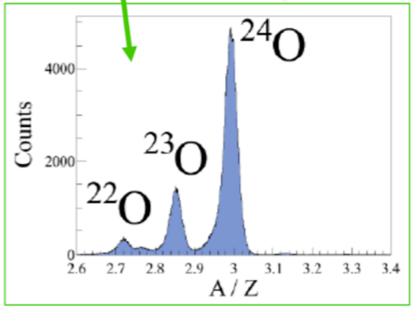
$R_m$ = 0.035%

Fragmentation of $^{48}$Ca(345MeV/u) → $^{24}$O *(V. Lapoux)*









(PPAC normalization) rate (%)of HI
$^{24}$O 35% ; $^{23}$O 9.7%
$^{25}$F 23% ; $^{21}$N 9.6 %
$^{24}$O rate/TOTAL (including tritons) 4%

Very good identification of heavy ions

Tagging does not eliminate the contaminants

Some are difficult to suppress → counting rate limits

*T. Onishi & al., J. the Phys Soc of Japan 79 (2010) 073201*

# Perspectives

## Other related aspects

-Solenoids

-Very low energy spectrometers

-Ions traps

-…

## New challenges: high intensity beams (stable or radioactive)

-Very high power: rotating targets, liquid targets, beam dump

-Induced radioactivity: biological shielding, durability of equipment

-Noise on detection: shielding, neutron fluxes, damage on detectors

## Coupling with detection

-The spectrometer reduces the amount of unwanted events

➔ The detection has to cope with the rest !

-It must be designed with its detection

**Thank you for your attention**