Electromagnetic Spectrometers & Separators

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Ecole Joliot Curie 2015
Spectrometers & separators
Properties in nuclear physics

1) Why a spectrometer? Part 1

2) Designing a spectrometer
(1st approach)

3) Beam optics (Basics)
4) Spectrometer’s properties

Part 2
5) Fragments separators
(100MeV/A-500 MeV/A)

6) Recoil Spectrometers
(1-10 MeV/A)

7) Tuning And Diagnostics

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An experiment in nuclear physics

ACCELERATED ION

Thick Target

Detectors gammas, neutrons

Measuring \( \sigma \), \( \gamma \) spectroscopy,..

\[
A^Q_X Z + \text{Target} \rightarrow n + A^{-1} X Z^* \rightarrow \gamma + A^{-1} X Z
\]

Reaction of interest, but

Many reaction channels

\[
A^Q_X Z + \text{Target} \rightarrow 2n + A^{-2} X Z^*
\]
\[
A^Q_X Z + \text{Target} \rightarrow 3n + 1p + A^{-3} X Z_{-1}
\]

Reaction products not identified, ion energy not measured
An other experiment in nuclear physics

- **Primary beam very intense**
- **Thin target**
- **Dipole Magnet**
- **Detector Si**

**Eletromagnetic spectrometer**

- Eliminate primary beam ($\sim 10^{11-13}$ particles per second)
- Help to identify the reaction products
- Measure **Energy** with very good resolution
- Select very rare events (selectivity)
Is a magnetic spectrometer really needed?

? Complex question: YES and NO
What observables do you need?
  with what resolution?
    (ion energy, angle, A, Z, photon, neutrons)
  with which detectors (position, energy)

Do you need to eliminate the Primary beam from your detectors?
  primary beam separation

Without a magnetic spectrometer: limitation? (selectivity)
With a magnetic spectrometer: limitation? (efficiency)

Other possible limitations (primary beam intensity, ion identification, detector resolution)
Let’s design a simple **Magnetic** spectrometer

1) dispersion of the particles as function of $M,v,...$

**MAGNETIC DIPOLE**: $B_y=\text{Constant}$

**Coils**: (a current $i$ induces and magnetic induction in the pole)

**Yoke**: (guide the field lines to the pole)

2 flat poles: $B_y=\text{Constant}$

Positions $X_f$ ?

$X_f= F(\text{Mass of ions},...)$
Equations for an ion in a magnetic field:

\[ \vec{F} = q (\vec{v} \times \vec{B}) \]

\[ \frac{d}{dt}[\gamma mv] = \vec{F} \]

\[ \frac{dv}{dt} = \frac{v^2}{R} \]

Relativistic factor:

\[ \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]

If \( B=\text{const} \), for an ion \((m, q, v)\)

The Trajectory is a circle with a radius \(R\)

We define the magnetic rigidity \( B\rho = [\text{Tesla.m}] \)

\[ B\rho = \frac{mv}{q} \]

How to tune the dipole field \( B= [\text{Tesla}] \)?

\[ B = \frac{B\rho_{\text{ref}} [T.m]}{R [m]} \]
2 problems with 1 dipole magnet:
Acceptance & identification

Consider a secondary beam

Beam losses

-1: Many particles are lost in the magnet (**very bad**)
-2: Trajectories are complex (**bad**)

\[ \text{Xfinal} = f( B_\rho, \theta_i, \phi_i, X0,Y0) \]

- Final position \( x_f \) depend on the
  - \( B_\rho \) (**good for identification or separation**)
  - position & Angle after the reaction (**bad**)
Beam divergence after target 2 problems solved with focusing lenses

Imagine that focusing lenses exist like in light optics

With Focusing lenses $X_f = F(B_\rho, \theta_i, \phi_i, x_0, y_0)$

Less unknowns! Less beam losses!!

At one location $s$ (the detector location, called focal plan)
The trajectories are independent of the angles $\theta_i, \phi_i$
And the initial position is $x_0=0, y_0=0$

$X_f = F(B_\rho, \theta_i, \phi_i, x_0, y_0)$
How to construct a **Focusing lens for ions**:

**Magnet with 4 poles** (+,−,+−)

\[ F = q (v \times B) \]

4 coils

+4 hyperbolic poles

\[ B_y = G \cdot x \]

\( G = \frac{dB_y}{dx} \)

The quadrupole magnet is focusing in HORIZONTAL PLAN

*Nota: In the center, the force is zero*
A quadrupole magnet
Focusing lens in horizontal
But defocusing in vertical

The beam becomes narrow in X and large in Y

$B_x = G \cdot Y$
$B_y = G \cdot X$
$B_s = 0$

Focusing in X (G > 0)
Defocusing in Y (G > 0)

Since the Force is defocusing in vertical
How to construct a Focusing lens System
In horizontal AND vertical plan

Add 2 quadrupoles magnets :

If you tune \(i_1\) and \(i_2\) with opposite polarities, the beam can be focused in \(X\) and \(Y\)
Beam optics (basics)

- Focalisation with quadrupoles
- Dispersion with dipole
- Magnetic rigidity: $B\rho = \gamma \frac{Mv}{Q} = \frac{P}{Q}$

- Particles coordinates
- Equations in field $B$ & $E$
- 1rst order approximation: Optical Matrices
  - Resolution
  - Angular Acceptance
  - $B\rho$ Acceptance

DONE
DONE
DONE

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At a given $S$, a particle is described with **6 coordinates**:

- 2 positions $(X-X_0), (Y-Y_0)$
- 2 angles $\theta, \phi$
- Rigidity $B_\rho = B_\rho_0 (1+\delta)$
- $(t-t_0)$ time advance

**Optical convention:**

Angle in Horizontal plan noted as $X' = \frac{dx}{ds} = \tan \theta$

Angle in Vertical plan $Y' = \frac{dy}{ds} = \tan \phi$

Time coordinate expressed in meter $L = v_0 (t - t_o)$
Beam optics notation

The reference particle: \( B_{\rho_0} = P_0/Q_0 = B_{\text{dipole}} \times R_{\text{dipole}} \)

It is traveling in the Center of the beam lines
So \( X_0 = 0, \ Y_0 = 0 \)
« angles »: \( X'_0 = 0, \ Y'_0 = 0 \)

At the location \( s_0 \), a particle is represented by a vector \( Z(s_0) \)

\[
Z = (x, x', y, y', l, \delta)
\]

\( \text{6Dim} \)
Trajectory equations for 1 particle

How to compute \( x(s), y(s) \) ?

We use a curvilinear Reference Frame which follow the reference particle:

\[
\frac{d}{dt} \left[ m \gamma \mathbf{v} \right] = q \cdot \left( \mathbf{E} + \mathbf{v} \times \mathbf{B} \right)
\]

Coordinate change \( t \quad \rightarrow \quad s \)

\( x(t), y(t) \Rightarrow x(s), y(s) \)

We want to compute \( x, y \) at a detector location \( s = s_0 \).
Trajectories: exact equations

\[
\frac{d}{ds} \left( m\gamma \dot{x} \right) = m\gamma s \left( 1 + \frac{x}{\rho} \right) + q(t' E_x + y' B_s) - s(1 + \frac{x}{\rho}) \cdot B_y
\]

\[
\frac{d}{ds} \left( m\gamma \dot{y} \right) = q(t' E_y + (1 + \frac{x}{\rho}) \cdot B_x - x'B_s)
\]

\[
\frac{d}{ds} \left( m\gamma s \left( 1 + \frac{x}{\rho} \right) \right) = -\frac{m\gamma x}{\rho} + q(t' E_s + x'B_y - y'B_x)
\]

Trajectory simulation (x(s), y(s))

1) knowing B(x,y,s) AND E(x,y,s,t) [field map 3D]

2) Integrate the equations for **ALL the particles**
   (computer + Numerical method: Runge-kutta)

Generally we can do **simpler**

Matrix approach (1rst order approximation)
Beam optics with Matrices

\[ Z_1 = (x, x', y, y', l, \delta) \]

\[ Z_2 = f_{1 \rightarrow 2} (Z_1, B, E, l \ldots) \]

\[ = R_{1 \rightarrow 2} \cdot Z_1 + 0(Z_1^2) + \ldots \]

\[ \approx R_{1 \rightarrow 2} \cdot Z_1 \]

Exact Dynamic (non linear)

Taylor expansion

(X and Y Are small..)

Linear dynamics

\[
\begin{bmatrix}
    x \\
    x' \\
    y \\
    y' \\
    l \\
    \delta
\end{bmatrix}
= 
\begin{bmatrix}
    R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\
    R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\
    R_{31} & R_{32} & R_{33} & R_{34} & R_{35} & R_{36} \\
    R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\
    R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\
    R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66}
\end{bmatrix}
\begin{bmatrix}
    x \\
    x' \\
    y \\
    y' \\
    l \\
    \delta
\end{bmatrix}
\]

\[ l = v_0 (t - t_0) \]

\[ \delta = \frac{B \rho - B \rho_0}{B \rho_0} \]
The transport Matrix $R$ allows the computation of a coordinate of a particle at the end of a spectrometer.

$Z_{in} = (x, x', y, y', l, \delta)_0$ at the entrance

$Z_{out} = (x, x', y, y', l, \delta)_1$ at the exit

$Z_{out} = R.Z_{in}$

Interpretation of $R$

$R_{ij} = \left(\frac{\partial Z_{out}}{\partial Z_{in}}\right)_{j \in i}$

Example:

$R_{11} = \left(\frac{\partial Z_1}{\partial Z_1}\right) = \left(\frac{\partial x \text{ out}}{\partial x \text{ in}}\right)$

$R_{12} = \left(\frac{\partial Z_1}{\partial Z_2}\right) = \left(\frac{\partial x \text{ out}}{\partial x' \text{ in}}\right)$

$R_{16} = \left(\frac{\partial Z_1}{\partial \delta}\right) = \left(\frac{\partial x \text{ out}}{\partial \delta \text{ in}}\right)$

The transport Matrix $R = R_{ij}$ is related to

- spectrometer geometry
- tuning of the quadrupoles
SPECTROMETER TRANSPORT MATRIX $R$

allow the simulation of 1 trajectory (easily)

$$\frac{d}{dt} \gamma = \gamma \left[ \frac{1}{p} + q(\gamma E + y' B_z - \bar{y}(1 + \frac{1}{p}) B_z) \right]$$

$$\frac{d}{dt} \gamma' = q(\gamma E_y + (1 + \frac{1}{p}) B_y - x' B_y)$$

$$\frac{d}{dt} \gamma(1 + \frac{x}{p}) = -\frac{\gamma x}{p} + q(\gamma E_x + x' B_y - y' B_y)$$

Typical spectrometer Matrix is simple

$$X_{\text{Final}} = R_{11} X_{\text{target}} + R_{16} \delta$$

$$\approx R_{16} \delta$$

$$\delta = \frac{(B \rho - B \rho_0)}{B \rho_0}$$

$B \rho_0 = B_{\text{dipole}} \cdot R_{\text{dipole}}$
More on Transport Matrices: how to compute the Rmatrix for a spectrometer?

The total transport matrix $R$ is the product of the matrices representing each element (drift, quad, dipole).

**Quad matrix**

$$
R_{M1} = \begin{bmatrix}
\cos k_x L & \sin k_x L & 0 & 0 & 0 & M_{16} \\
-k_x \sin k_x L & \cos k_x L & 0 & 0 & 0 & M_{26} \\
0 & 0 & \cos k_y L & \frac{\sin k_y L}{k_y} & 0 & 0 \\
0 & 0 & -k_y \sin k_y L & \cos k_y L & 0 & 0 \\
M_{26} & M_{16} & 0 & 0 & 1 & M_{56} \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
$$

**Free space:**

- **Drift Matrix**

  $$
  R_{df} = \begin{bmatrix}
  1 & L1 & 0 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 & 0 & 0 \\
  0 & 0 & 1 & L1 & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 & 0 \\
  0 & 0 & 0 & 0 & 1 & L1/\gamma^2 \\
  0 & 0 & 0 & 0 & 0 & 1
  \end{bmatrix}
  $$

- **Quad matrix**

  $$
  k_x = GL/\rho_0
  $$

**Matrix product**

$$
R = R_{df} \cdot R_{M1} \cdot R_{d3} \cdot R_{Q2} \cdot R_{d2} \cdot R_{Q1} \cdot R_{\text{drift1}}
$$
The beam size: important for the design

- A particle has 1 trajectory: \( Z = Z(s) \)

We are not interested by only 1 trajectory/particle

A beam is an ellipsoid in 6D with a given size

The beam size (width) has to be simulated to avoid beam losses

\( \sigma_x \) (horizontal width), \( \sigma_y \) (vertical width)

\[
\sigma_x^2 = \frac{1}{N} \sum_{\alpha=1}^{N} x_\alpha^2
\]
Focusing a beam in a simulation get a small size at some point S

Beam envelop:

With 1 quad  \hspace{1cm} \text{with 2 quads}

\begin{itemize}
  \item \text{Vertical plane}
  \item \text{Horizontal plane}
\end{itemize}

\begin{align*}
  \text{Beam pipe limitations} \\
  \text{Beam losses}
\end{align*}

Adjust

Quad gradient

\[ G_q = \frac{\mathrm{dB_y}}{\mathrm{dx}} \]

Focusing in \( X \) and \( Y \): at least 2 quads required
Angular distribution \( (x') \) in a beam line?

The beam ellipse is rotating in \( (x, x' = dx/ds) \)

...The **Area of the beam ellipse** \((x, x')\) **is a constant** in a beam line... but, **Area is not constant** in a target
Resolution of a separator

Particles are separated if $R_{16} \delta > 4 \sigma_x$

Resolution = $4 \sigma_x / R_{16}$

= Minimal difference in $B\rho$

for the identification or for separation

$R_{16} = \left( \frac{\partial Z_1}{\partial Z_6} \right) = \left( \frac{\partial x}{\partial \delta} \right)_{\text{out}} \left( \frac{\partial x}{\partial \delta} \right)_{\text{in}}$

R=1/100 Resolution means: capacity for a spectrometer to distinguish two beams with 1% $B\rho$ difference
The resolution (separation) is optimal at the focus point (size is minimal)

The 2 beams with ≠rigidities

\[ B_{\rho_{\text{ref}}} = B_{\rho_0} = B \times R_{\text{dipole}} \]
\[ B_{\rho} = B_{\rho_0}(1-\delta) \]

The 2 beams are separated «at the focal plan» But not everywhere!!

Resolution (\( R = \sigma_x/R_{16} \)) is optimal

When \( \sigma_x \) is small

and \( R_{16} \) (dispersion) is large
Angular acceptance

The **reaction products** exit from the target with an Angular dispersion.

Vacuum chamber limitation induces **beam losses** = less transmission.

The acceptance is measured in steradian.

\[
 d\Omega (\text{strd}) = \frac{dS}{r^2}
\]

**Example**: If particles inside \( \pm 50\text{mrd} \) (Horizontal & vertical) are transmitted.

Acceptance is \( d\Omega \approx 0.01\text{strd} = 10\text{ mstrd} \) at \( r=1\text{m} \)

\[
 dS \# 0.1\text{m} \times 0.1\text{m} = 0.01 \text{ m}^2
\]
The particles are dispersed by dipole magnets with 
\[ \delta = \frac{[B_\rho - B_\rho^0]}{B_\rho^0} \]

\[ X_{\text{final}} = R_{16} \delta \]

Beam pipe limit: \( X_{\text{max}} \)

\[
\begin{pmatrix}
R_{11} & 0 & 0 & 0 & 0 & R_{16} \\
R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\
0 & 0 & R_{33} & 0 & 0 & 0 \\
0 & 0 & R_{43} & R_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & L/\gamma^2 \\
0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}
\]

\[ B_\rho \text{ Acceptance} = \pm \frac{X_{\text{max}}}{R_{16}} \]

Example: If \( R_{16}=5 \text{ cm/\%} \) and \( X_{\text{max}}=10 \text{ cm} \)

\[ B_\rho \text{ Acceptance} = \pm 2 \% \]
How to simulate an experiment with a spectrometer

LISE++ code*
Tarasov et Al.
To be Downloaded
Exercise 1: Imagine a spectrometer with a dispersion $R_{16} = 2 \text{ m} (=2\text{cm}/\%)$ and beam width $\sigma_x = 0.5 \text{ mm}$ on the focal plan detector.

What is the resolution $R$ in $B_\rho$?

Exercise 2:

A spectrometer ($R_{16} = 1.5 \text{ cm}/\%$) is tuned for $B_\rho 0 = 2.0 \text{ T.m}$

A particle arrives on the focal plane at $X_f = 3\text{cm}$,

What is the particle rigidity?

Exercise 3:

How to measure the dispersion ($R_{16}$) in a spectrometer?
Part 1:

- The need of focalisation (quad)
- Magnetic rigidity define the trajectory
- Dynamics can be approximated with a matrix \( R \)

\[ B\rho \overset{\text{def}}{=} \gamma \frac{mv}{q} \]

End part n°1

Part 2: technical details and examples

- Resume of part 1
- Fragment separators (E>100 MeV/A)
- Recoil Spectrometers (E<10 MeV/A)
- Diagnostics and tuning
Part n°1 : Spectrometer components

Magnetic Dipole : 2 poles : $B_y = B_0$

Magnetic quadrupole : 4 poles

$B_y = G \times$

focusing is good for **Angular acceptance** and **Resolution**
Beam optics coordinates

- At the location $S$, a particle is represented by a vector $Z(s) = (x, x', y, y', l, \delta)$

\[
\begin{pmatrix}
x \\
x' = \frac{dx}{ds} \\
y \\
y' = \frac{dx}{ds} \\
l = v_0(T - T_0) \\
\delta = \frac{B\rho - B\rho_0}{B\rho_0}
\end{pmatrix} =
\begin{pmatrix}
horizontal displacement \\
horizontal "angle" \\
vertical displacement \\
vertical angle \\
longitudinal difference \\
"momentum(B\rho)" deviation
\end{pmatrix}
\]

**HORIZONTAL ANGLE**

$X' = \frac{dX}{ds} = \tan(\theta) \approx \theta$
Magnetic Spectrometer: A tool for identification

Suppose 2 ions beams

-Field measurement \( B \)

\[ B_{\rho o} = B_{\text{dipole}} \times R_{\text{dipole}} \]

-Position measurement \( (X_f = X_1) \)

\[ \delta = \frac{(B_{\rho 1} - B_{\rho o})}{B_{\rho o}} \times \frac{X_1}{R_{16}} \quad B_{\rho 1} = B_{\rho o} \times \left( 1 + \frac{X_1}{R_{16}} \right) \]

If same velocity \( v \)

\[ M_1/Q_1 \approx M_o/Q_o \left( 1 + \frac{X_1}{R_{16}} \right) \]
The $R$ matrix of spectrometer

: first order theory

A spectrometer

A) starts with a focus (on target)

B) End up with a focus ($R_{12} = R_{34} = 0$)

C) The spectrometer is chromatic ($R_{16} \neq 0$)

typical matrix (8 coefficients)

$$
\begin{bmatrix}
  x \\
  x' \\
  y \\
  y' \\
  l \\
  \delta
\end{bmatrix} =
\begin{bmatrix}
  R_{11} & 0 & 0 & 0 & 0 & R_{16} \\
  R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\
  0 & 0 & R_{33} & 0 & 0 & 0 \\
  0 & 0 & R_{43} & R_{44} & 0 & 0 \\
  - & - & 0 & 0 & 1 & L/\gamma^2 \\
  0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x \\
  x' \\
  y \\
  y' \\
  l \\
  \delta
\end{bmatrix}
$$

\[ l = v_0 (t - t_0) \]

\[ \delta = \frac{B \rho - B \rho_0}{B \rho_0} \]

$R_{16}$ is called dispersion

$R_{11}$ is called MAGNIFICATION

$R_{11} = \Delta X_F / \Delta X_{Target}$

Coordinates

At focal (detectors)

Coordinates on target

\[ x^F \approx \sum_{i=1...6} R_{ij} Z_i^0 = R_{11} x_0 + R_{12} x'_0 + R_{13} y_0 + R_{14} y'_0 + R_{15} l^0 + R_{16} \delta^0 \]
Fragment Separators: 100-500 MeV/A

Reaction: in-flight fragmentation (0° degree)

Goal:
1) Primary beam suppression (Separator)
2) Identification of particles
3) purification (selection of some reaction products)
Fragment separator

2 symmetric sections:
« ACHROMATIC » MAGNETIC SPECTROMETER

From the top

section A

section B

Rotative Target
(high intensity primary beam)

Nuclear fragmentation reaction

Total Transport matrix \( R \)

\[ R = R_B \cdot R_A \]
Fragment separator: principle

Ion trajectory

$\text{XA} = \text{F}(B\rho)$

$XB \sim 0$

« Achromatic »

$R_{16}(A) \neq 0$

$R_{16}(B) \neq 0$

$R_{16}(A+B) = 0$ (achromatic)

---

**A:** 1st section

- $B\rho$ selection
- $R_{16}(A) \neq 0$

**B:** 2nd section

- $B\rho$ compensation
- $R_{16}(A+B) = 0$ (achromatic)
2 Trajectories in a Fragments separator

Trajectory N°1: reference
- \( B_\rho = B_\rho 0 \)
- \( \delta = 0 \)
- \( X_A = 0 \) and \( X_B = 0 \)

Trajectory N°2
- \( B_\rho = B_\rho 0 \ (1 + \delta) \)
- \( X_A = R_{16} \delta \) and \( X_B = 0 \)

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Section A:

Focusing 
\[ R_{12} = 0 \] (Horizontal) 
\[ R_{34} = 0 \] (Vertical)

\[
\delta = \frac{B_\rho - B_{\rho_0}}{B_{\rho_0}}
\]

\[ B_{\rho_0} = B_{dipole}, \quad R_{dipole} \]

Dispersion
\[ R_{16} (A) \neq 0 \]
1 Selection in Fragments separators is not sufficient

After the section A
We can select in $B_\rho$
with movable slit

$B_\rho$ Selection
Is not good enough

After the section B
No selection

Primary beam is eliminated, but
Too Many isotopes ($\neq Z$)
produced by fragmentation
are transported up to the end

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Magnetic separator with degrador increase the purification (Z dependance)

We consider 2 isobares \((A=34, Z=14)\), \((A=34, Z=15)\) with same \(B_\rho\)

\[ B_\rho \text{ selection is independant from } Z \]

\[ B_\rho = \frac{\gamma M v}{Q} \]

in a target Energy loss is

« Z dependant »

Bethe-Bloch formula

\[ \Delta E = k \frac{Z^2}{A} * \Delta x \]
2 Selections in Fragments separators $B_\rho + Z$ (degrador)

1) After the section A
   We can select in $B_\rho \sim M/Q \ (v+\Delta v)$

2) After the section B
   Z selection (energy loss separation)

$B_{\rho\text{REF}} = B_{\rho1}$

$B_{\rho\text{REF}} = B_{\rho2}$
Selection in Fragments separators & identification

$\Delta E \sim Z$

Time of Flight $\sim M/Q$

$\Delta E$

Time of Flight

Detector: Thin Silicone

$B_\rho$ selection

$B_\rho +$degrador selection

2 selections Is much better for purity
Often, Isotopes are not well identified (ΔE,TOF)

Isotopes are mixed in TOF
Large velocity distribution Δv

Solution: Measure XA for each ion:

\[ B_\rho = B_\rho 0 \left( 1 + \frac{XA}{R16} \right) \]

The two measurements (TOF,\( B_\rho \)) => give \( M/Q \)

\[ v = \frac{\text{ToF}}{L} \]

\[ \frac{M}{Q} = \frac{B_\rho}{(v \cdot \gamma)} \]
Isotopes are not well identified with \((\Delta E, \text{ToF})\)

Install a Detector position for \(XA\) : \(B_\rho = B_\rho 0 (1+XA/R16)\)

**NOT POSSIBLE**
(too much intensity before Z selection)

Solution choosen in BigRIPS:
Construct an additiv spectrometer to measure \(B_\rho (\epsilon \text{!!})\)

Install the position Detector in the second separator
1 example :BIG RIPS (Riken)

**Specifications**

- \( L = 77 \text{ m} \)
- \( B_{p_{\text{max}}} = 7 \text{ Tm} \)
- \( \Delta p/p = \pm 3\% \)
- \( \Delta \theta = \Delta x' = \pm 50 \text{ mrad} \)
- \( \Delta \varphi = \Delta y' = \pm 60 \text{ mrad} \)

**BigRIPS : Tandem (Two-stage) Separator**

**Fig. 2.** A schematic diagram of the RI-beam tagging in the BigRIPS separator.
BIG RIPS (Riken) quads

**Beam very rigid**: \[ B_\rho = \gamma m v / Q = 7 \, \text{T.m} \] (Beam 300MeV/A)

with **high \( v \)!**

**Super-ferric quadrupole triplet**: Very strong focusing: supraconducting coils (NbTi), with pole (Fe)

- Supra-conducting coils (i very large, B close to saturation)
- Raperture very large = 0.1m ; Bpole-max# 2 Teslas
- GradientMax = 2T/0.1m = 20.T/m

Figure 22: Schematic view of the RIKEN prototype quadrupole triplet (left side) and its installation into the cryostat (right side) [24].

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## Comparaison of the fragment separators

<table>
<thead>
<tr>
<th></th>
<th>Lise3</th>
<th>FRS GSI Mode1 or mode2</th>
<th>A1900 MSU //NSCL</th>
<th>BigRips Riken</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Angular Acceptance</strong></td>
<td>1.6 mstrd</td>
<td>0.32 mstrd or 3.4 mstrd</td>
<td>8 mstrd ±40* ±50 mrad</td>
<td>10 mstrd ±50* ±60 mrad</td>
</tr>
<tr>
<td><strong>$B_p$ Acceptance</strong></td>
<td>±2.5%</td>
<td>±2.0%</td>
<td>±3.0%</td>
<td>±3.0%</td>
</tr>
<tr>
<td><strong>R16 (m=cm/%)</strong></td>
<td>1.7 m 1/600 42 m</td>
<td>6.8 m 1/1600 or 1/160 69 m</td>
<td>5.95 m 1/2900 35 m</td>
<td>3.3 m 1/3300 77 m</td>
</tr>
<tr>
<td><strong>$B_p \text{max}$</strong></td>
<td>4.3 T.m //3.2 T.m</td>
<td>18 T.m or 8.6 T.m</td>
<td>6.3 T.m</td>
<td>9. T.m</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>2 Dipôles + Wien filter</td>
<td>4 dipoles</td>
<td>4 dipoles</td>
<td>1 pre-separator (2 dipoles) + 1 separator (4 dipoles)</td>
</tr>
</tbody>
</table>
« Recoil » spectrometer:
at low energy (1-10MeV/A)

Reactions: fusion-evaporation, transfer, ...

Goals:
1) Very efficient primary beam suppression
2) Help identification

Many experimental problems => A Large variety of devices

B.Jacquot // Ganil
Recoil spectrometer at low energy (1-10MeV/A)

* Velocity filter
  - ship@GSI : 1MeV/A (heavy superheavy)

* « RMS » (Recoil Mass Spectrometer)
  - (fusion evaporation,...)

* Gas filled (Dubna, Darmstadt, Berkeley, Jyvaskyla, Riken)
  - Gas filled (1-5MeV/A)
  - Fusion evaporation
  - super-heavy production

* Large Acceptance & Ray tracing Spectrometer
  - Ganil (VAMOS), Legnaro (Prisma), NSCL (S800)
  - (transfer reactions, fission,..)

....
1st problem at E<15 MeV/A: charge state distributions

Atomic reactions (xray, stripping)

#1 mg/cm²

Q distribution connected to:
- Z target
- Z projectile
- Exit energy
- Target thickness

Many charge states

many sources of pollution of the focal plan detectors

\( B_\rho = \gamma \frac{Mv}{Q} \)

B. Jacquot // Ganil
Magnetic selection = \( B_\rho = \gamma \frac{Mv}{Q} \)
Electrostatic selection = \( E_\rho = \gamma \frac{Mv^2}{Q} \)

« RMS like Spectro. » Implemented in 6 different Laboratoires:
(Oak ridge, Argonne, Legnaro, Jaeri, New Dehli, Vancouver):

For Fusion Reaction: the Velocity is a good parameter for the selection

Electrostatic devices are efficient (but sparking)
RMS (Recoil « Mass » Spectrometer) : beam optics, M/Q dependance

Electrostatic selection compensates Magnetic selection

With E + B selection:
Achromatic Selection X = f(M/Q, velocity)

Resolution: \( R_{M/Q} = 1/300 \)

Resolution = 4 \( \sigma x_{\text{final}} / R_{17} \)

« \( R_{17} \) » is the « M/Q dispersion »
Gas filled separator for heavy ion

At low energy: too many charge states
Beam charge are spilled over the focal plan

\[ \langle q \rangle_{\text{gas}} \propto v Z^{1/3} \]

\[ \langle B \rho \rangle = \frac{m}{\langle q \rangle} v \propto m Z^{-1/3} \]

In the gas, the collisions make the charge state oscillating around an average \( \langle q \rangle \)
« Charge focusing » + selection Mass = good rejection

Beam dump (stop primary beam)

B. Jacquot // Ganil
Large acceptance spectro

Optics is **non-linear** in $x,x',y,y'$
(Aberrations come with large angle $x',y'$)

$$B_\rho = B_\rho_0 \left( 1 + \frac{x}{R_{16}} + a x'^2 + b x^2 + c x^3 + \ldots \right)$$

**Vamos example:**
In the focal plane, 7 quantities are measured:
$T, x_1, y_1, x_2, y_2, \Delta E, E$

- $T$ : Multi Wire PPAC
- $x_1, y_1$
- $x_2, y_2$

$$x' = \frac{(x_1-x_2)}{d} = \tan(\theta)$$
$$y' = \frac{(y_1-y_2)}{d} = \tan(\phi)$$

$\Delta E, E$ : ionisation CHAMBER
SPECTROMETER TUNING
AND DIAGNOSTICS

**Tuning** rely on
- B field measurement
- Beam measurement

**Beam Diagnostics**: dedicated Robust detectors for beam tuning

Statistical information on the beam \((\bar{x}, \sigma_x, \sigma_T, <I>\ldots)\)

1rst step: check the primary beam

- profil measurement (alignement, focus)
- intensity check

B. Jacquout // Ganil
SPECTROMETER TUNING

Beam diagnostics: scintillator screen

- Scintillation screen ($Y_2Al_5O_{12}$, ...)
- CCD Camera

Relatively low cost, but:
- only 1 profil measurement
- not very precise
SPECTROMETER TUNING

Beam diagnostics: **profil monitor**

*Reconstruct the beam intensity in X and Y*

**Profil monitor: HORIZ. and VERT. wire**

Usefull for **beam alignment**

focusing check

**R16 measurement**

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SPECTROMETER TUNING

Many Profil monitors for different beam intensities

Rotating wire ibeam# 10^{12-14} pps (Cern)

Wires i# 10^{9-11} pps (Ganil)

Gas ArCO_2 +HV

Proportional counter

Specific technologies adapted for ≠(intensities, Energies)
TUNING

Checking size and alignment with profil monitor

Steerer magnets

Beam Profil monitor

ellipsoid area = $\pi \Delta x \cdot \Delta x' = \text{Emittance}$

Emittance = constant if Energy=constant

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SPECTROMETER TUNING: check the intensity

Beam diagnostics: **Faraday cup**

Intensity measurement

\[ \text{Particle per second} \quad \text{Npps} = \frac{I \mu A}{Q} \times 10^6 \quad [Q = 1.6 \times 10^{-19}] \]
SPECTROMETER TUNING

Adjusting field in dipoles and quadrupoles

For adjusting dipole field (B) or quad Gradient (G) adjust $i$ in the coils

$B = B(i)$

and Gradient $= G(i)$ are given by the constructor

**PROBLEM**: hysteresis curve

$B = B(i)$

The current $i$ gives an information About B but

**Solutions**
- Raise the current to $i_{\text{max}}$, then get down & adjust $i$: for reproducibility
- Measure B with Hall probe or NMR probes (dipole)
SPECTROMETER TUNING

Hall Probes: measuring field in dipole

LOW COST, But not very precise
NMR probes are more precise (Resolution=10^{-5})

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Spectrometer tuning: before experiments

**Quad Gradient**: By = G(icoil) * X

- **G_Q1(icoil)** given by constructor
- **B_dipole(icoil)** measured on test bench

**R_{dipole}** has to be known (curvature of the ideal trajectory \( R_{dipole} = \frac{L}{\theta} \))

**Beam optics (Design step)**

« Beam optics » (quad setting for focusing on detectors, target..)

Compute **G_Q1, G_Q2...** For \( B_{\rho \text{ref}} = 1 \) Tm (simulation)

to get the right focus on the detectors

**Experiment preparation: step 0**

- Evaluate the \( B_{\rho} \) of the desired Ion beam
- Which beam optics to be used? (detector location?, ...)
Spectrometer tuning: **during the experiment**

**Step 1**: Check the beam alignment

**Step 2**: Check the focus on target

**Step 3**: Set the quad & dipole magnets (icoils)

With the « **Control command software** »

Select

the quad setting: « the beam optics » (focus on your detector)

the Rigidity $B\rho_0$ of the desired ions: $B = \frac{B\rho_0}{R}$

**The Software Computes the fields by scaling:**

- $G_{Q1} = G_{Q1} \times \frac{B\rho_0}{B\rho_{Ref}}$ (beam optics N°xxx)
- $B_{dipole} = \frac{B\rho_0}{R_{dipole}}$

The **software computes the currents icoils** For the quads & dipoles coils

then, **check the dipole field $B_{dipole}$ with probes**
End
The historical paper for fragment separators:

More on wedge (degrador)

Interesting details in : Kubo et Al, Bigrips NIM

Large acceptance spectrometer :
M. Rejmund, Nucl. Instr. and Meth. A (2011)

Beam diagnostics
Peter Forck : Joint University Accelerator School 2006

Part of this lecture inspired by
B. Jacquot : JoliotCurie school 2008

Many Thanks to Catherina Michelagnoli,...
to my colleagues from Riken, GSI,NSCL, Jyvaskyla,
Triumf, Dubna,Legnaro, and Ganil
Back-up slides

- More on matrices
- Real Performance of a set-up (spectrometer+detector)
- How to optimise beam quality & Acceptance
- The Lise fragment separator & the wien filter
- Why the degrador thickness (Wedge) is not constant in a fragment separator?
- Non linear effect in optical systems
- Examples
More on Transport Matrices:

**Rmatrix for a straight section L (drift)**

Particle Evolution in drift length between \( s_1 \) & \( s_2 \):

\[
\begin{align*}
x &= x(s) \quad y = y(s) \\
x_2 &= x_1 + \tan(\theta_1)(s_1-s_2) \\
\theta_1 &= \theta_2 \\
y_2 &= y_1 + \tan(\varphi_1)(s_1-s_2) \\
\varphi_1 &= \varphi_2
\end{align*}
\]

**Nota:** \( \tan(\theta_1) = \frac{dx_1}{ds} = x_1' \)

and \( (s_2-s_1) = L \)

\[
\begin{pmatrix}
x_2 \\
x_2' \\
y_2 \\
y_2'
\end{pmatrix} =
\begin{pmatrix}
1 & L & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & L \\
0 & 0 & 1 & 0
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_1' \\
y_1 \\
y_1'
\end{pmatrix}
\]

\[ R_{st} = \begin{pmatrix}
1 & L & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & L & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & L/y^2 \\
0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix} \]
The beam: N particles in a 6D ellipsoid

\[ \sigma_x^2 = \sigma_{xx} = \sigma_{11} = \frac{1}{N} \sum_{\alpha=1,..N} (x_\alpha - \bar{x}).(x_\alpha - \bar{x}) \]

\[ \sigma_{x'x} = \sigma_{12} = \frac{1}{N} \sum_{\alpha=1,..N} (x_\alpha - \bar{x}).(x'_\alpha - \bar{x}) \]

1) \( \sigma_{ij} \) is a statistical definition of the beam

2) An optical code

Computes \( \sigma_{\text{Final}} \) with the \( R \) matrix at the end of the spectrometer

\[ \sigma_{\text{final}} = R^T \cdot \sigma \cdot R \]

Done by simulation code

R Matrix allows the simulation

a) -of the beam size \( \sigma(s) \)
b) -of one trajectory \( Z(s) \)
Real performance of a (spectro+detector) depend on the experiment

**efficiency** = $\epsilon_{\text{detector}} \times \text{Transmission\_spectro}$

**Rejection** = primary beam on target / primary particle on final detector

**Selectivity** = ability to see the desired events in the background (coincidence, identification)

**Sensitivity** = the smallest measurable cross section

**Maximal intensity** of incident primary beam
- thermal limit on target (rotative or not,....)
- maximal intensity on detection sytem
- beam losses in spectro (electrostatic sparking,....)
- radioprotection
More on Fragment separators
how to optimise selection in separator

Small spot: $\Delta x_0 = \pm 1\text{mm}$

big spot: $\Delta x_0 = \pm 5\text{mm}$

The spot size $\Delta x_{\text{target}}$ on target defines the beam size at focal plan

$$\Delta X_{\text{focal}} = R_{11} \cdot \Delta x_{\text{target}}$$

Big spot on Target Decrease the selection  (Worse resolution)

Resolution=$4 \frac{\Delta X_{\text{focal}}}{R_{16}}=4 \frac{R_{11} \cdot \Delta x_{\text{target}}}{R_{16}}$

CHECK FOCUS ON TARGET (\(\Delta x_{\text{target}} \text{ small} \!!\))
More on Fragment separators

LISE separator with Wien filter (ganil)

Specifications

\[ L = 35 \text{m} \]
\[ Bp_{1\text{max}} = 4.3 \text{Tm} \]
\[ \Delta p/p = \pm 2.5\% \]
\[ \Delta x' = \pm 20 \text{mrad} \]
\[ \Delta y' = \pm 20 \text{mrad} \]
The velocity filter (so-called Wien filter)

The wien filter use Electric field

\[ F = F_E + F_B = q(E + v_x B) \]

+ magnetic field

The particles with \( v_0 = -Ex/By \) are not deflected (\( F = 0 \))

The particles with a Large velocity deviation (\( v \neq v_0 \)) are deflected

Nota: trajectories in Electric field depend on the « electric rigidity » of the particles: \( \rho = \gamma MV^2/Q \)

\[ \frac{1}{\rho_{trajectory}} = \frac{Ex}{E\rho} - \frac{By}{B\rho} \]

B. Jacquot // Ganil
LISE separator with wien filter

B\(\rho\) selection

\[\text{dE} - \text{TOF}\]

B\(\rho\)+wedge selection

\[\text{dE} - \text{TOF}\]

B\(\rho\)+velocity filter selection

\[\text{dE} - \text{TOF}\]

B\(\rho\)+wedge+velocity filter selection

\[\text{dE} - \text{TOF}\]

B.Jacquot// Ganil
How to get a Fragment separator achromatic

Trajectories are Independant from δ (achromatic)

IF \( R_{16} (A+B)=0 \)

Dipole geometry and quad setting are adjusted to get \( R_{16} (A+B)=0 \)

\[
\begin{align*}
R(A+B) &= R(B) \times R(A) = \\
&=egin{bmatrix}
R_{11}^B & 0 & 0 & 0 & R_{16}^B \\
R_{21} & R_{22} & 0 & 0 & R_{26} \\
0 & 0 & R_{33} & 0 & 0 \\
0 & 0 & R_{43} & R_{44} & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix} \times \\
&\times \\
&=egin{bmatrix}
R_{11}^A & 0 & 0 & 0 & R_{16}^A \\
R_{21} & R_{22} & 0 & 0 & R_{26} \\
0 & 0 & R_{33} & 0 & 0 \\
0 & 0 & R_{43} & R_{44} & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\end{align*}
\]

Achromaticity if \( R_{16} (A+B)= R_{16} (B)+R_{16}(A) \ \ \ \ R_{11}(B)= 0 \)
1) Why a degrador (wedge) in not uniform in $x$:

**Goal of the degrador:**
All the same particles $(Z,A)$ should re-focus at end of the B stage whatever their $B_\rho$ ($\delta$) => achromatic degrador (Wedge) : $R16(A+B)=0$

**Adding a uniform degrador makes the optics chromatics at the End**

Before degrador $\delta_A$, the momentum deviation of the 2 trajectories is $\delta_1 = -\Delta p/p_0$

After degrador $\delta_B = [p_0-\Delta p- \Delta pw -(p_0-\Delta pw)]/[p_0-\Delta pw]$

$\delta_B = [-\Delta p]/[p_0-\Delta pw] \neq \delta_A = \delta_B$

if the Optics is achromatic without degrador ($\delta_A=\delta_B$)
Optics will not be achromatic with a uniform degrador with $\delta_A \neq \delta_B$
2) Why a degrador (wedge) in not uniform in x

Optics will be achromatic with degrador if \( \delta_A = \delta_B \)

The solution for having \( \delta_A = \delta_B \) : degrador thickness \( T = T(x) \)

Proof :

Before degrador, the \( B_p \) deviation of the 2 trajectories

\( \delta_A = -\Delta p/p_0 = xA/R_{16} \) after the wedge (degrador) \( P \Rightarrow P - \Delta p \)

After degrador

\[
\delta_B = \frac{[p_0 - \Delta p - \Delta p_w(xA) - (p_0 - \Delta p_w(xA=0))] - [p_0 - \Delta p_w(xA=0)]}{[p_0 - \Delta p_w(xA=0)]}
\]

\( = \frac{-\Delta p - \Delta p_w(xA) + \Delta p_w(xA=0)}{[p_0 - \Delta p_w(xA=0)]} \)

\( (\delta_A = \delta_B) \Rightarrow \Delta p_w(xA) \neq \Delta p_w(x=0) \times [1 + xA/R_{16}(A)] \)

Thickness of the Wedge \( \# K \times [1 + xA/R_{16}(A)] \)
Beam emittance : (# optical quality)

The emittance is a volume of phase space occupied by a beam

**6 Dimensions**

For practical reasons we use the subspace measurement \((x,x')\) & \((y,y')\)

Horizontal Emittance : area in \((x,x')\)
Vertical Emittance : area in \((y,y')\)
Longitudinal Emittance : area in (energy ,time)

\[
\varepsilon_{\text{rms}} = 4 \left( \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2 \right)^{1/2}
\]

\(\varepsilon\) = area of the ellipse, which correspond to \(x\%\) particles

Liouville theorem: emittance is conserved in a beam line..
Example n°1: fragments separator @Riken(Japan)
E#300-500 MeV/A   L=77m
6 dipoles magnets, 42 quadrupole magnet

Suppression of the primary beam
(many dipoles, degrador selection)

Help the selection of very rare nuclei
Selection of 4-5 nuclei
Identification (DE-TOF)

Superferric quads
B.Jacquot// Ganil

Fig. 2. A schematic diagram of the RI-beam tagging in the BigRIPS separator.
Quadrupole technology

1: Normal conducting quad
   hyperbolic pole (Fe)
   coils (Cu)
   G~ 10 Tesla/m

2: Superferric quad
   hyperbolic pole (Fe)
   coils (NbTi)
   Higher Gradient, larger aperture possible (A1900, BigRips, Synchro.)
   G~ 20-30 Tesla/m

3: Superconducting quad
   No pole !!!!!!!
   cos(2θ) coils (NbTi)
   G~ 40-200 Tesla/m (Cern LHC...)

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Example n°2: VAMOS Spectrometer

L=8 meters, 1 dipole, rotative platform

Suppression of the primary beam
(by rotation)

Selection of 20-300 nuclei
Help Identification (ΔE-TOF,
position and angle measurements)

300 fission fragments id.

B.Jacquot// Ganil
In the focal plane, 7 quantities are measured: $T, x_1, y_1, x_2, y_2, \Delta E, E$

- $T$: Multi Wire PPAC
- $x_1, y_1$
- $x_2, y_2$:
  
  $x' = \frac{(x_1 - x_2)}{d} = \tan(\theta)$
  
  $y' = \frac{(y_1 - y_2)}{d} = \tan(\phi)$

- $\Delta E, E$: ionisation CHAMBER

**Equation is non-linear in $x, x', y, y'$ (Aberrations)**

$B_\rho = B_\rho_0 \left(1 + \frac{x}{R_{16}} + a x'^2 + b x^2 + c x^3 + \ldots\right)$
Non linear effects in optical system

Linear Approximation holds for small angle, small $B\rho$ deviation... ($\#30\text{mrad}, \delta<2\%$)

\[ Z_2 = R \cdot \vec{Z}_2 + \ldots \varepsilon \]

for large angle, large $B\rho$ deviation 2\textsuperscript{nd} order, third order is required.

\[ Z_{2i} = \sum_{j=1}^{6} R_{ij} \cdot Z_{1j} + \sum_{k=1}^{6} \sum_{j=1}^{6} T_{ijk} \cdot Z_{1j} \cdot Z_{1k} + \ldots \]

Effect of second order:
- Inclination of focal plane
- The focusing strength of quads is $B\rho$ dependant
- Large angle particles are not well focused

Non linearities (ABERRATIONS) come
- with large acceptance (large $x'$ and large $\delta$)
- but also, with field defects in quads and dipoles
Non linear effects in optical system

**Ex1**: Inclination $\alpha$ of the focal in a spectrometer

\[ \tan(\alpha) = \frac{R_{16}}{T_{126} \cdot R_{11}} \]

- Choice of the dipole Angle
- Magnetic sextupole has to be used for correction

**Ex2**: Distortion of beam ellipse

In phase space

Inducing Distribution wings

Optical aberrations (non linearities)
Non linear effects in optical system

Beam optics is linear when
\[ x < 5\text{cm} \]
\[ x' < 30\text{mrad} \]
\[ \delta < 2\% \]

Beam is a nice ellipse in phase space, R matrix is sufficient

If \[ |X'| > 30\text{mrad} \text{ or } |\delta| > 2\% \]

Beam are not well represented by an ellipse

R matrix is not sufficient for the calculation
( field maps + tracking with « Runge kutta » simulation needed )
Example n°2: VAMOS Spectrometer

Particle identification Method

\((M,q,Z)\)

1) Measurement of the time of flight (TOF) => velocity
2) Measurement of the position \(x_{\text{focal}}\) after the spectrometer => \(B_0 = B \times R_{\text{dipole}} \left(1 + \frac{x}{R_{16}} + \ldots\right)\)
3) Measurement of the energy loss \(\Delta E\) in a thin detector (Ionization Chamber)
4) Measurement of residual energy \(E_r\) \((E_{\text{kinetic}} = (\gamma - 1)Mc^2)\)

\(v = \frac{T \text{ flight}}{L_0}\)
\(M/q = \frac{B_0}{\gamma v}\)
\(Z \# k \Delta E \ldots\)
\(M_1 = \frac{(E_r + \Delta E)}{[c^2 (\gamma - 1)]}\)

finally
\(Q = M_1 / [M/q]\)
\(M = [M/q]. Q\)
\(Z \# k(E) \Delta E\)
Example: S3 spectrometer @Ganil

S3:
1 Magnetic achromatic separator (2 dipoles) + 1 mass spectrometer (M/q)

Electr. deflector ±300 kVolts

Beam dump

Lise++ simulation:
fusion reaction, 5 charge states (horizontal plane)
Example: S3 spectrometer @Ganil

S3:
1 Magnetic achromatic separator (2 dipoles)
+ 1 mass spectrometer (M/q)

Superconducting quadrupole triplet: Coil (NbTi), without pole
- Supra-conducting coils with multipolar corrections (hexapole+octupole)
- Quadrupoles: Raperture very large = 0.15m;