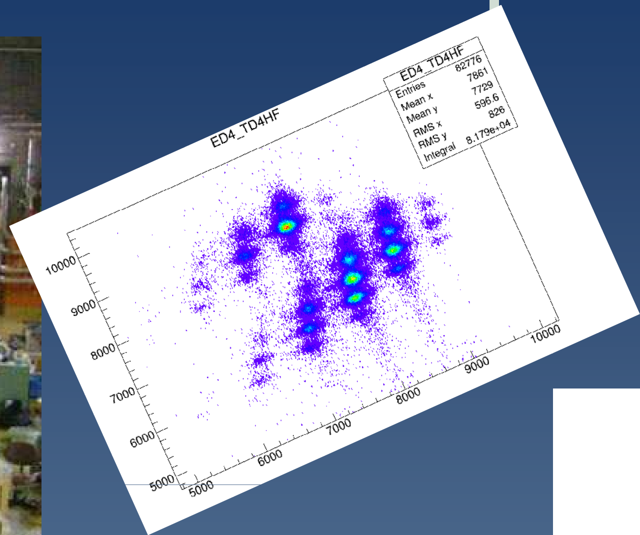
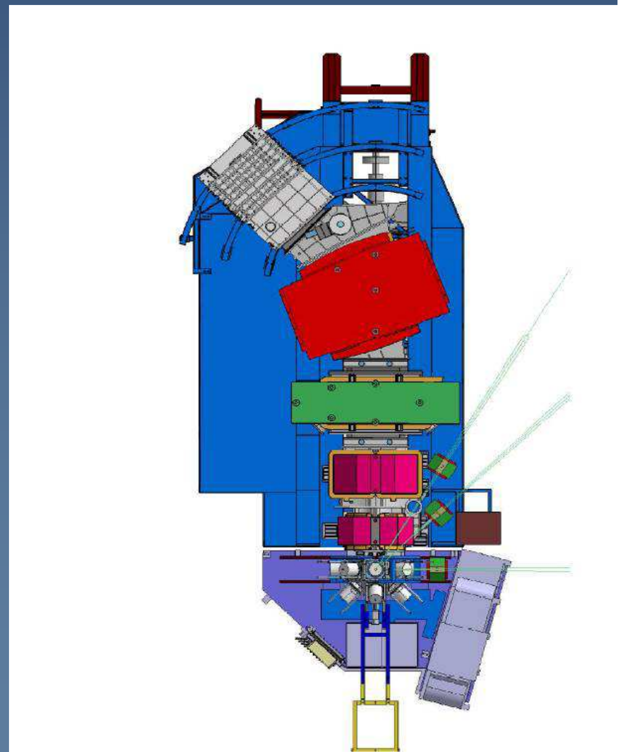
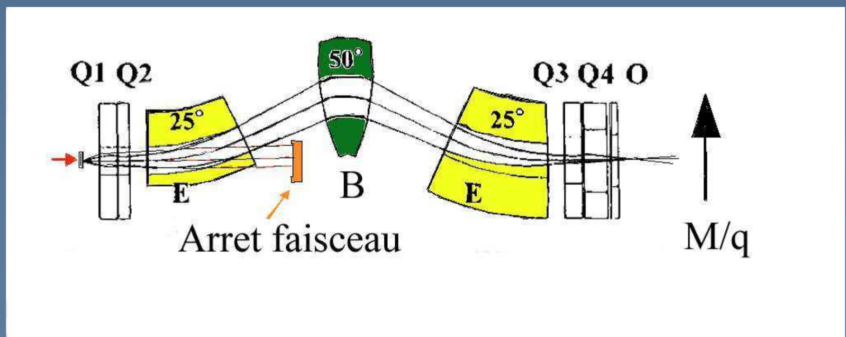
Electromagnetic Spectrometers & Separators







Spectrometers & separators Properties in nuclear physics

1) Why a spectrometer ? Part 1

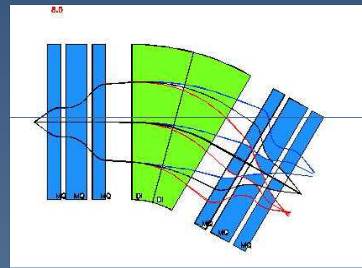
2) Designing a spectrometer (1rst approach)

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

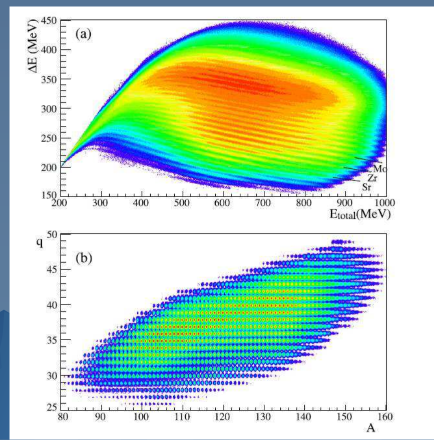
Part 2
5) Fragments separators
(100MeV/A-500 MeV/A)

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

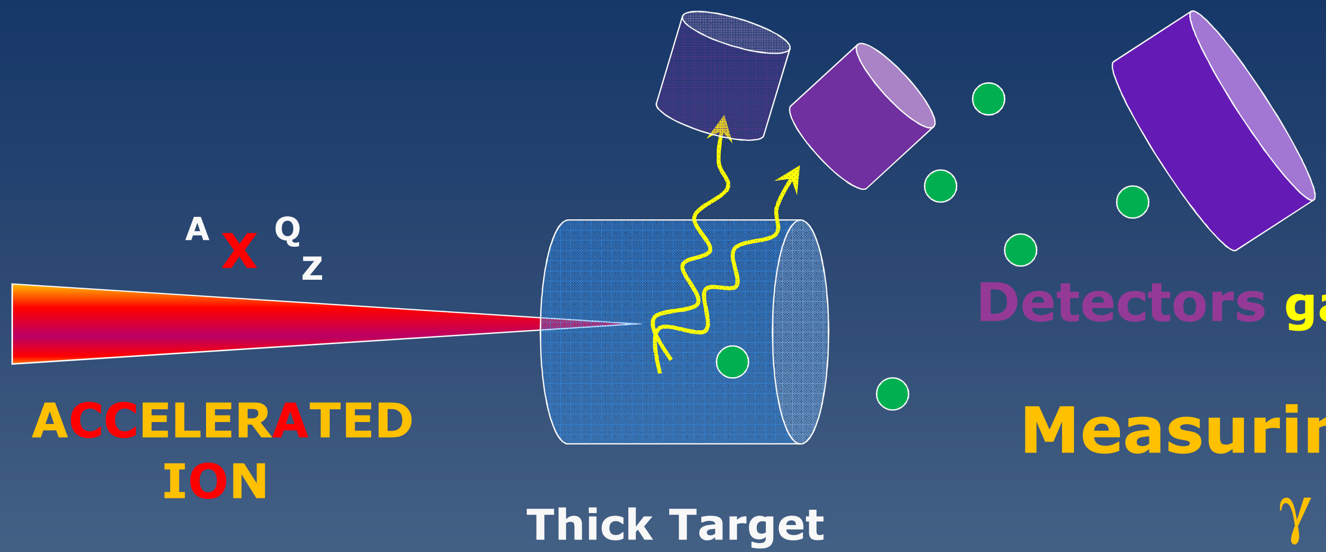
7) Tuning And Diagnostics



$$\begin{bmatrix} R_{11} & 0 & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & 0 & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & L/\gamma^2 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$



An experiment in nuclear physics



Measuring σ, γ spectroscopy,..

$^{A}X_{Z}$ + Target -> n + $^{A-1}X_{Z}^{*}$ -> γ + $^{A-1}X_{Z}$

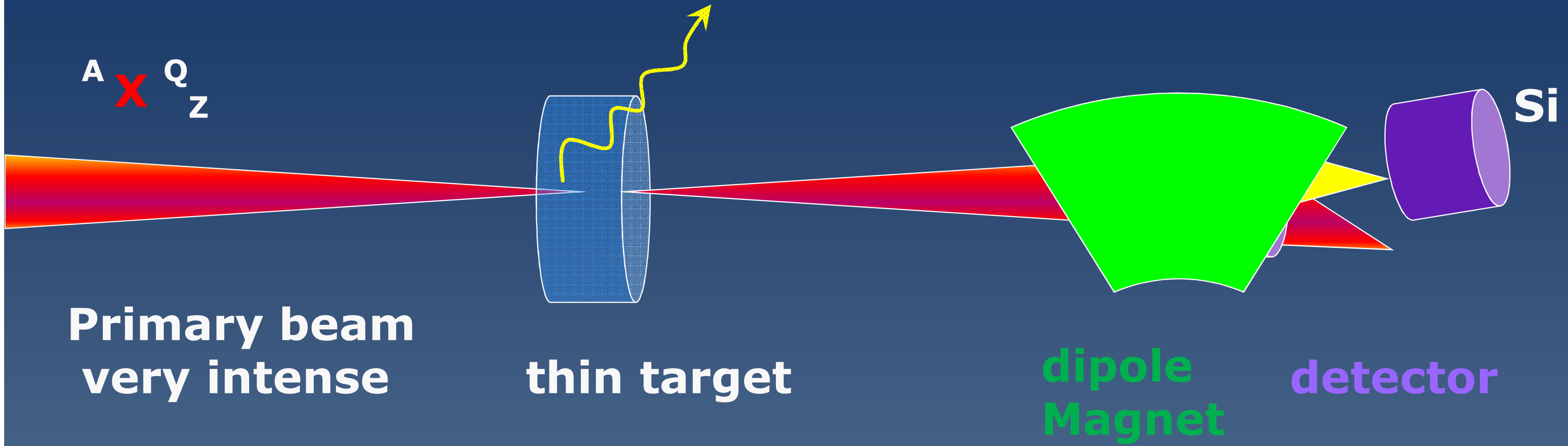
Reaction of interest, but

Many reaction channels $^{A}X_{Z}$ + Target -> 2n + $^{A-2}X_{Z}^{*}$

$^{A}X_{Z}$ + Target -> 3n + 1p+ $^{A-3}X_{Z-1}$

Reaction products not identified , ion energy not measured

An other experiment in nuclear physics



Eletromagnetic spectrometer

- **Eliminate primary beam (~ 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 yo need ?

with what resolution ?

(ion energy ,angle, A, Z, photon ,neutrons)

➡ with wich detectors (position, energy)

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

➡ primary beam separation

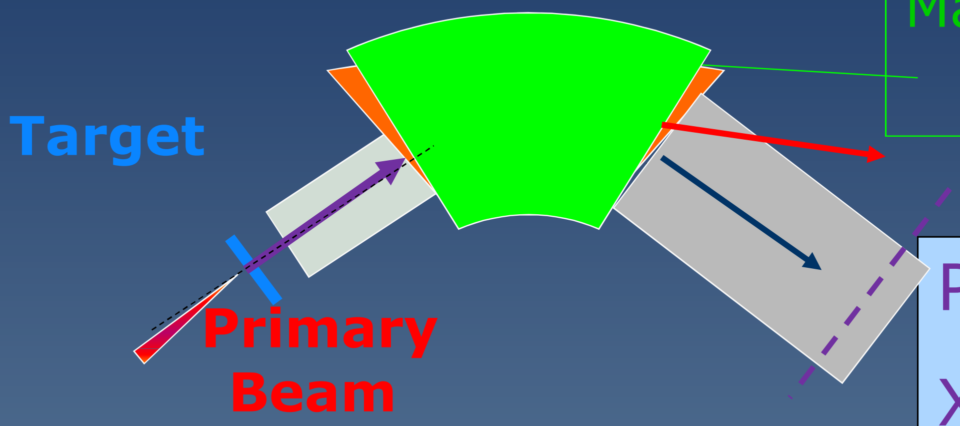
Without a magnetic spectrometer : limitation? (selectivity)

With a magnetic spectrometer : limitation ? (efficiency)

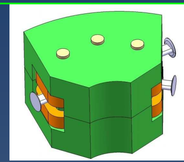
Other possible limitations (primary beam intensity, ion identification, detector resolution)

Let's design a simple Magnetic spectrometer

1) dispersion of the particles as function of M,v ,…



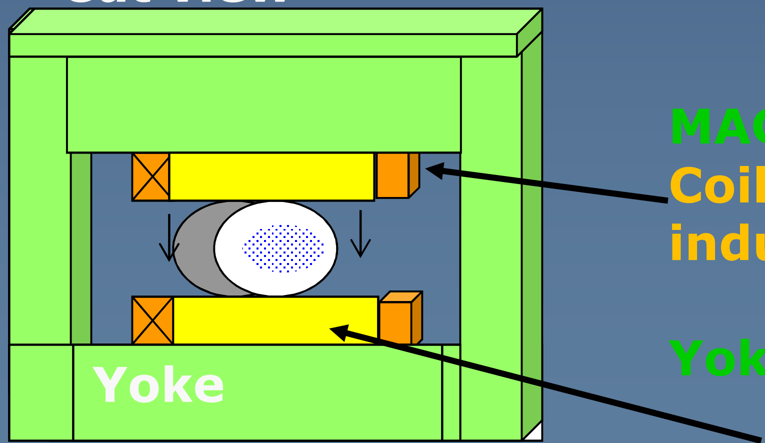
Magnetic dipole



Positions Xf ?

Xf=F(Mass of ions,…)

Cut view



MAGNETIC DIPOLE : B*y*=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*=Constant

Equations for an ion in a magnetic field :

$$\vec{F} = q\,(\vec{v} \times \vec{B})$$
$$\frac{d}{dt}[\gamma\, m v] = \vec{F}$$

$dv/dt = v^2/ R\ \mathbf{e_r}$

Relativistic factor : $\gamma = \dfrac{1}{\sqrt{1 - \dfrac{v^2}{c^2}}}$

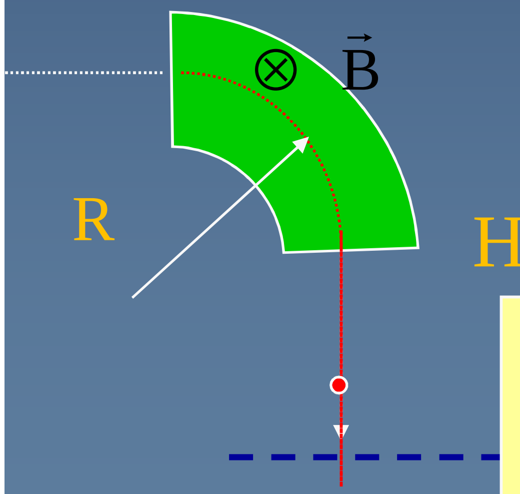
If B=const , for an ion (m ,q , v)

The Trajectory is a circle with a radius R

$$R = \gamma \frac{mv}{q\,B}$$

We define the magnetic rigidity Bρ =[Tesla.m]

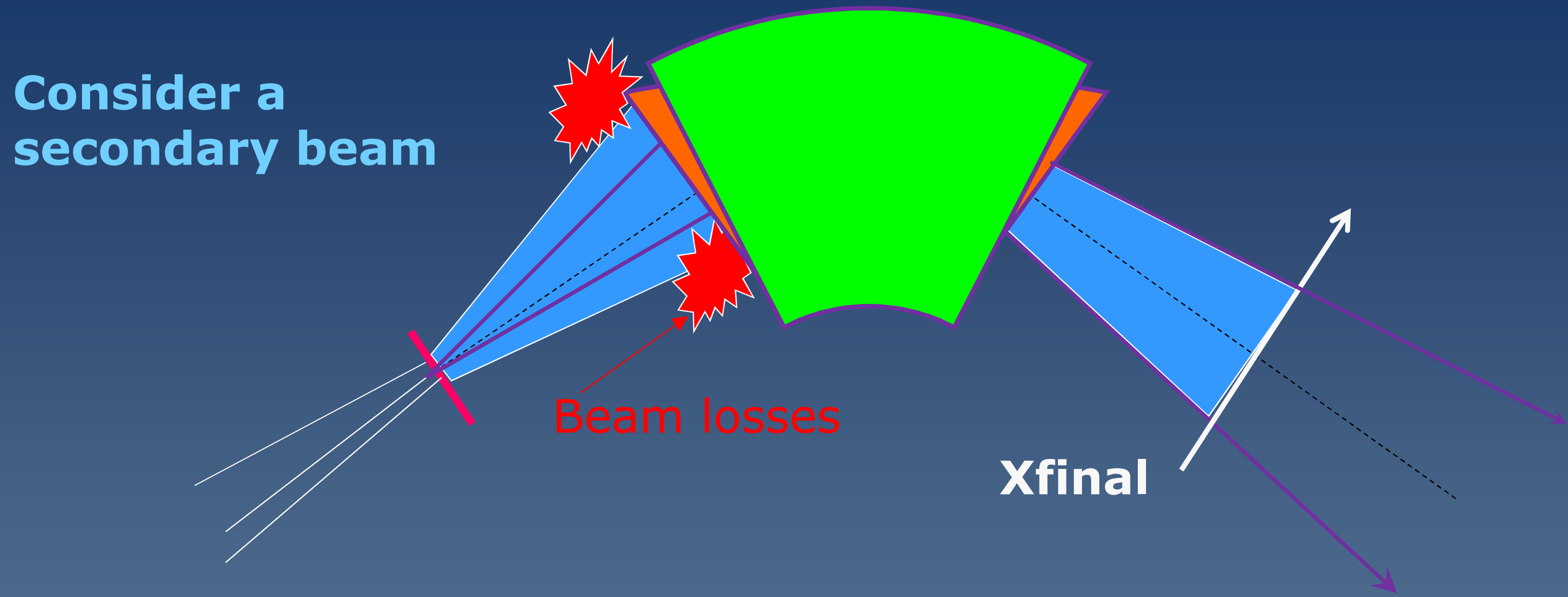
$$B\rho \overset{def}{=} \gamma \frac{mv}{q}$$



How to tune the dipole field B= [Tesla] ?

$$B = \frac{B\rho_{ref}\,[T.m]}{R\,[m]}$$

2 problems with 1 dipole magnet : Acceptance & identification

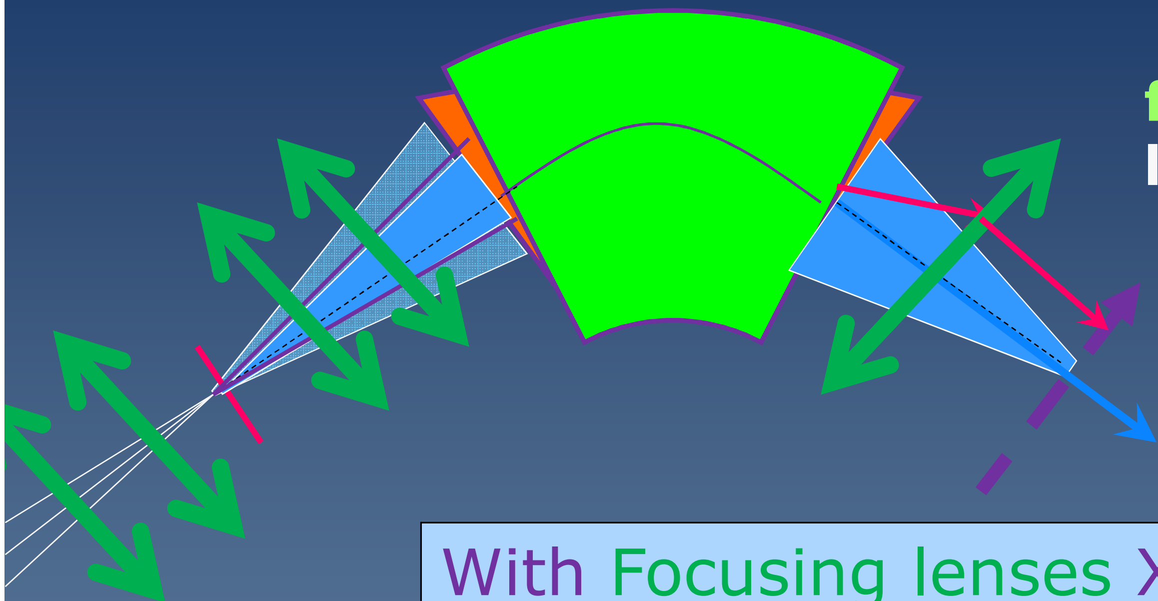


- **-1: Many particles are lost in the magnet (very bad)**
- **-2: Trajectories are complex (bad)**

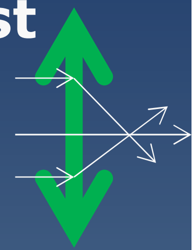
Xfinal =f(Bρ , θi, φi , X0,Y0)

- **Final position xf depend on the**
  - **Bρ (good for identification or separation)**
  - **position & Angle after the reaction (bad)**

Beam divergence after target
2 problems solved with focusing lenses



Imagine than
focusing lenses exist
like in light optics



Xf

With Focusing lenses Xf=F(Bρ, ~~θi~~, ~~φi~~ , ~~X0~~,~~Y0~~)

less unknowns ! Less beam losses!!

At one location s (the detector location, called focal plan)
The trajectoires are independant of the angles θi, φi
And the initial position is x0=0, y0=0

Xf=F(Bρ , ~~θi~~, ~~φi~~ , ~~X0~~,~~Y0~~)

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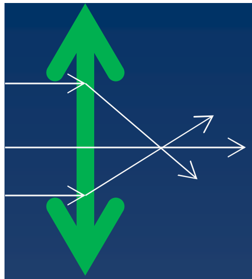
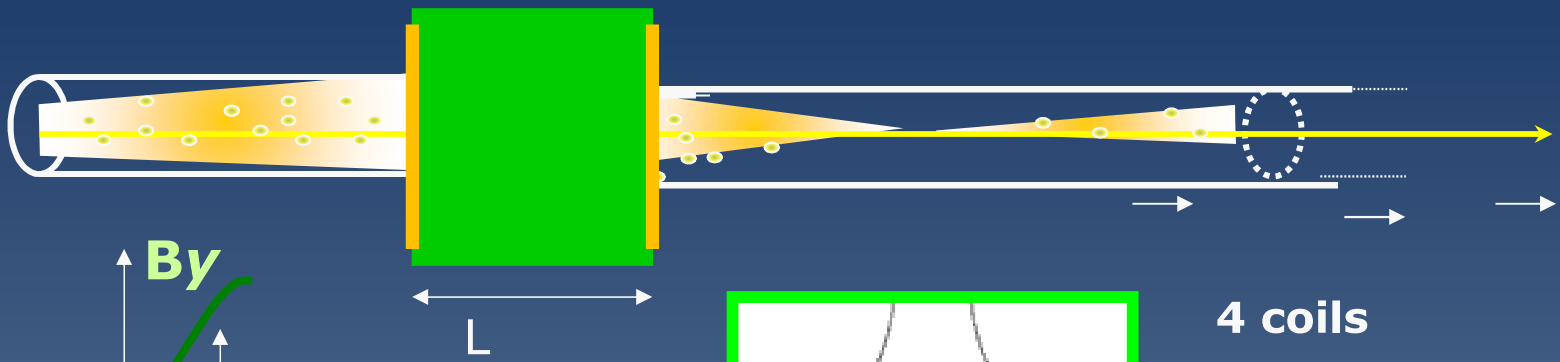
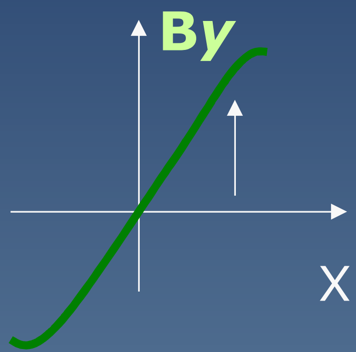
How to construct a Focusing lens for ions :
Magnet with 4 poles (+,-,+,-)

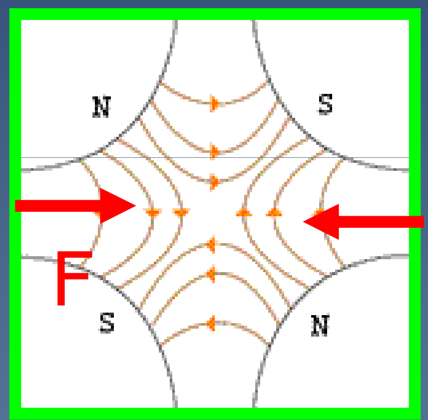


$F = q\,(v \times B)$





G=dBy/dx

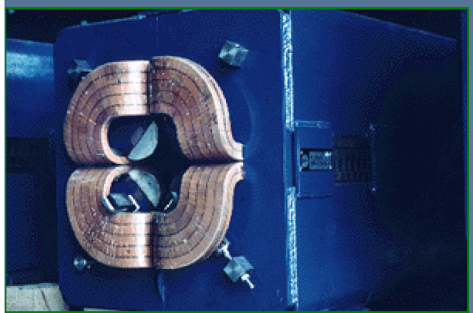


4 coils

+4 hyperbolic poles

By=G.X

G is called GRADIENT [Tesla/m]



The quadrupole magnet is focusing

in HORIZONTAL PLAN

Nota: In the center, the force is zero

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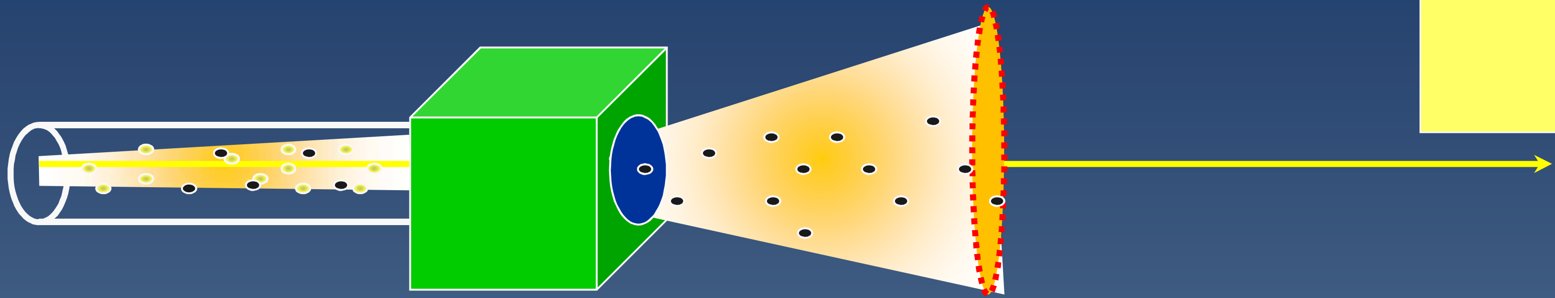
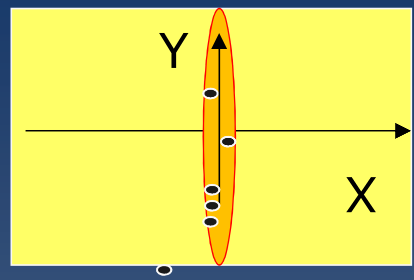
A quadrupole magnet
Focusing lens in horizontal
But defocusing in vertical





The beam becomes narow in X and large in Y

B*x*= G.Y

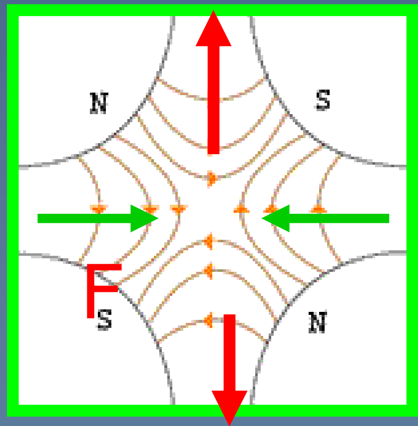
B*y*= G.X

B*s*= 0

Focusing in X (G>0)

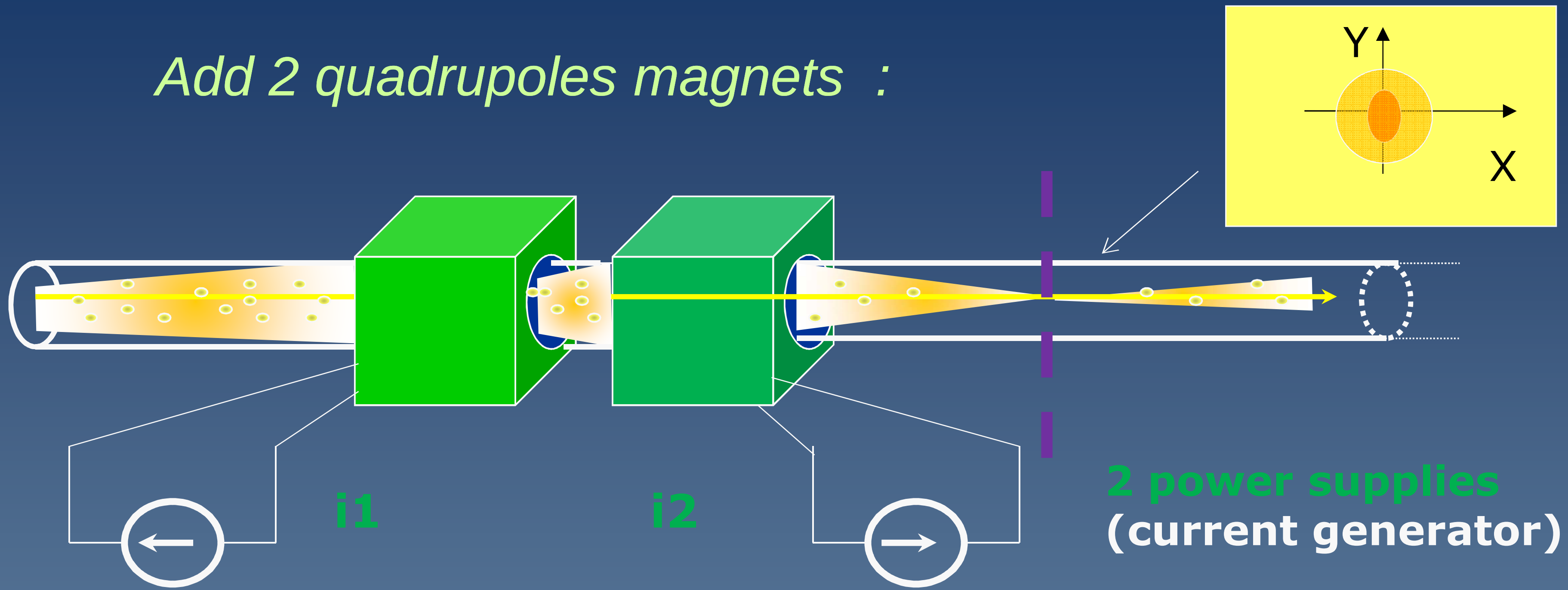
Defocusing in Y (G>0)

Since the Force is defocusing in vertical



How to construct a Focusing lens System In horizontal AND vertical plan

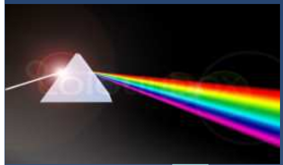
Add 2 quadrupoles magnets :



If you tune i1 and i2 with opposite polarities , the beam can be focused in X and Y

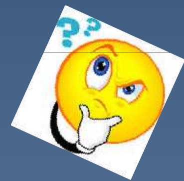
Beam optics (basics)

- Focalisation with quadrupoles DONE



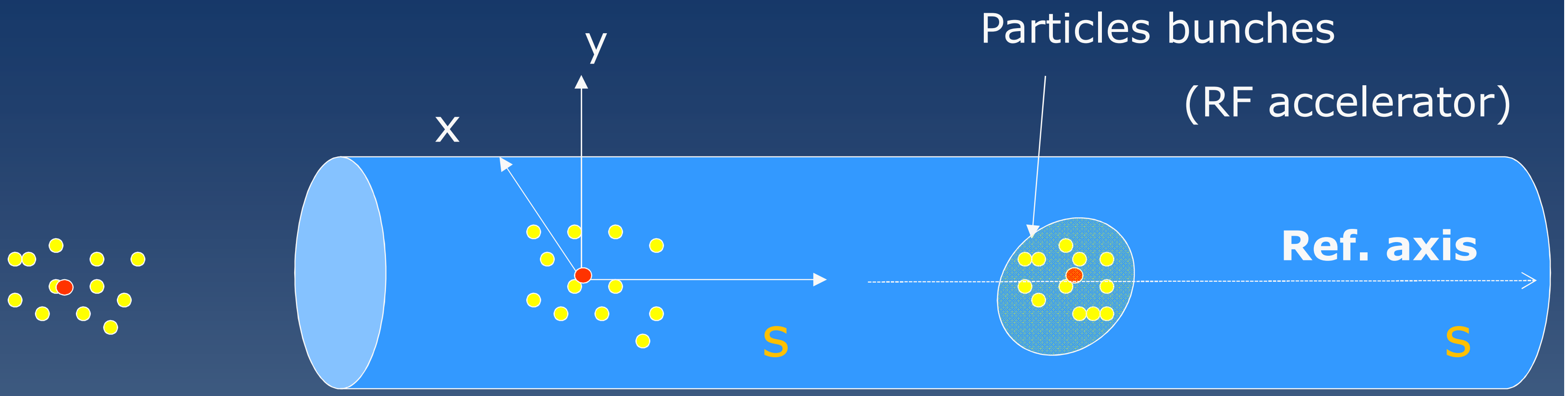
- Dispersion with dipole DONE
- Magnetic rigidity : $B\rho = \gamma Mv/Q = P/Q$ DONE

- Particles coordinates
- Equations in field B & E
- 1rst order approximation :Optical Matrices



- Resolution
- Angular Acceptance
- $B\rho$ Acceptance

Beam Optics convention : Particle coordinates



particle coordinates ? (energy, velocity, angle, $B\rho$, ??)

DEFINE A REFERENCE PARTICLE ($x_0, y_0, B\rho_o, t_o$)

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

2 positions $(X-X_0)$, $(Y-Y_0)$

+ *2 angles* θ, ϕ

+ rigidity $B\rho = B\rho_o (1+\delta)$

+*$(t - t_o)$ time advance*

Optical convention :

Angle in Horizontal plan noted as

$$X' = dx/ds = \tan\theta$$

Angle in Vertical plan

$$Y' = dy/ds = \tan\phi$$

Time coordinate expressed in meter

$$L = v_o (t - t_o)$$

Beam optics notation

The reference particle : $B\rho_0 = P_0/Q_0 = B_{dipole} \times R_{dipole}$

it is traveling in the **Center of the beam lines**
So $X_0=0$, $Y_0=0$
« angles » : $X'_0=0$, $Y'_0=0$

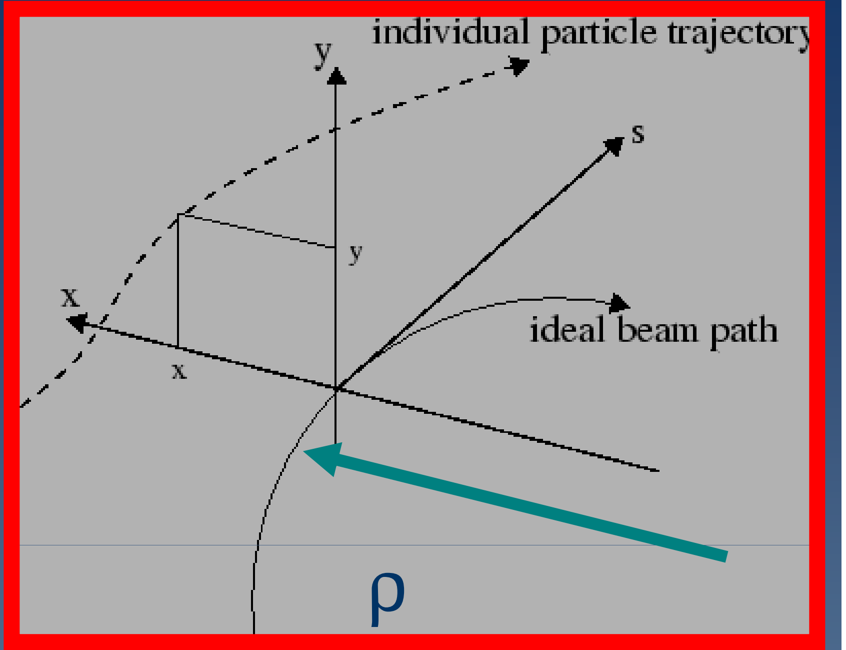
At the location s_0 ,
a particle
is represented
by a vector *Z*(s_0)

Z=(x,x', y ,y', l, δ)
6Dim

$$\vec{Z} = \begin{pmatrix} z1 \\ z2 \\ z3 \\ z4 \\ z5 \\ z6 \end{pmatrix} = \begin{pmatrix} x \\ x' = \frac{dx}{ds} \\ y \\ y' = \frac{dy}{ds} \\ l = \mathrm{v}_0 (T - T_0) \\ \delta = \frac{B\rho - B\rho_0}{B\rho_0} \end{pmatrix} = \begin{pmatrix} \text{horizontal displacement} \\ \text{horizontal "angle"} \\ \text{vertical displacement} \\ \text{vertical angle} \\ \text{longitudinal difference} \\ \text{"momentun}(B\rho)\text{" deviation} \end{pmatrix}$$

Trajectory equations for 1 particle

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



We use a

curvilinear Reference Frame

which follow the reference particle

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

$$\frac{d}{dt} = \dot{s}\,\frac{d}{ds}$$

Coordinate change t ⟹ s

x(t),y(t) => x(s),y(s)

We want to compute x,y at a detector location $s=s_0$

$$\frac{d}{ds}[m\gamma\,\mathbf{v}] = \ldots$$

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Trajectories : exact equations

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

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

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

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

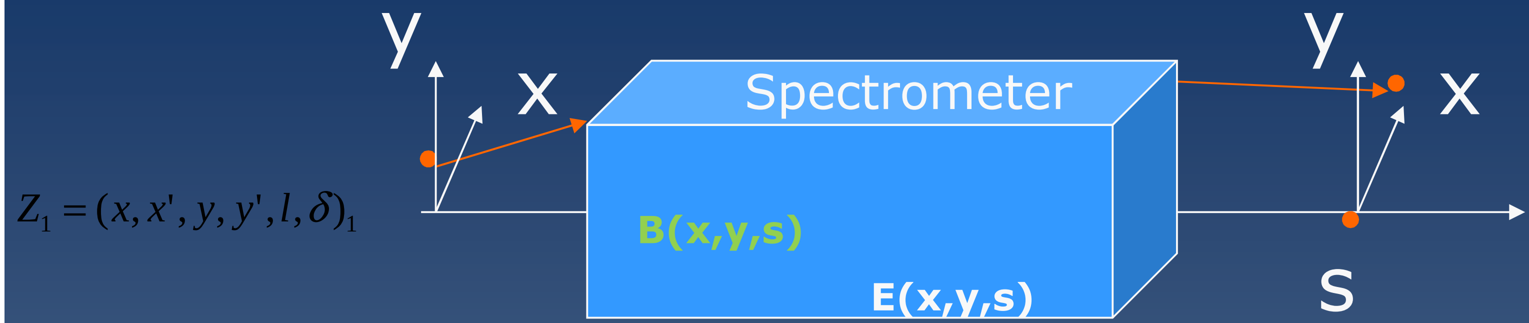
1) knowing B(x,y,s) AND E(x,y,s,t) [field map 3D]

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

Generally we can do <u>simpler</u>

Matrix approach (1rst order approximation)

Beam optics with Matrices



$$\mathbf{Z}_2 = f_{1\to 2} \quad (\mathbf{Z}_1, B, E, l......)$$
$$= R_{1\to 2} \quad .\mathbf{Z}_1 + 0(\mathbf{Z}_1.^2) + ...$$
$$\approx R_{1\to 2} \quad .\mathbf{Z}_1$$

Exact Dynamic (non linear)

Taylor expansion

(X and Y Are small..)

Linear dynamics

$$\begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix}_2 = \begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{31} & R_{31} & R_{36} \\ R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\ R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{66} & R_{66} \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix}_1$$

$$l = \mathrm{v}_0 (t - t_0)$$
$$\delta = \frac{B\rho - B\rho_0}{B\rho_0}$$

The transport Matrix R : allow the computation of a coordinate of a particle at the end of a spectrometer

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

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

$$\overrightarrow{Zout} = R.\overrightarrow{Zin}$$

$$\begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix}_1 = \begin{bmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{31} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & R_{55} & R_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix}_0$$

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

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

Interpretation of R

$$Rij = (\frac{\partial Zi\ out}{\partial Zj\ in})$$

$ex:$

$$R_{11} = (\frac{\partial Z_1}{\partial Z_1}) = (\frac{\partial x\ out}{\partial x\ in}) \quad R_{12} = (\frac{\partial Z_1}{\partial Z_2}) = (\frac{\partial x\ out}{\partial x'\ in})$$

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

The transport Matrix R=R*ij* is related to

- spectrometer geometry
- **tuning** of the quadrupoles

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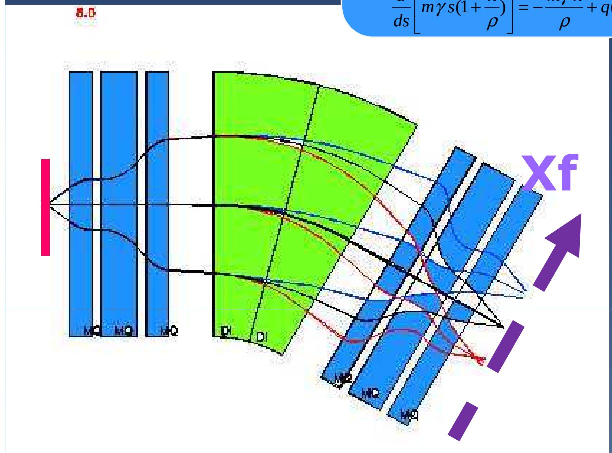
SPECTROMETER TRANSPORT MATRIX R

allow the simulation of 1 trajectory (**easily**)

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

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

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



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

Typical spectrometer Matrix is simple

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

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

$$R_{16} = \left(\frac{\partial x_F}{\partial \delta}\right)_{Target}$$

$$\delta = (B\rho - B\rho_o)/\ B\rho_o$$

$$B\rho_o = \mathbf{Bdipole}.\ Rdipole$$

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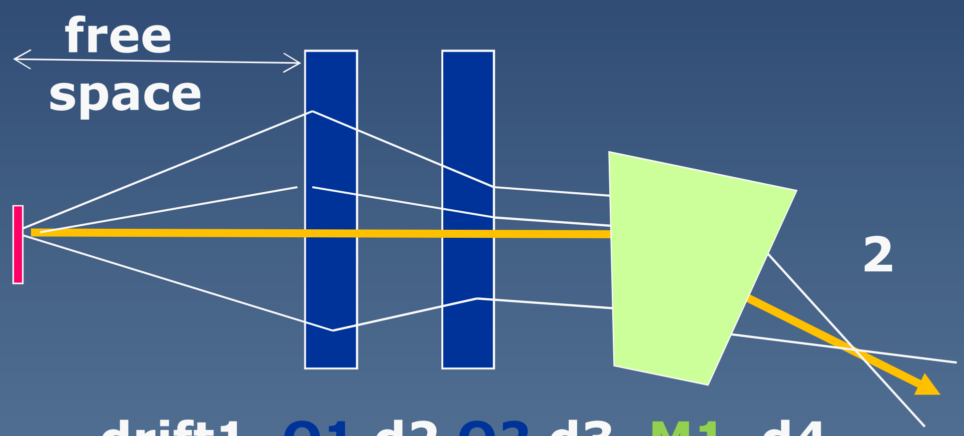
More on Transport Matrices:

how to compute the Rmatrix for a spectrometer ?

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



drift1 Q1 d2 Q2 d3 M1 d4

Quad matrix

$$R_{M1} = \begin{bmatrix} \cos k_x L & \frac{\sin k_x L}{k_x} & 0 & 0 & 0 & M_{16} \\ -k_x \sin k_x L & \cos k_x L & 0 & 0 & 0 & M_{26} \\ 0 & 0 & \cos k_y L & \frac{\sin k_x L}{k_x} & 0 & 0 \\ 0 & 0 & -ky \sin k_y L & \cos k_y L & 0 & 0 \\ M_{26} & M_{16} & 0 & 0 & 1 & M56 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$k_x = GL/B\rho_0$

$$R_{d1} = \begin{bmatrix} 1 & L1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & L1/\gamma^2 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Free space: Drift Matrix

Matrix product $R = d4 . R_{M1} . R_{d3} . R_{Q2} . R_{d2} . R_{Q1} . R_{drift1}$

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The beam size : important for the design

- A **particle** has 1 trajectory : $Z = \vec{Z(s)}$

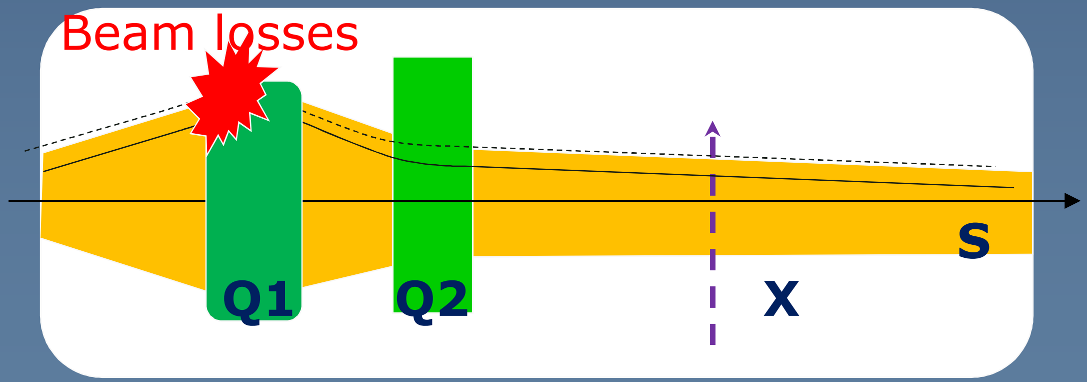
We are not interested by only 1 trajectory/particle

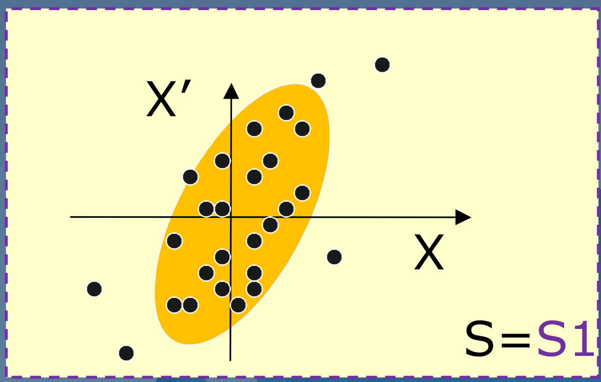
A beam is an ellipsoid in 6D with a given size

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

σx (horizontal width) , σy (vertical width)

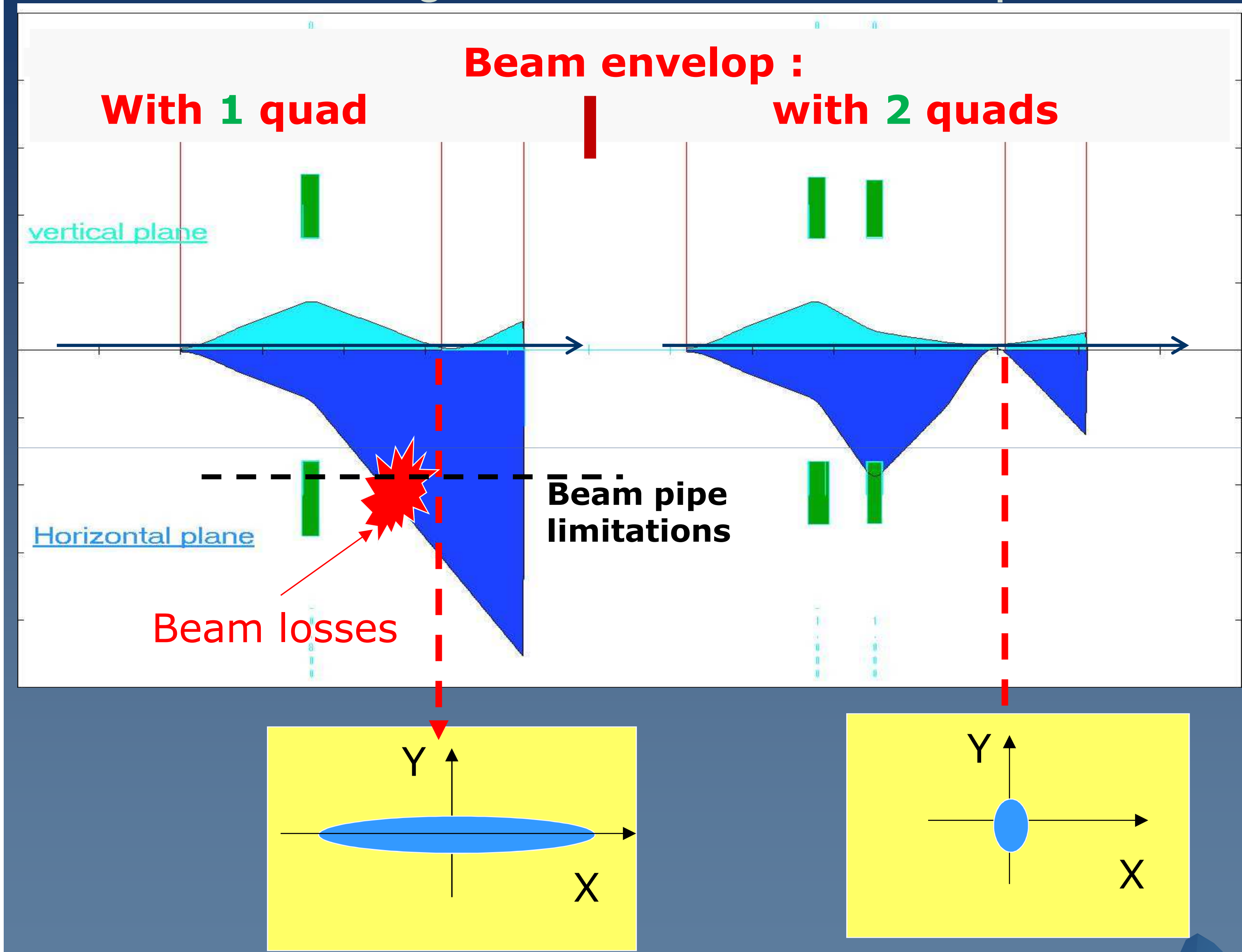
$$\sigma_x^{\,2} = \frac{1}{N} \sum_{\alpha=1,..N} x_\alpha^{\,2}$$





Focusing a beam in a simulation

get a small size at some point S



Adjust

Quad gradient

$G_q = dB_y/dx$

Focusing in X and Y : at less 2 quads required

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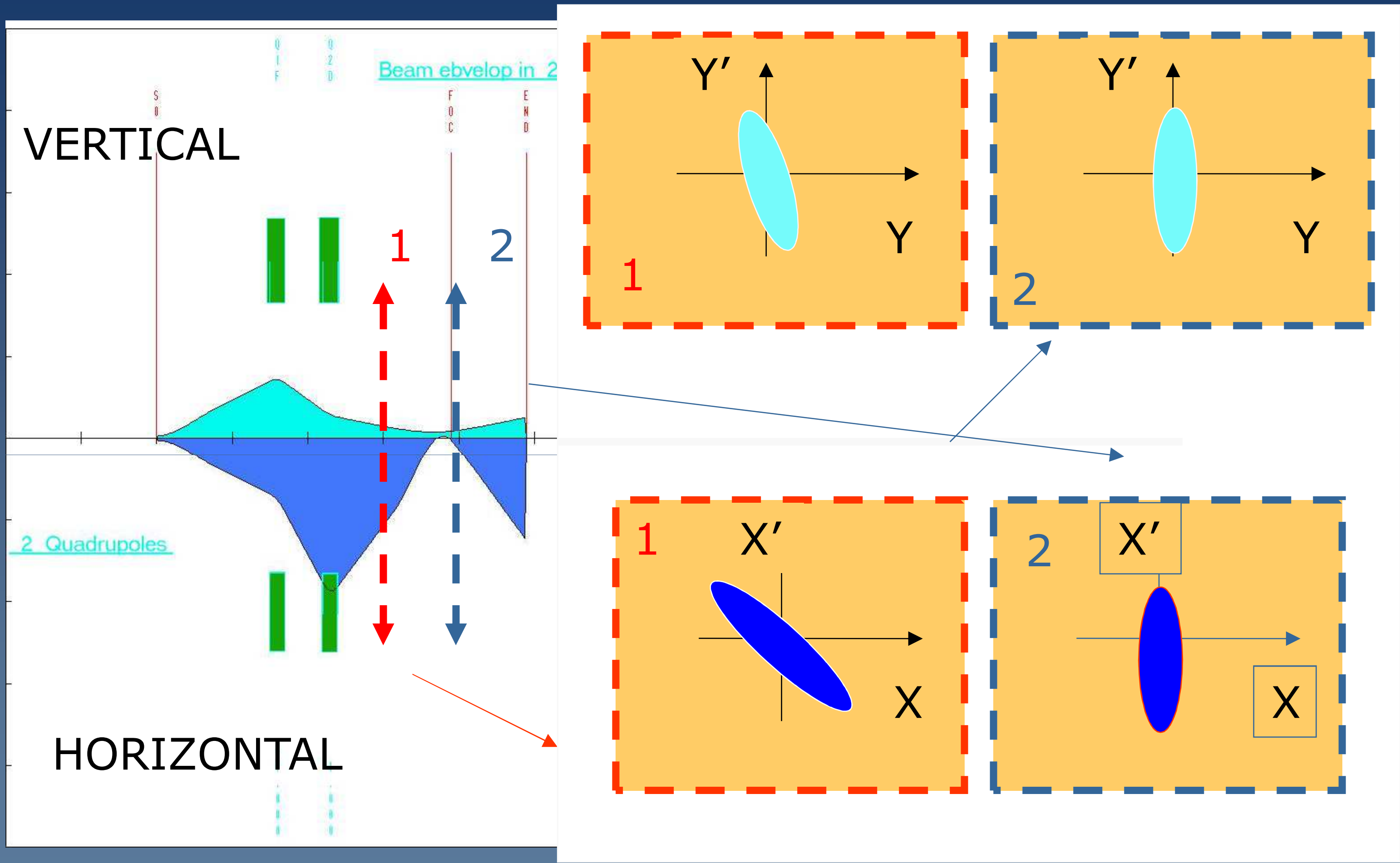
Angular distribution (x') in a beam line ?
The beam ellipse is rotating in (x, x'=dx/ds)



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

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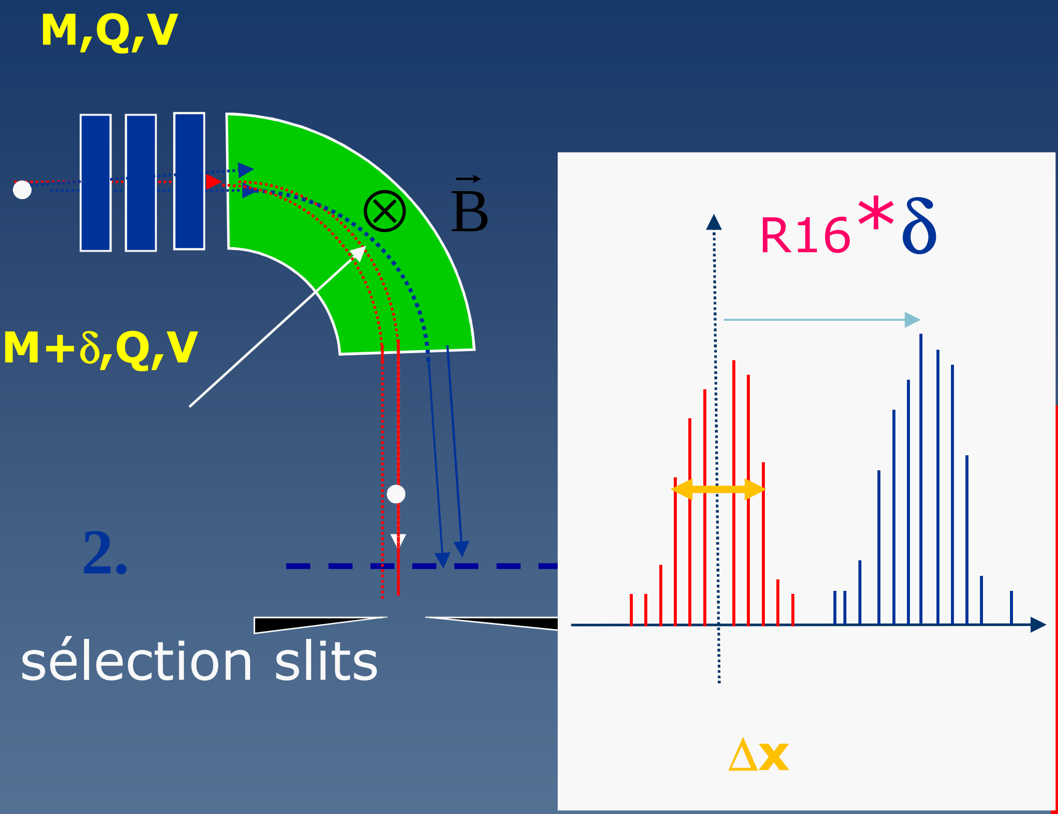
Resolution of a separator



particles are separated

IF $R_{16} * \delta > 4\ \sigma x$

Resolution $= 4\ \sigma x / R_{16}$

= Minimal difference in Bρ

for the identification

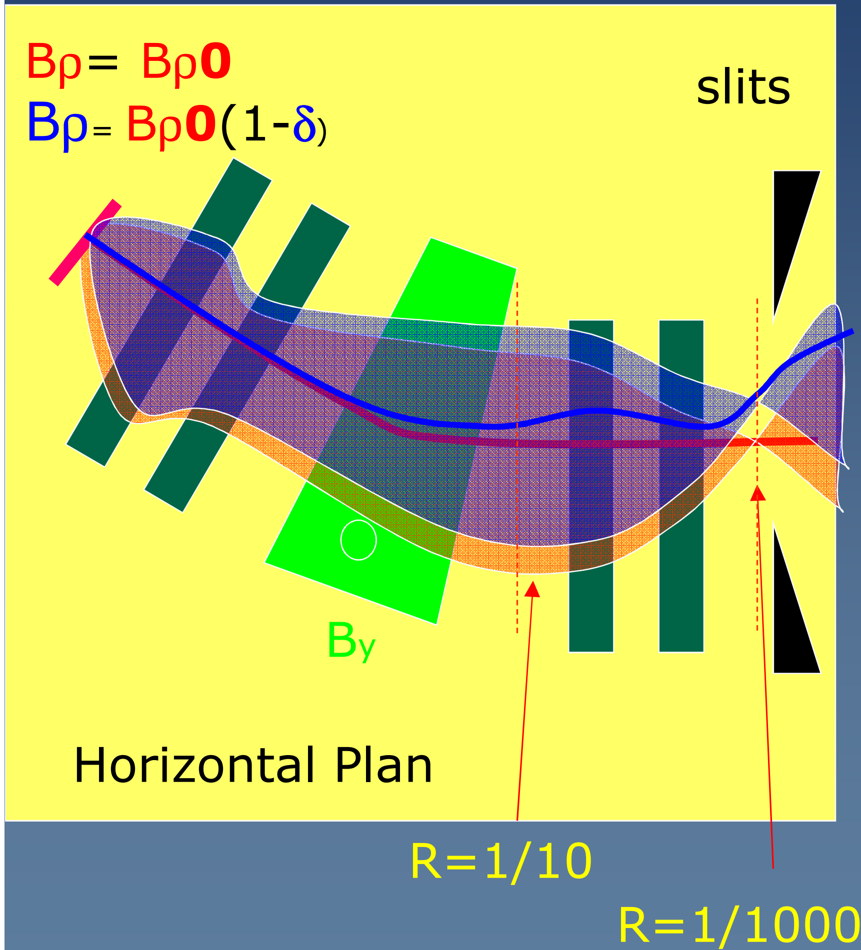
or for separation

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

R=1/100 Resolution means : capacity for a spectrometer to distinguish two beams with 1% Bρ difference

The resolution (separation)

is optimal at the focus point (size is minimal)



The 2 beams with ≠rigidities

$B\rho_{ref} = B\rho_0 = B \times R_{dipole}$

$B\rho = B\rho_0(1-\delta)$

The 2 beams are separated

« at the focal plan »

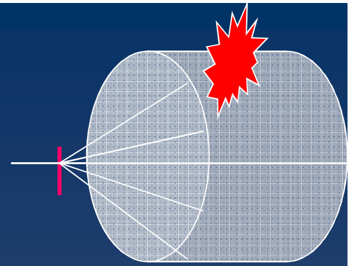
But not everywhere !!

Resolution (R= σx/R16) is optimal

When σx is small

and R16(dispersion) is large

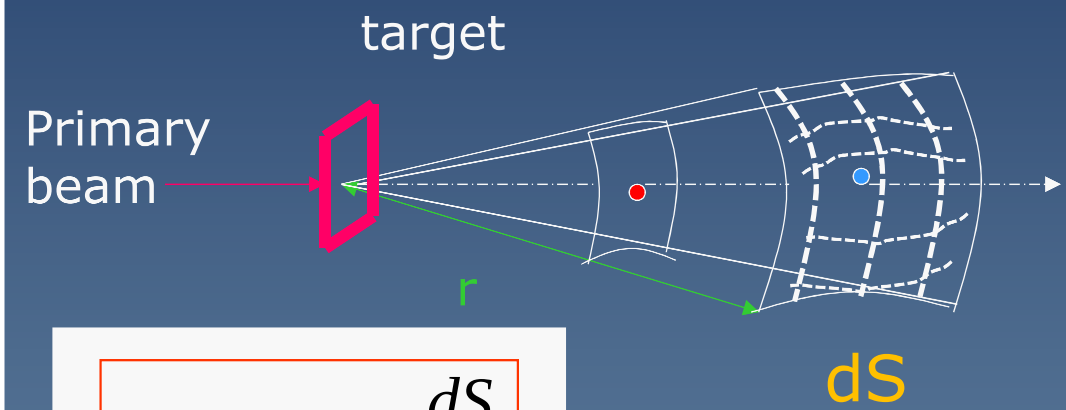
Angular acceptance



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.

$$d\Omega(strd) = \frac{dS}{r^2}$$

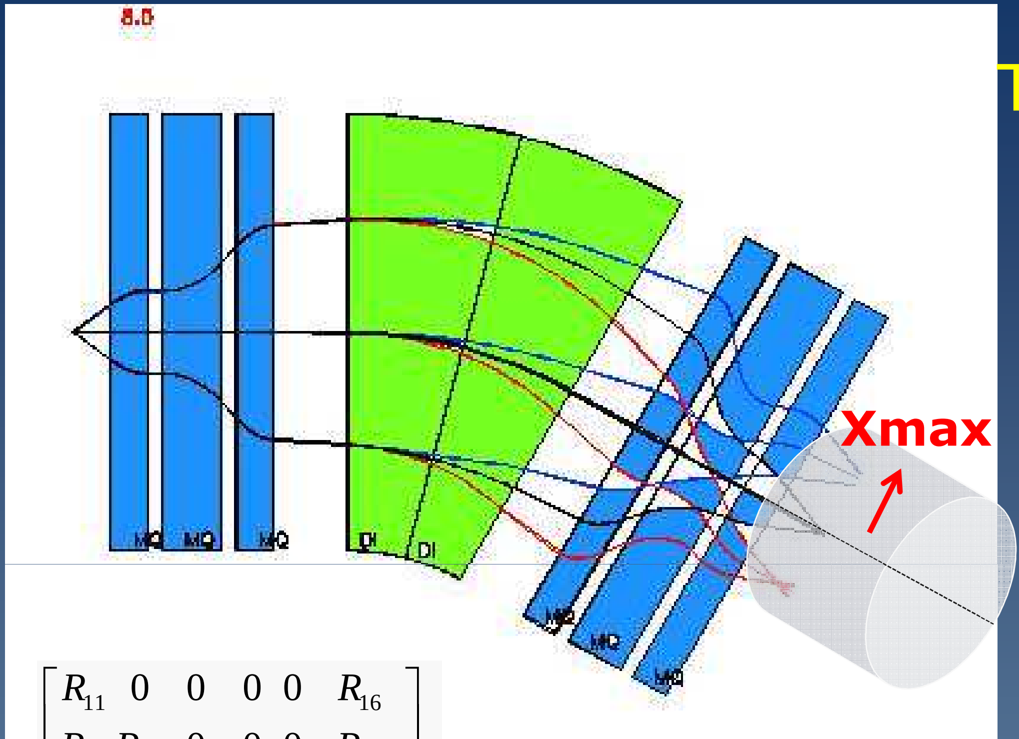
Example: If particles inside **±50mrd** (Horizontal & vertical) are transmitted

Acceptance is $d\Omega \approx 0.01$**strd= 10 mstrd**

at r=1m

dS#0.1m*0.1m=0.01 m^2

« Bρ » Acceptance



$$\begin{bmatrix} R_{11} & 0 & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & 0 & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & L/\gamma^2 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

The particles are dispersed by dipole magnets with $\delta = [B\rho - B\rho_0] / B\rho_0$

$X_{final} = R_{16}\,\delta$

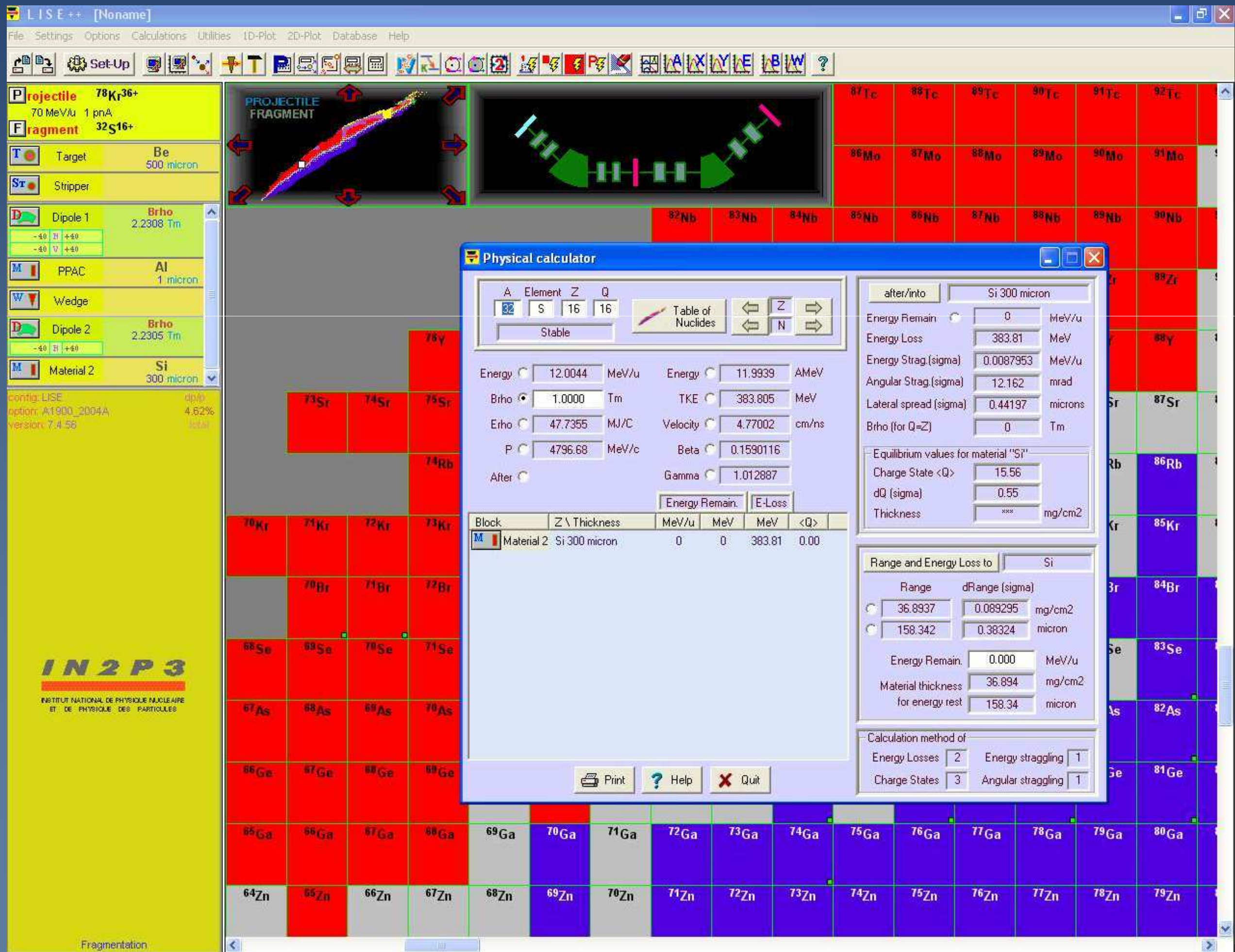
Beam pipe limit: Xmax

Bρ Acceptance = ± Xmax / R_{16}

Example : If R_{16}=5 cm/% and Xmax=10 cm

Bρ Acceptance= ± 2 %

How to simulate an experiment with a spectrometer



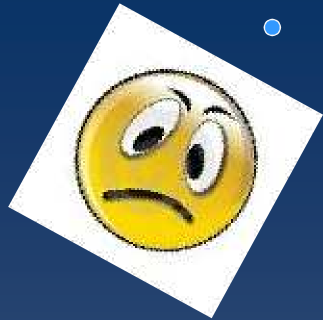
LISE++

code*

Tarasov et Al.

To be Downloaded

HOMEWORK :



Exercise 1: Imagine a spectrometer with a dispersion R_{16}=2 m (=2cm/%) and beam width σx =0.5 mm on the focal plan detector,

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

Exercise 2 :

A spectrometer (R16=1.5 cm/%) is tuned for $B\rho 0$=2.0 T.m

A particle arrives on the focal plane at Xf=3cm,

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

$$B\rho \overset{def}{=} \gamma \frac{mv}{q}$$

- Dynamics can be approximated with a matrix R

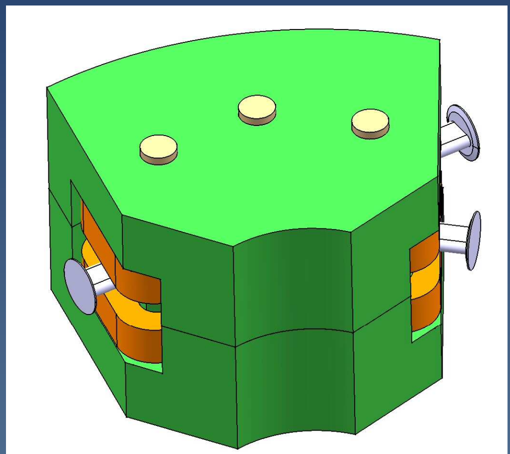
End part n°1

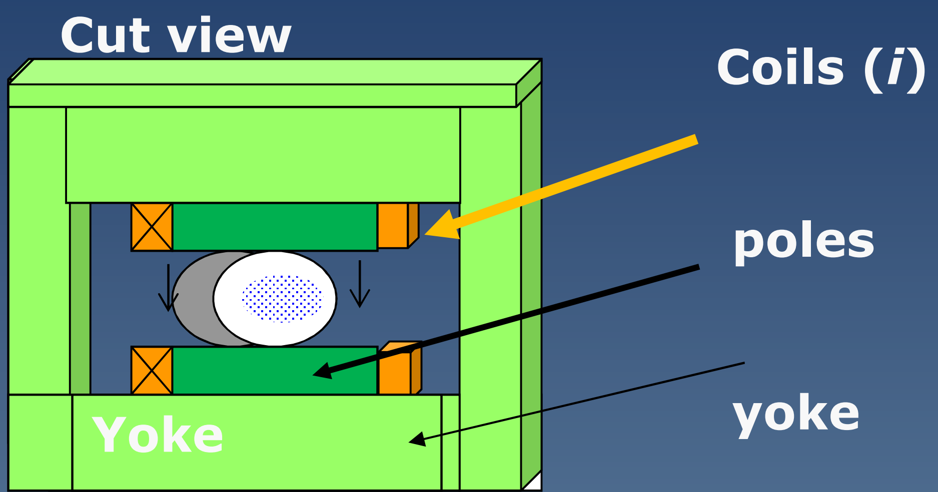
Part 2 : technical details and examples

- Resume of part 1
- Fragment separators (E>100 MeV/A)
- Recoil Spectrometers (E<10 MeV/A)
- Diagnostics and tuning

Part n°1 : Spectrometer components

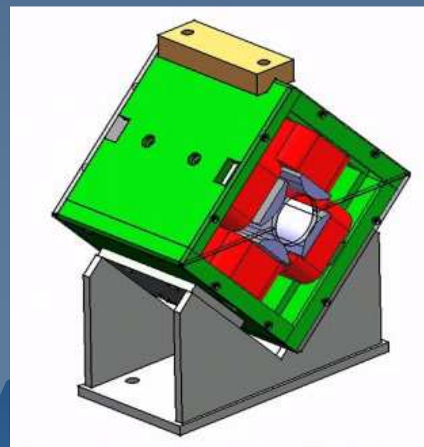
Magnetic Dipole : 2 poles : By= B0





Magnetic quadrupole : 4 poles

B*y*= G x



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, δ)***

$$\vec{Z} = \begin{pmatrix} z1 \\ z2 \\ z3 \\ z4 \\ z5 \\ z6 \end{pmatrix} = \begin{pmatrix} x \\ x' = \dfrac{dx}{ds} \\ y \\ y' = \dfrac{dx}{ds} \\ l = \mathrm{v}_0 (T - T_0) \\ \delta = \dfrac{B\rho - B\rho_0}{B\rho_0} \end{pmatrix} = \begin{pmatrix} \text{horizontal displacement} \\ \text{horizontal "angle"} \\ \text{vertical displacement} \\ \text{vertical angle} \\ \text{longitudinal difference} \\ \text{"momentun}(B\rho)\text{" deviation} \end{pmatrix}$$

HORIZONTAL ANGLE

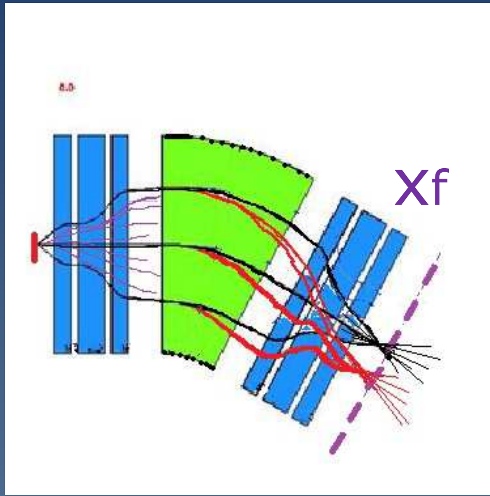
$X' = dX/ds = \tan(\theta) \approx \theta$

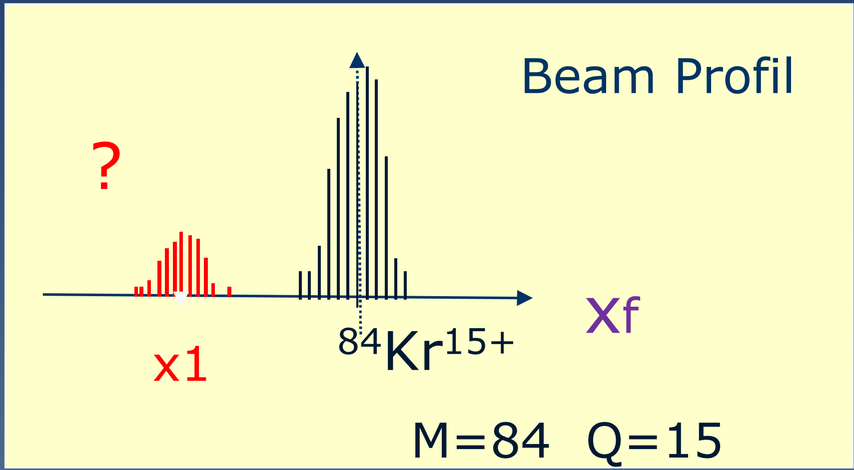
B.Jacquot// Ganil

Magnetic Spectrometer :

A tool for identification

Suppose 2 ions beams





-Field measurement B $B\rho o = Bdipole*Rdipole$

-Position measurement (Xf =X1)

$\delta = (B\rho 1 - B\rho_o) / B\rho_o = X1 / R16$ $B\rho 1 = B\rho o \ (1 + X1/R16)$

If same velocity v $M1/Q1 \approx Mo/Qo \ (1 + X1 / R_{16})$

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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)

$$\begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix}_1 = \begin{bmatrix} R_{11} & 0 & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & 0 & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ - & - & 0 & 0 & 1 & L/\gamma^2 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix}_0$$

$$l = \mathrm{v}_0 (t - t_0)$$

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

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

$$x^F \approx \sum_{j=1\ldots6} R_{1j} Z_i^0 = R_{11}.x_0 + R_{12}.x'_0 + R_{13}.y_0 + R_{14}.y_0' + R_{15}.l^0 + R_{16}.\delta^0$$

Fragment Separators : 100-500 MeV/A

Reaction : in-flight fragmentation
(0° degree)

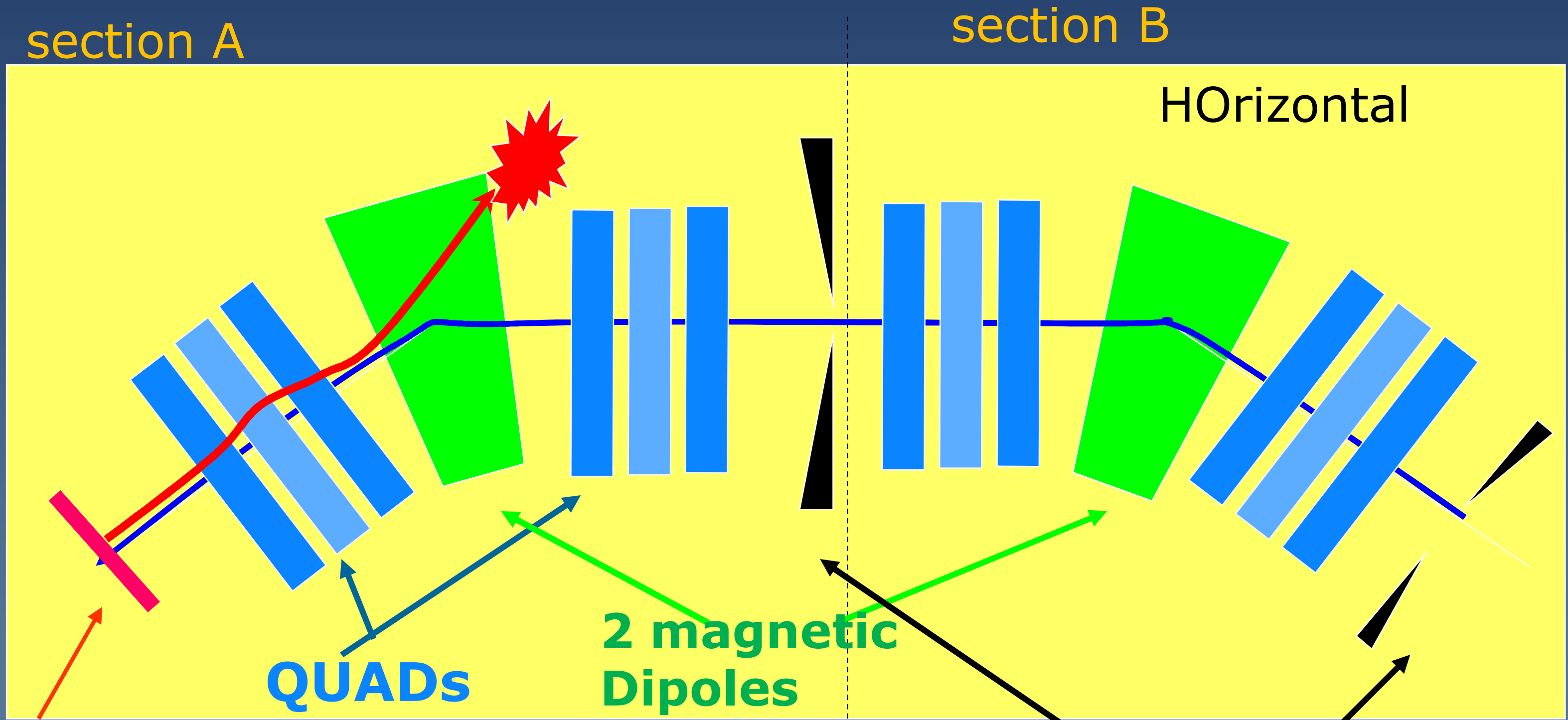
Goal :
1) Primary beam suppression (Separator)
2) Identification of particles
3) purification (selection of some reaction products)

Fragment separator

2 symmetric sections :

« ACHROMATIC » MAGNETIC SPECTROMETER

From the top



Rotative Target

(high intensity primary beam)

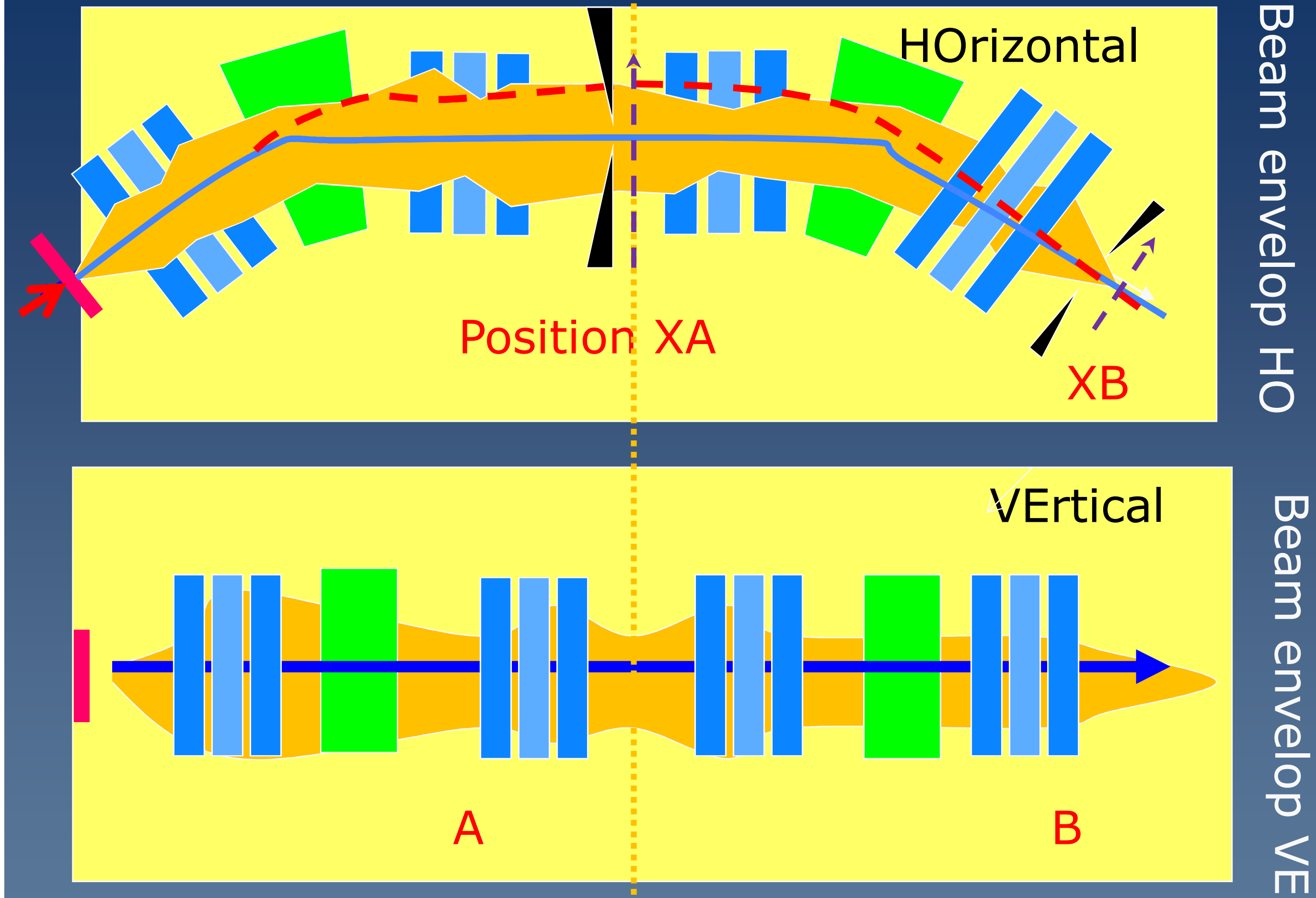
Nuclear fragmentation reaction

Selection slit

Total Transport matrix R

$$R = R_B \cdot R_A$$

Fragment separator : principle



Ion trajectory

$X_A = F(B\rho)$

$X_B \sim 0$

« Achromatic »

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

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

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

A: 1rst **section**

Bρ selection

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

B: 2nd **section**

Bρ compensation

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

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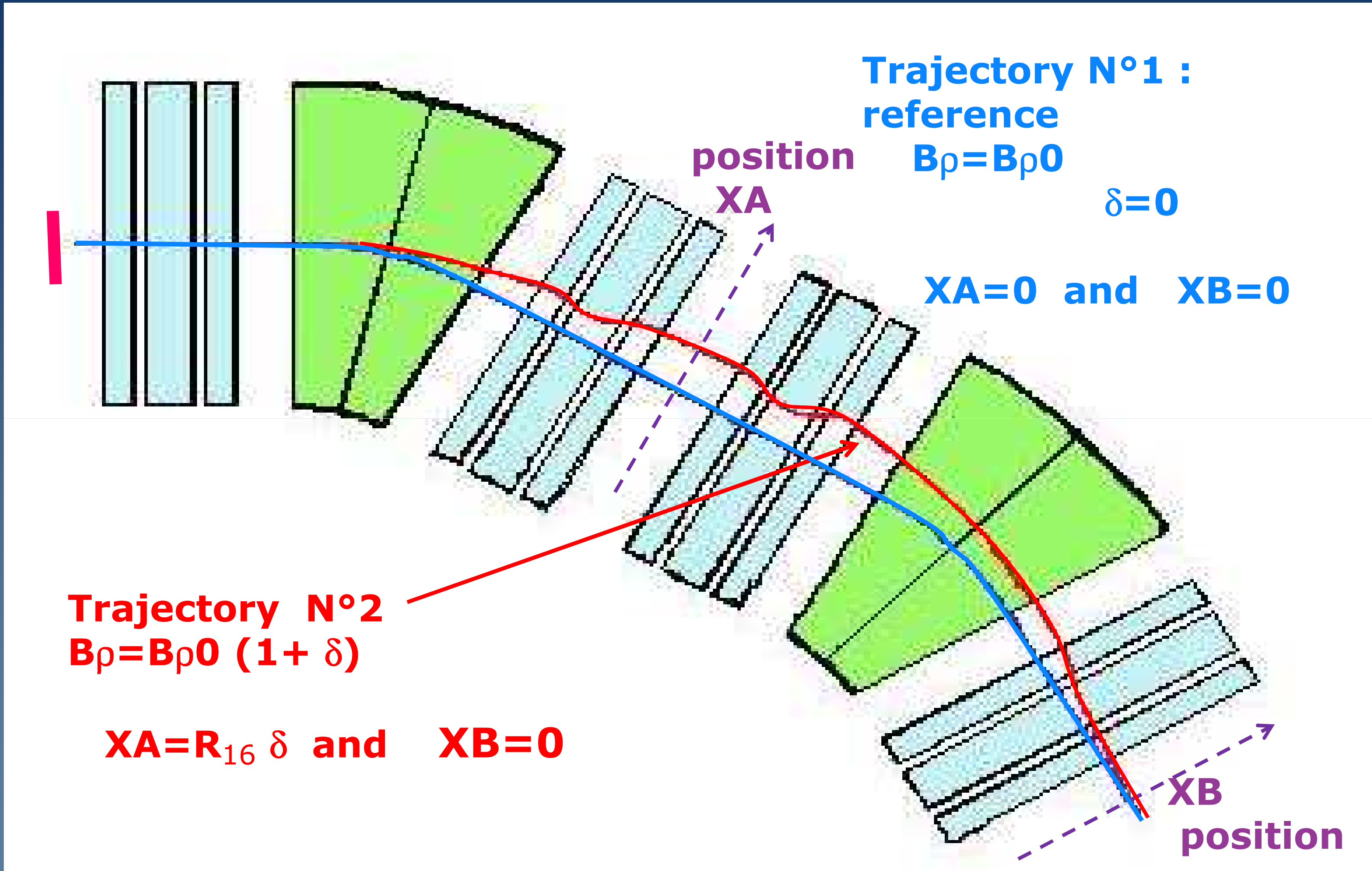
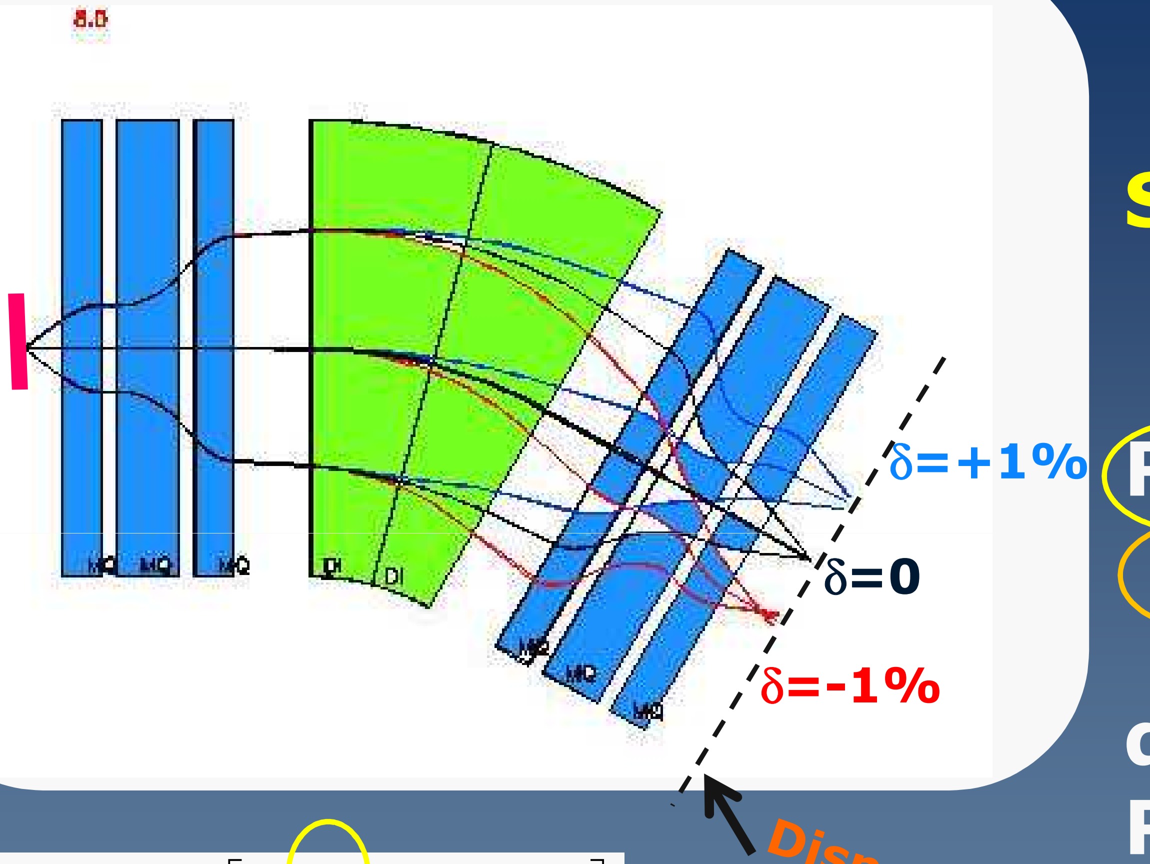
2 Trajectories in a Fragments separator



Fragments separators : dispersiv section optics



Section A :

Focusing

$R_{12}=0$ (Horizontal)

$R_{34}=0$ (Vertical)

dispersion

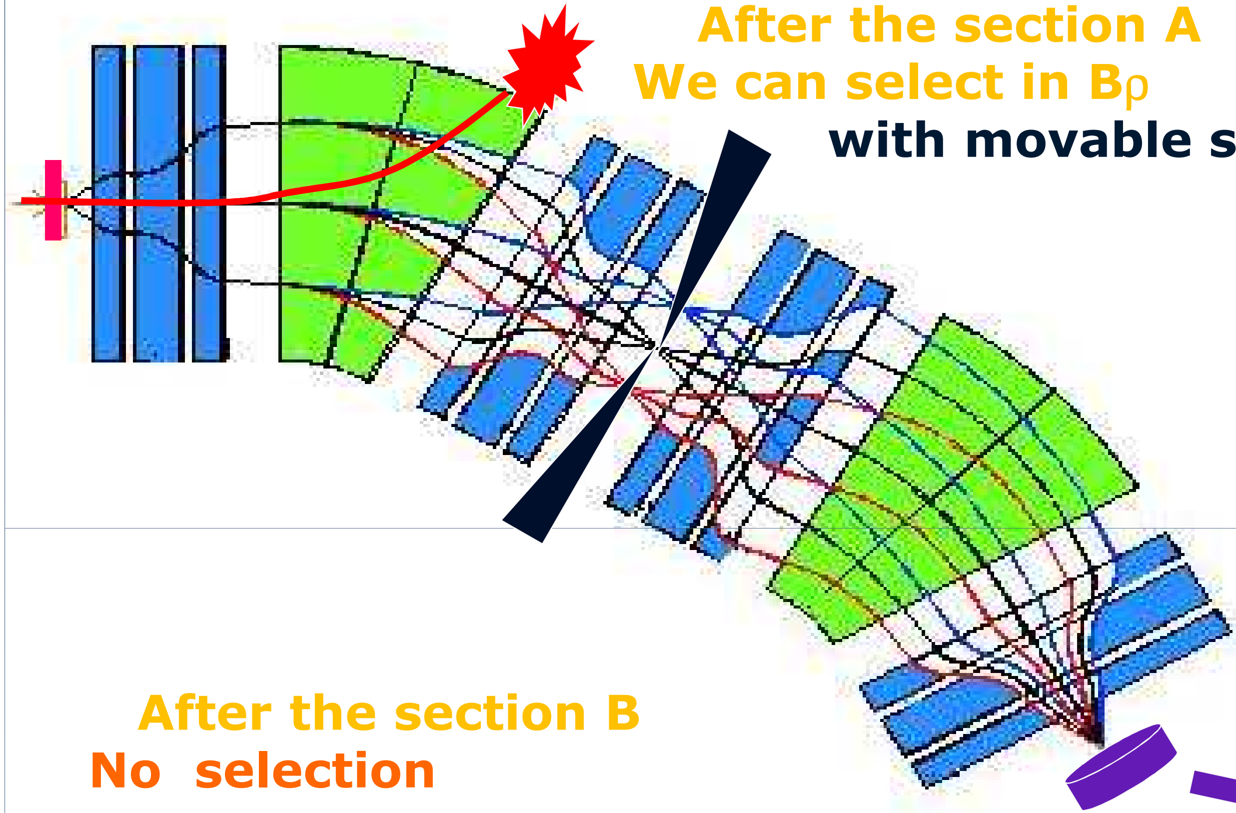
$R_{16}(A) \neq 0$

$$Rmatrix(A) = \begin{bmatrix} R_{11} & 0 & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & 0 & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & L/\gamma^2 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

$\delta = (B\rho - B\rho_o) / B\rho_o$

$B\rho_o = Bdipole . Rdipole$

1 Selection in Fragments separators is not sufficient



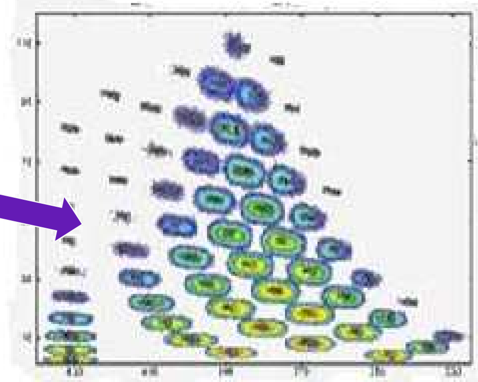
After the section A
We can select in Bρ
with movable slit

After the section B
No selection

Bρ Selection
Is not
good enough

Bρ selection

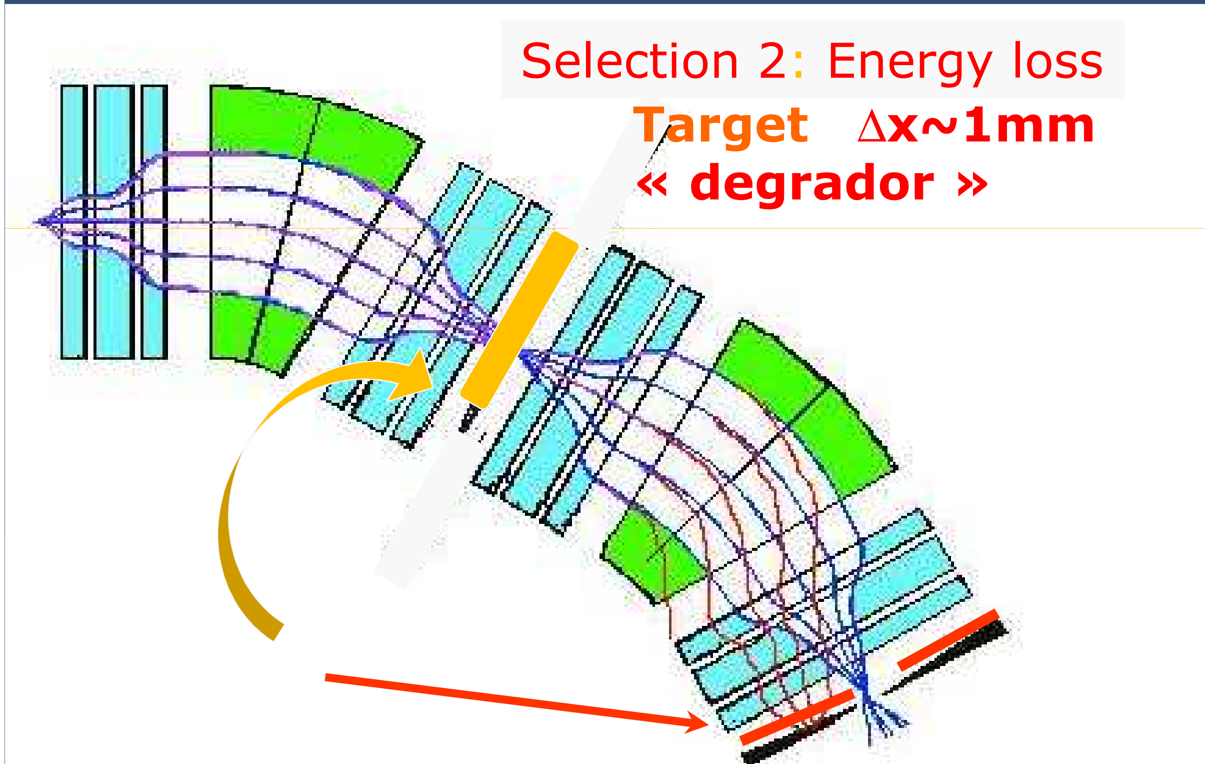
identification



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

Magnetic separator with degrador increase the purification (Z dependance)

We consider 2 isobares (A=34,Z=14) (A=34,Z=15) with same Bρ



Bρ selection is independant from Z

Bρ= γM v /Q

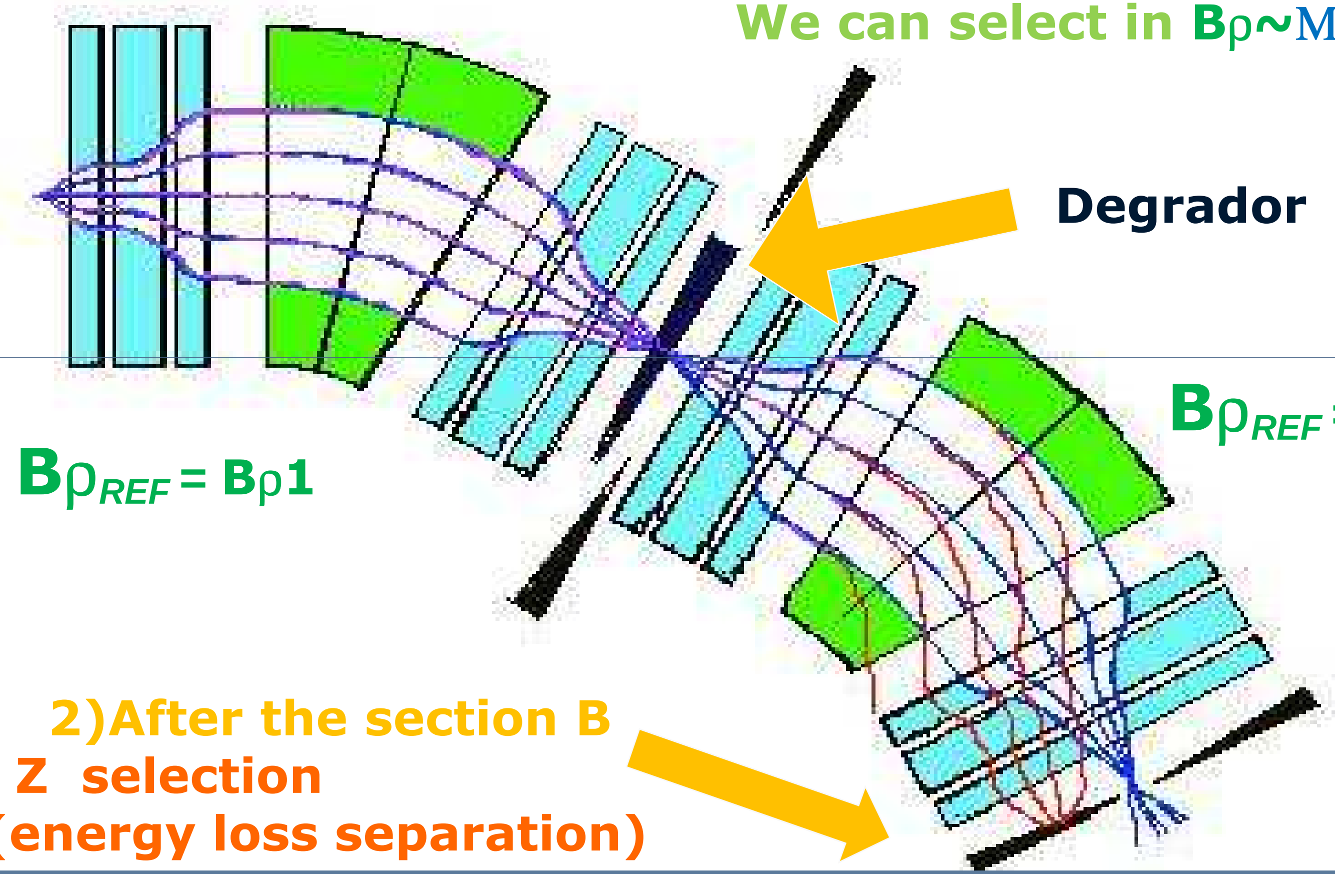
in a target Energy loss is

« Z dependant »

Bethe-Bloch formula

$\Delta E = k\, Z^2/A * \Delta x$

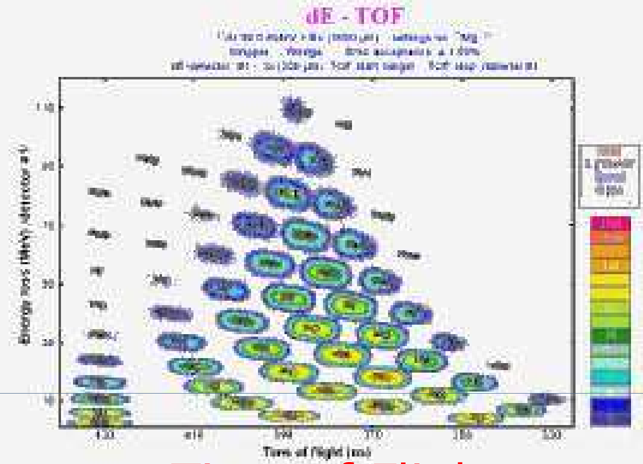
2 Selections in Fragments separators
Bρ + Z (degrador)



Selection in Fragments separators & identification

Bρ selection

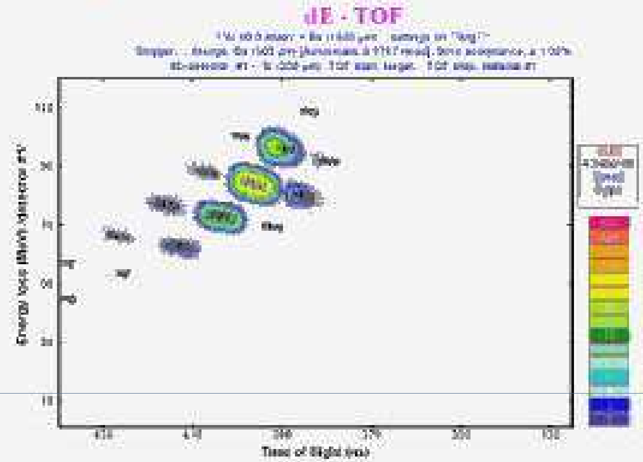
ΔE
~Z



Time of Flight~M/Q

Bρ +degrador selection

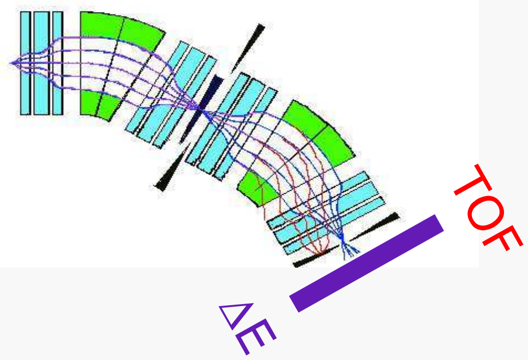
ΔE



Time of Flight

Detector :

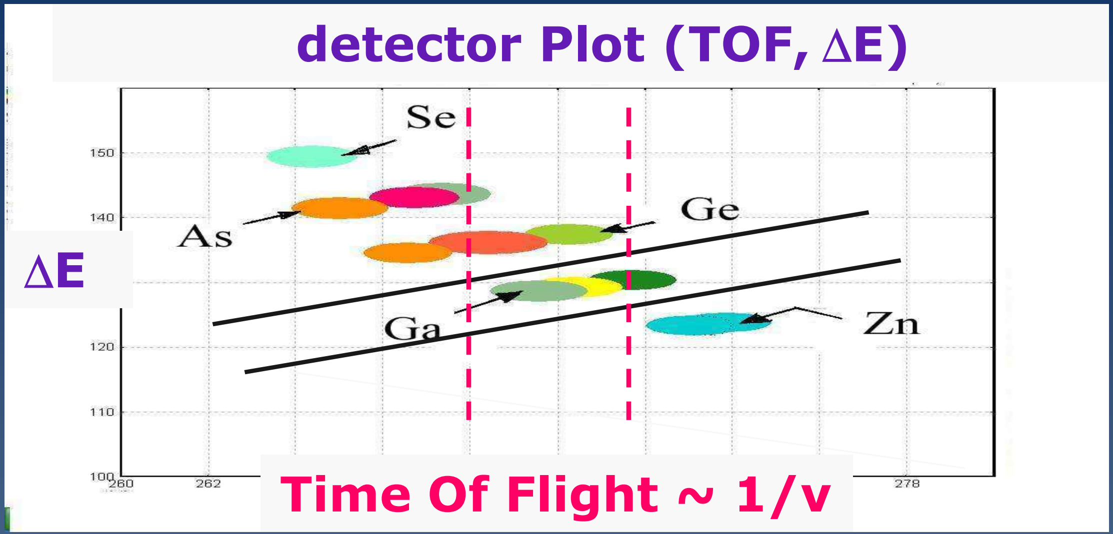
Thin Silicone



**2 selections
Is much**

**better for
purety**

Often, Isotopes are not well identified (ΔE,TOF)



Isotopes

are mixed in TOF

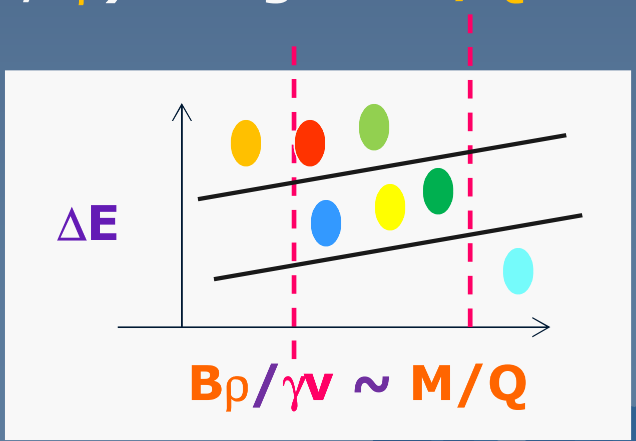
Large velocity distribution Δv

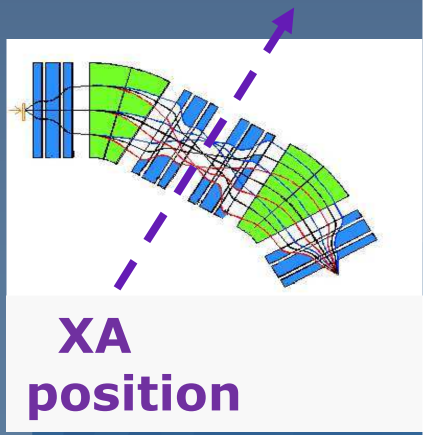
Solution : Measure XA for each ion : $B\rho = B\rho 0\ (1 + XA/R16)$

The two measurements (TOF,Bρ) => give M/Q

$v = ToF/L$

$M/Q = B\rho\ /(\ v\ .\gamma)$





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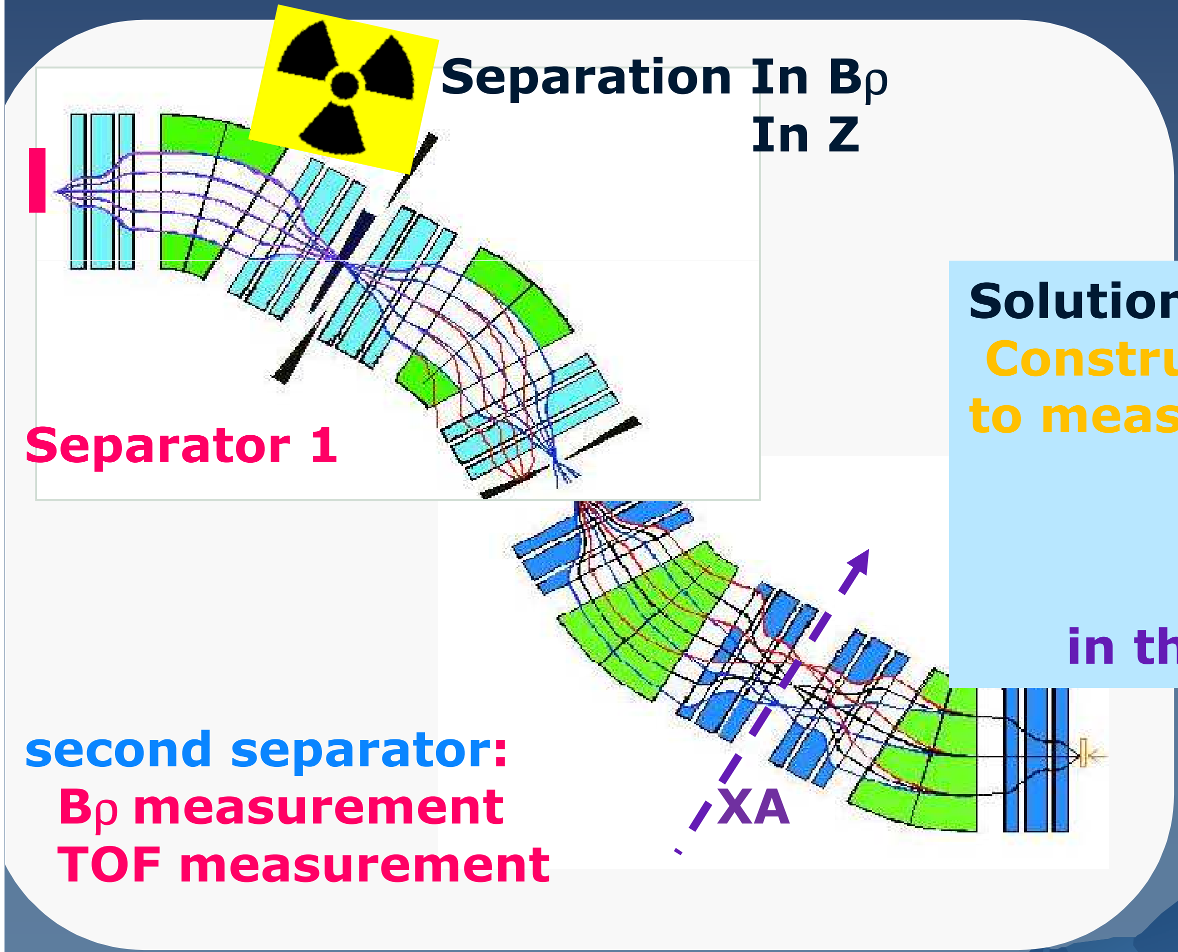
Isotopes are not well identified with (ΔE,ToF)

Install a Detector position for XA : Bρ=Bρ0 (1+XA/R16)

NOT POSSIBLE

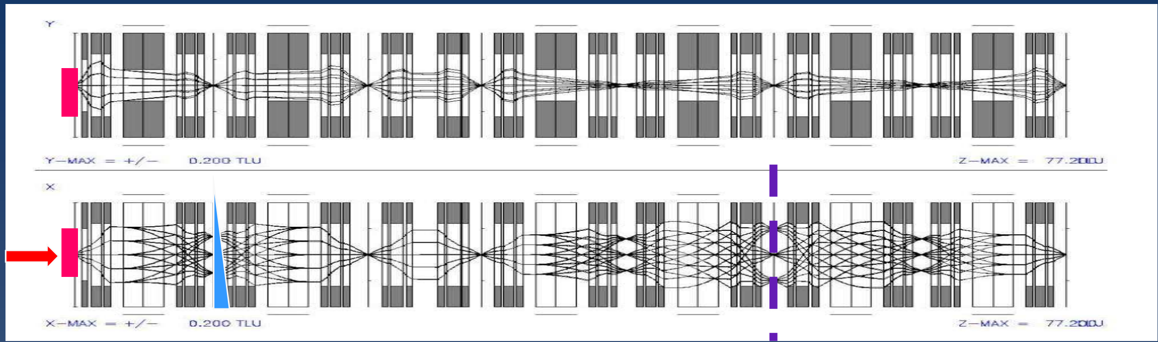
(too much intensity before Z selection)



Solution choosen in BigRIPS :
Construct an additiv spectrometer to measure Bρ (€ !!)

Install the position Detector in the second separator

1 example :BIG RIPS (Riken)



Specifications

L=77m

$B\rho_{max}$ = 7 Tm

$\Delta p/p = \pm 3\%$

$\Delta\theta = \Delta x' = \pm$ 50mrad

$\Delta\varphi = \Delta y' = \pm$ 60mrad

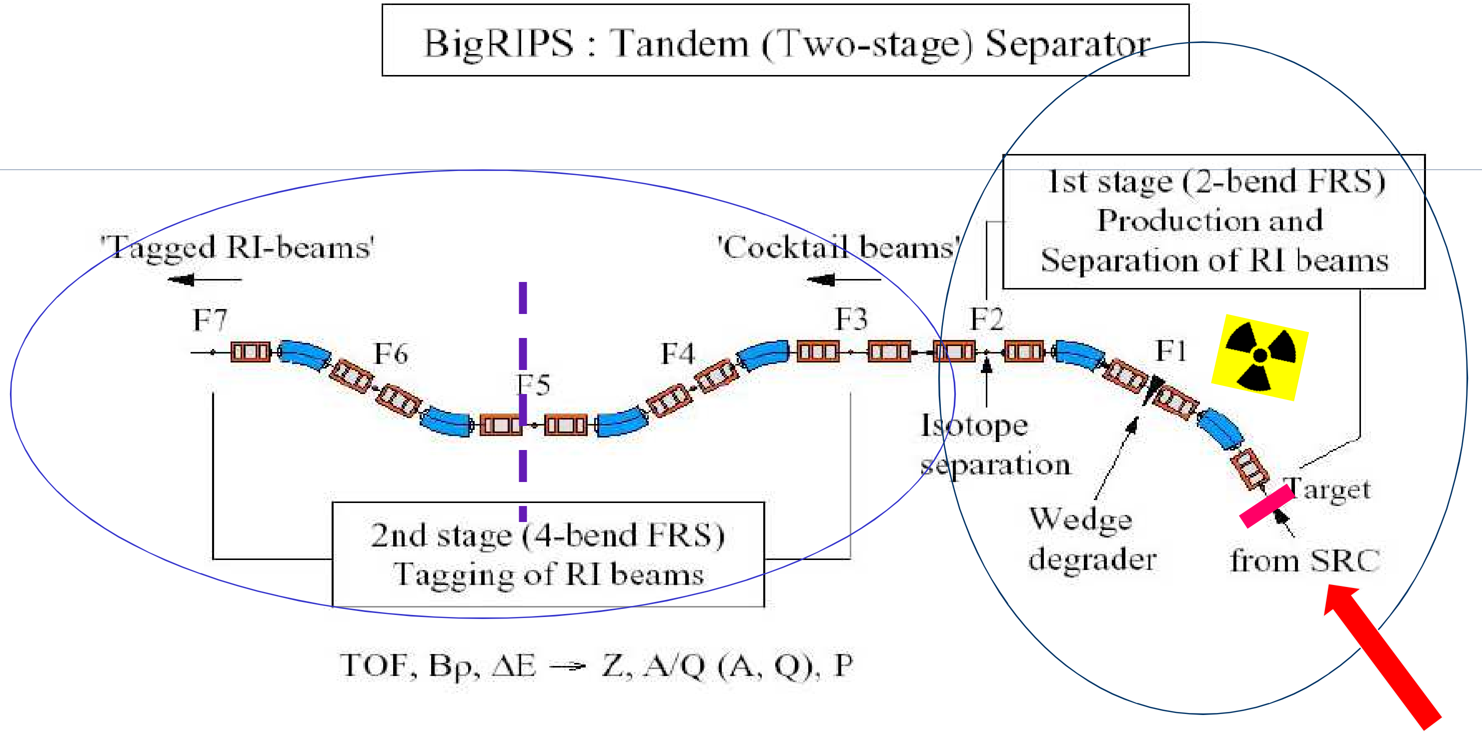


Fig. 2. A schematic diagram of the RI-beam tagging in the BigRIPS separator.

BIG RIPS (Riken) quads

Beam very rigid : **$B\rho = \gamma m V/Q$ = 7 T.m** **(Beam 300MeV/A)**

with high v !

Super-ferric quadrupole triplet :

Very strong focusing : supraconducting coils (NbTi), with pole (Fe)

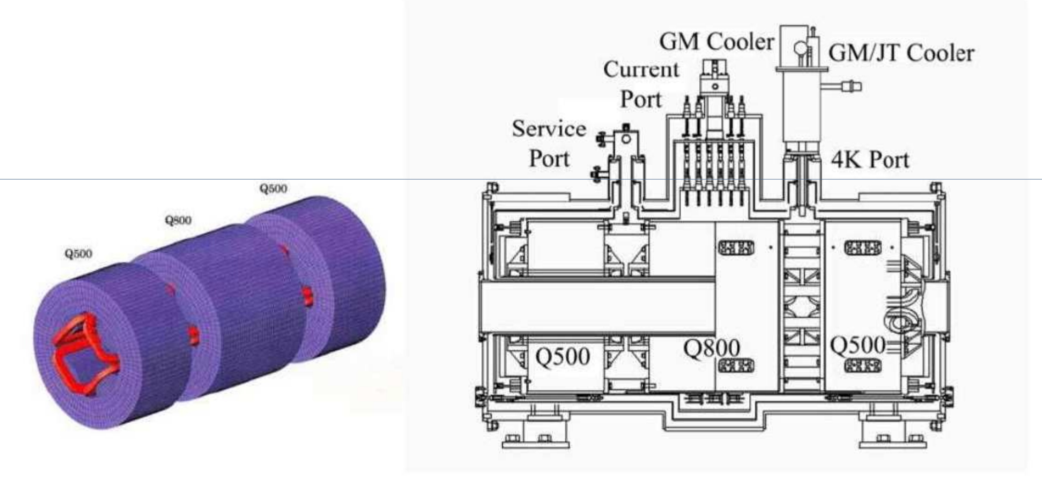


Figure 22: Schematic view of the RIKEN prototype quadrupole triplet (left side) and its installation into the cryostat (right side) [24].

- 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

Comparaison of the fragment separators

	Lise3 Ganil	FRS GSI Mode1 or mode2	A1900 MSU //NSCL	BigRips Riken
Angular Acceptance **Bρ Acceptance**	**1.6 mstrd** **±2.5%**	**0.32mstrd or 3.4 mstrd** **± 2.0%**	**8mstrd ±40* ±50mrad** **± 3.0%**	**10 mstrd ±50* ± 60mrad** **± 3.0%**
R16 (m=cm/%) **Bρ Resolution** Length	**1.7 m** **1/600** **42 m**	**6.8m** **1/1600 or1/160** **69m**	**5.95m** **1/2900** **35m**	**3.3 m** **1/3300** **77 m**
Bρmax	**4.3T.m //3.2T.m**	**18T.m or 8.6T.m**	**6.3 T.m**	**9. T.m**
Comments	2 Dipôles + Wien filter	4 dipoles	4 dipoles	1 pre-separator (2 dipoles) + 1 separator (4 dipoles)

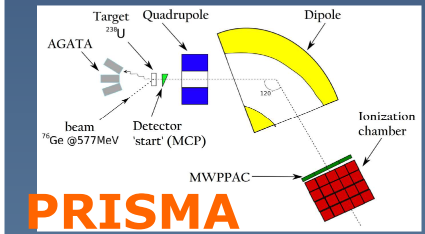
B.Jacquot// Ganil

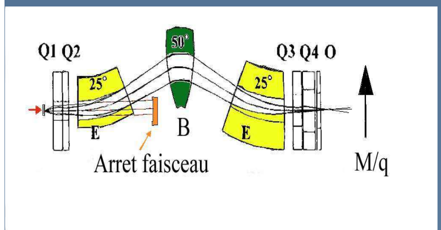
« Recoil » spectrometer : at low energy (1-10MeV/A)

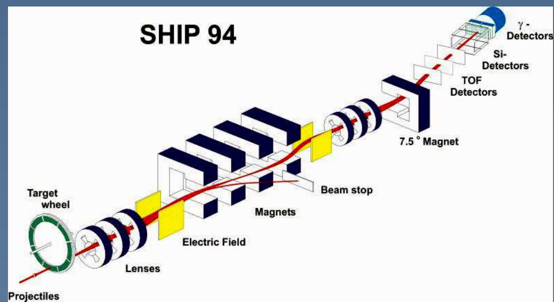
Reactions : fusion-evaporation, transfer,..

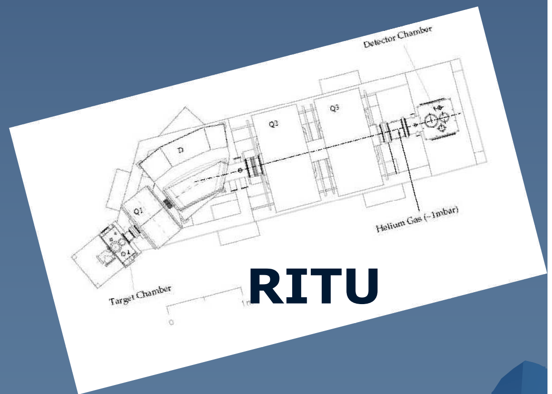
Goals :

1) Very efficient primary beam suppression
2) Help identification









Many experimental problems => A Large variety of devices

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)

1-5MeV/A Fusion evaporation

super-heavy production)

* Large Acceptance & Ray tracing Spectrometer

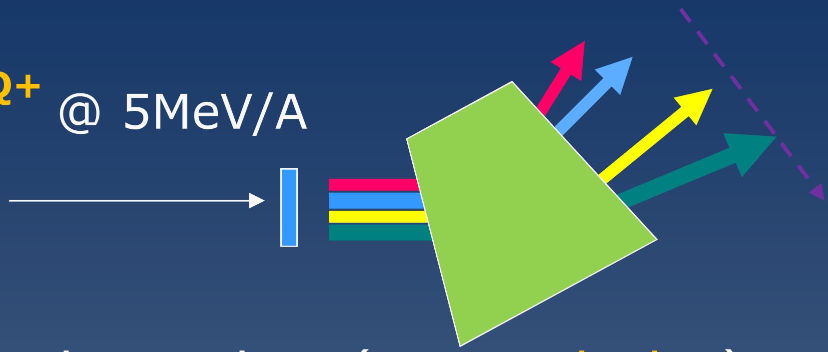
Ganil (VAMOS) , Legnaro (Prisma), NSCL (S800)

(transfer reactions, fission,..)

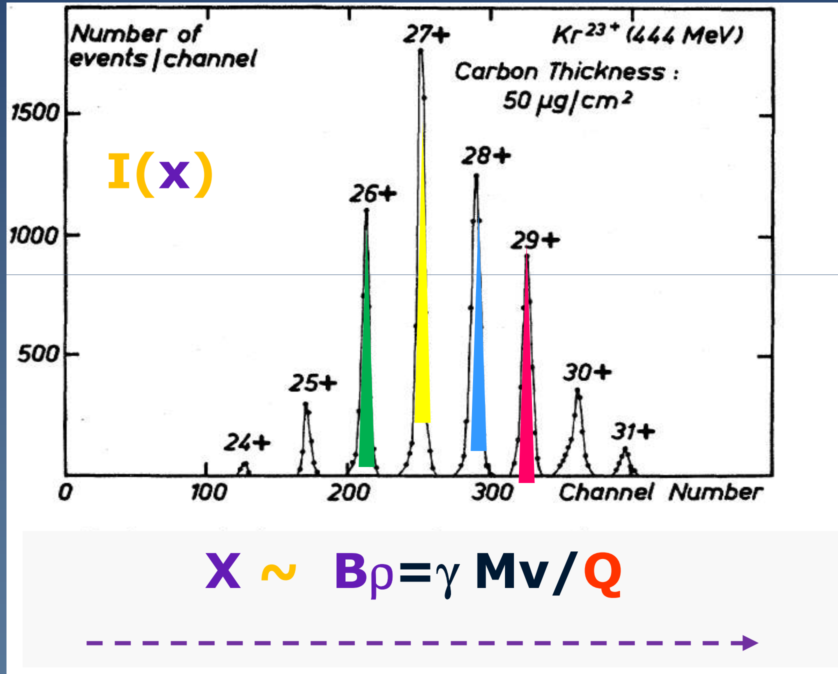
….

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

$^{A}X^{Q+}$ @ 5MeV/A



Stripping Probability



Atomic reactions (xray ,stripping)

#1mg/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

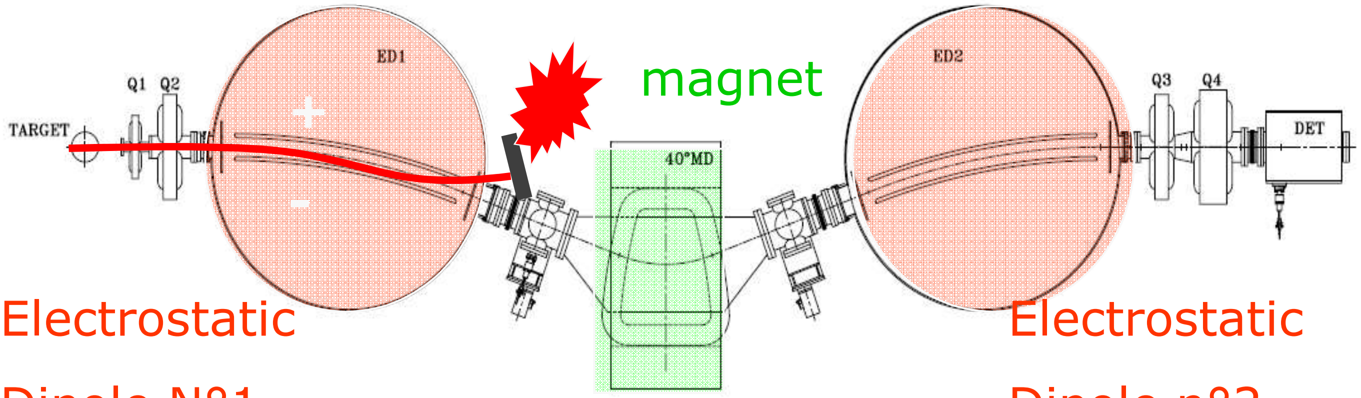
(Bρ is not a perfect for selection)

B.Jacquot// Ganil

Recoil Mass Separator

Emma @Triumf

E# [1-3MeV/A] Length=12 m



Electrostatic Dipole N°1

Electrostatic Dipole n°2

Magnetic selection = $B\rho = \gamma Mv/Q$

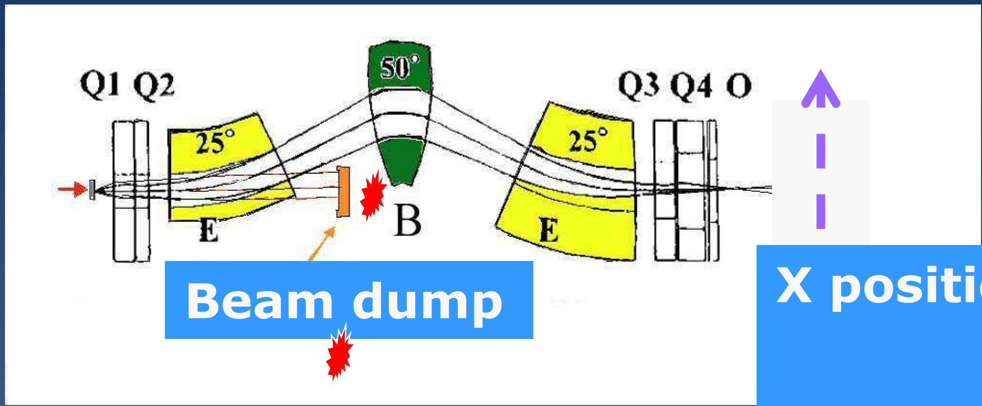
Electrostatic selection = $E\rho = \gamma Mv^2/Q$

« 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

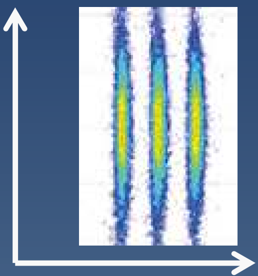
Electrostatic devices are efficient (but sparking)

RMS (Recoil « Mass » Spectrometer) : beam optics , M/Q dependance



X position~ M/Q

Electrostatic selection compensates Magnetic selection



M/Q=f(x)

With E + B selection :

Achromatic Selection X=f(M/Q, velocity)

Resolution : $R_{M/Q}=1/300$

Resolution $=4\ \sigma x_{final}/R_{17}$

« R_{17} » is the « M/Q dispersion »

$$\vec{Z} = \begin{pmatrix} z1 \\ z2 \\ z3 \\ z4 \\ z5 \\ z6 \\ z7 \end{pmatrix} = \begin{pmatrix} x \\ x' = \frac{dx}{ds} \\ y \\ y' = \frac{dx}{ds} \\ l = v_0(T - T_0) \\ \delta = \frac{B\rho - B\rho_0}{B\rho_0} \\ \delta_m = \frac{M/Q - M_0/Q_0}{M_0/Q_0} \end{pmatrix} = \begin{pmatrix} \text{horizontal displacement} \\ \text{horizontal "angle"} \\ \text{vertical displacement} \\ \text{vertical angle} \\ \text{longitudinal difference} \\ \text{"}(B\rho)\text{" deviation} \\ \text{"mass}(M/Q)\text{" deviation} \end{pmatrix}$$

B.Jacquot// Ganil

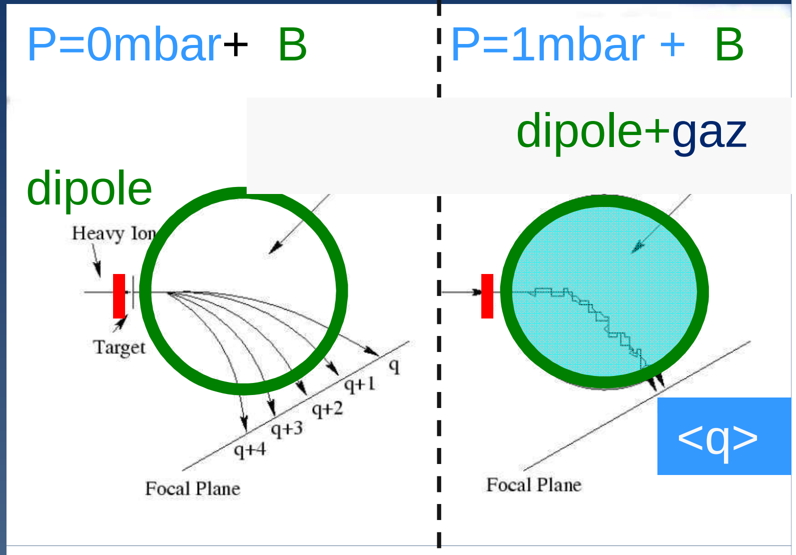
Gas filled separator for heavy ion

At low energy : too Many charge states

Beam charge are spilled over the focal plan

$$< q >_{gas} \propto \ v\, Z^{1/3}$$

$$< B\rho >= \frac{m}{< q >} v \ \propto m\, Z^{-1/3}$$

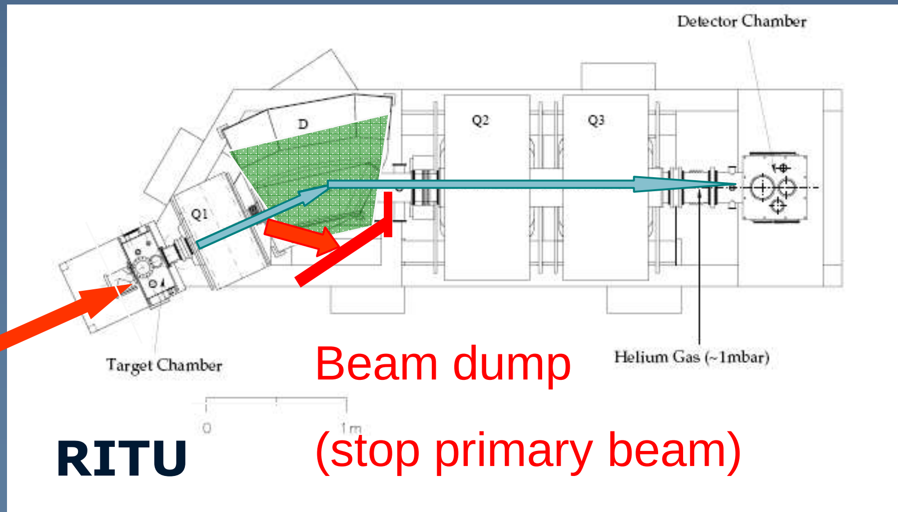


In the gaz, the collisionS make the charge

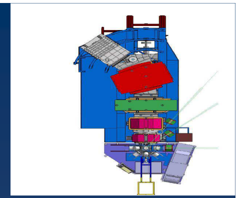
State oscillating around an average <q>

« Charge focusing »+ selection Mass

= good rejection



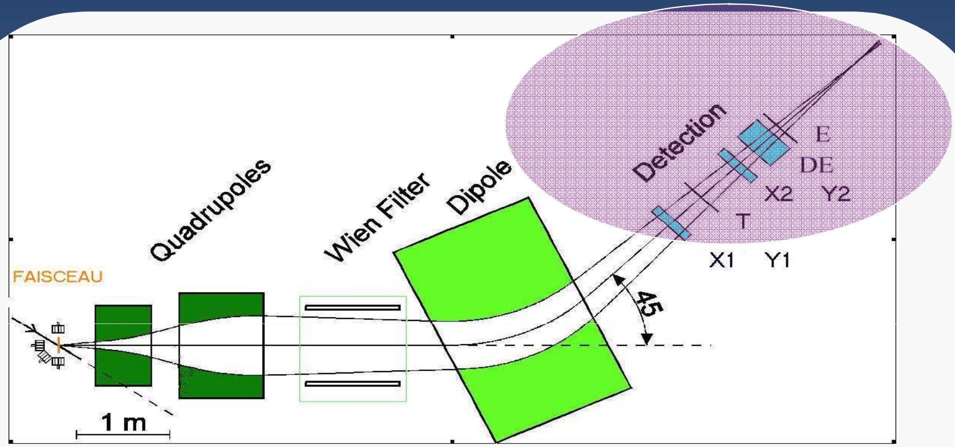
Large acceptance spectro

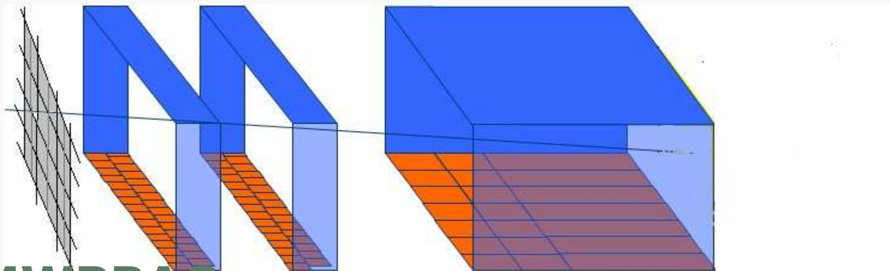


Optics is *non-linear* in x,x',y,y'

(Aberrations come with large angle x',y')

$$B\rho = B\rho_0\,(1 + x/R_{16} + a\,x'^2 + b\,x^2 + c\,x^3 + \ldots)$$





MWPPAC (Tof)

Drift Ch. (X,X',Y,Y').

Ionis. Ch. (ΔE,E)

Vamos example :

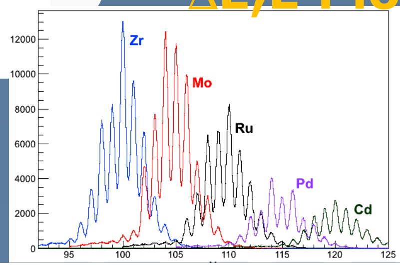
In the focal plane, 7 quantities are measured :
T, x1, y1, x2, y2, ΔE, E

T : Multi Wire PPAC

x1,y1
x2,y2 :

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

ΔE,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 ($\overline{x}$, σx, σT,<I>…

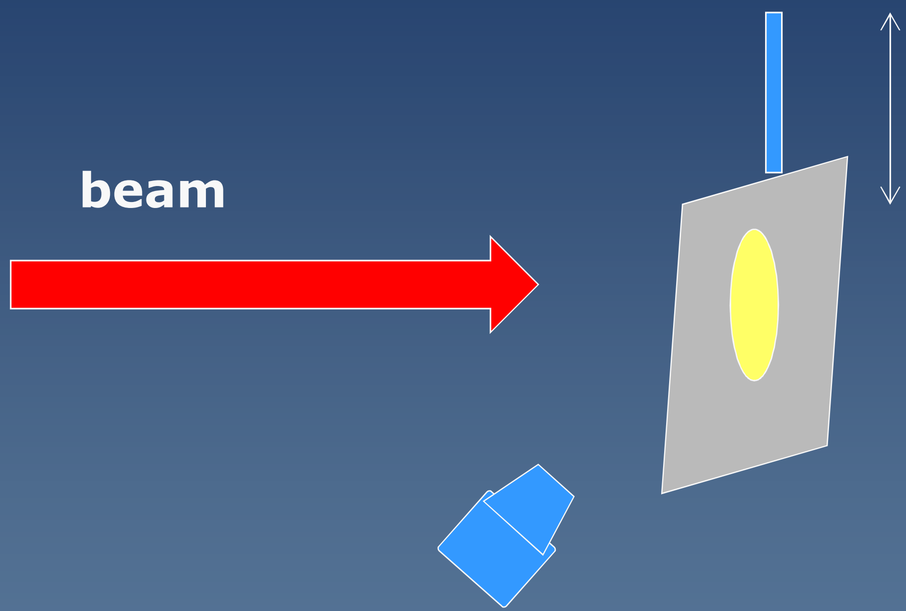
1rst step : check the primary beam

- profil measurement (alignement, focus)
- intensity check

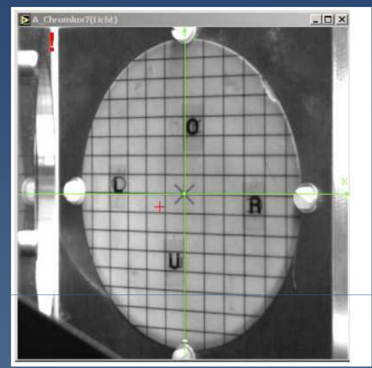
SPECTROMETER TUNING

Beam diagnostics : scintillator screen

beam

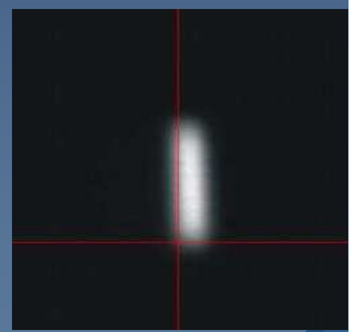


movement



beam spot

Scintillation screen ($Y_2Al_5O_{12}$,...



CCD Camera

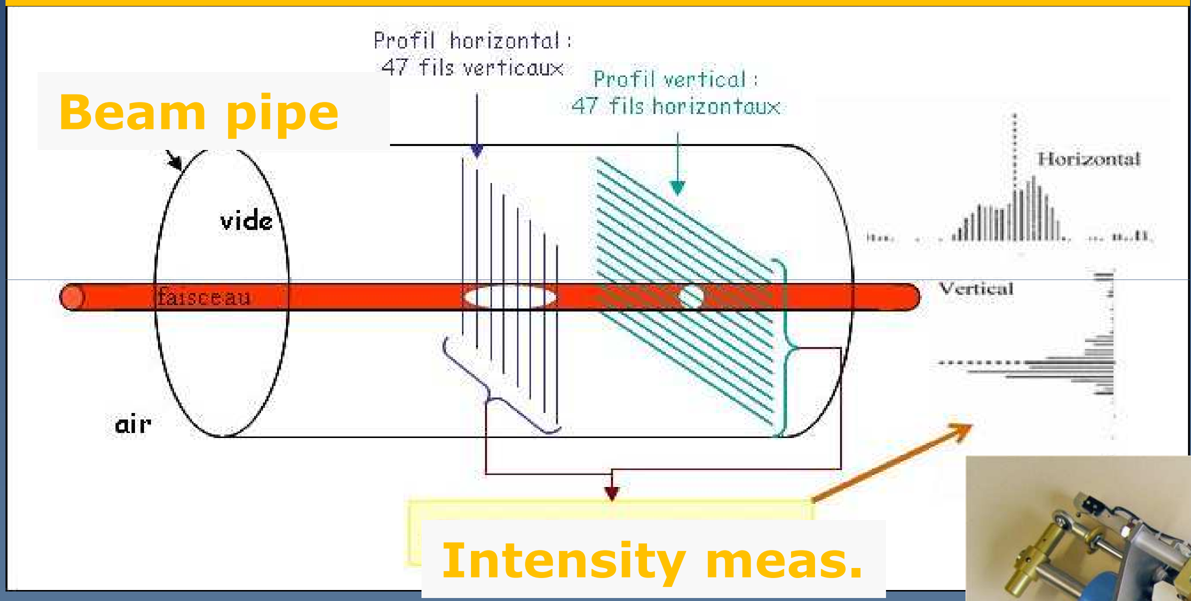
Relatively low cost , but
- **only 1 profil measurement**
- **not very precise**

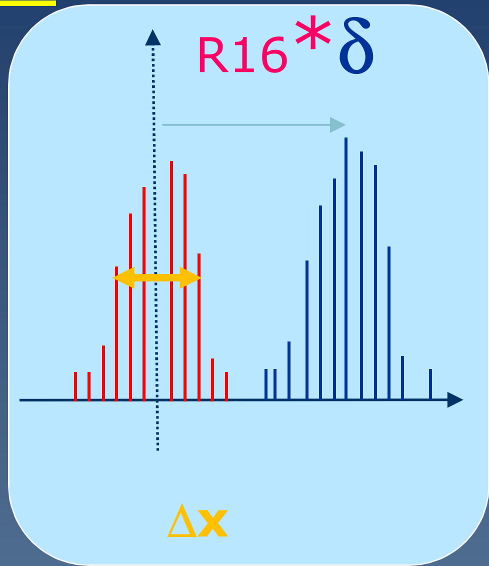
SPECTROMETER TUNING

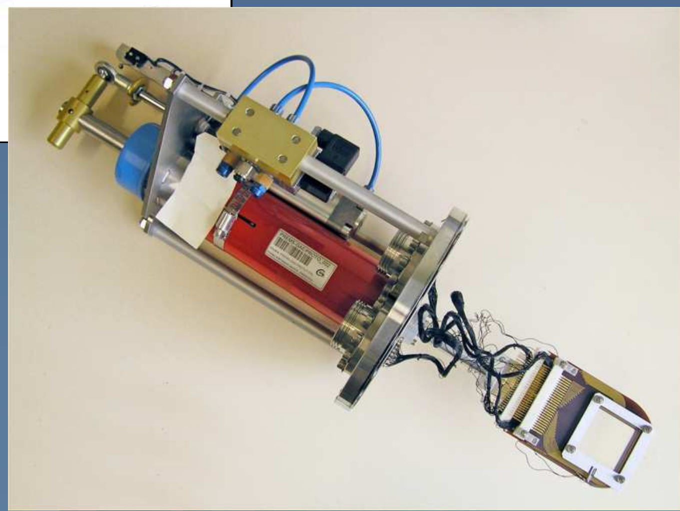
Beam diagnostics : **profil monitor**

Reconstruct the beam intensity in X and Y

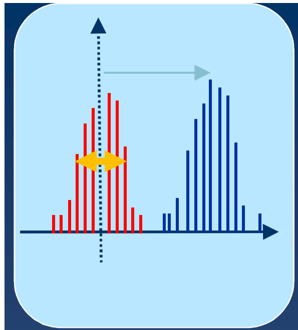
Profil monitor : HORIZ. and VERT. wire







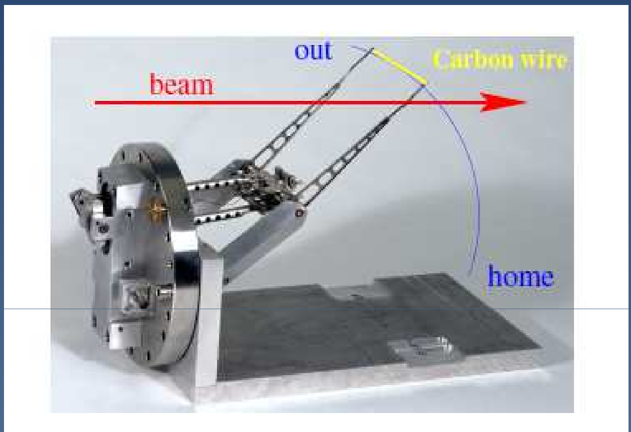
Usefull for beam alignement
focusing check
R*16* measurement



SPECTROMETER TUNING

Many Profil monitors

for different beam intensities



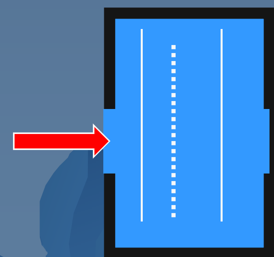
Rotating wire
ibeam# 10^{12-14}pps
(Cern)

Wires
i# 10^{9-11}pps

(Ganil)

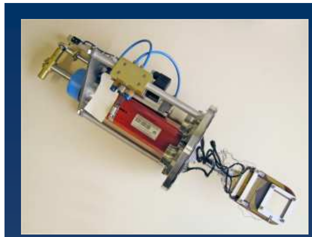
« Gas Profil »
i# 10^{3-7} pps

Gas ArC0$_2$ **+HV**



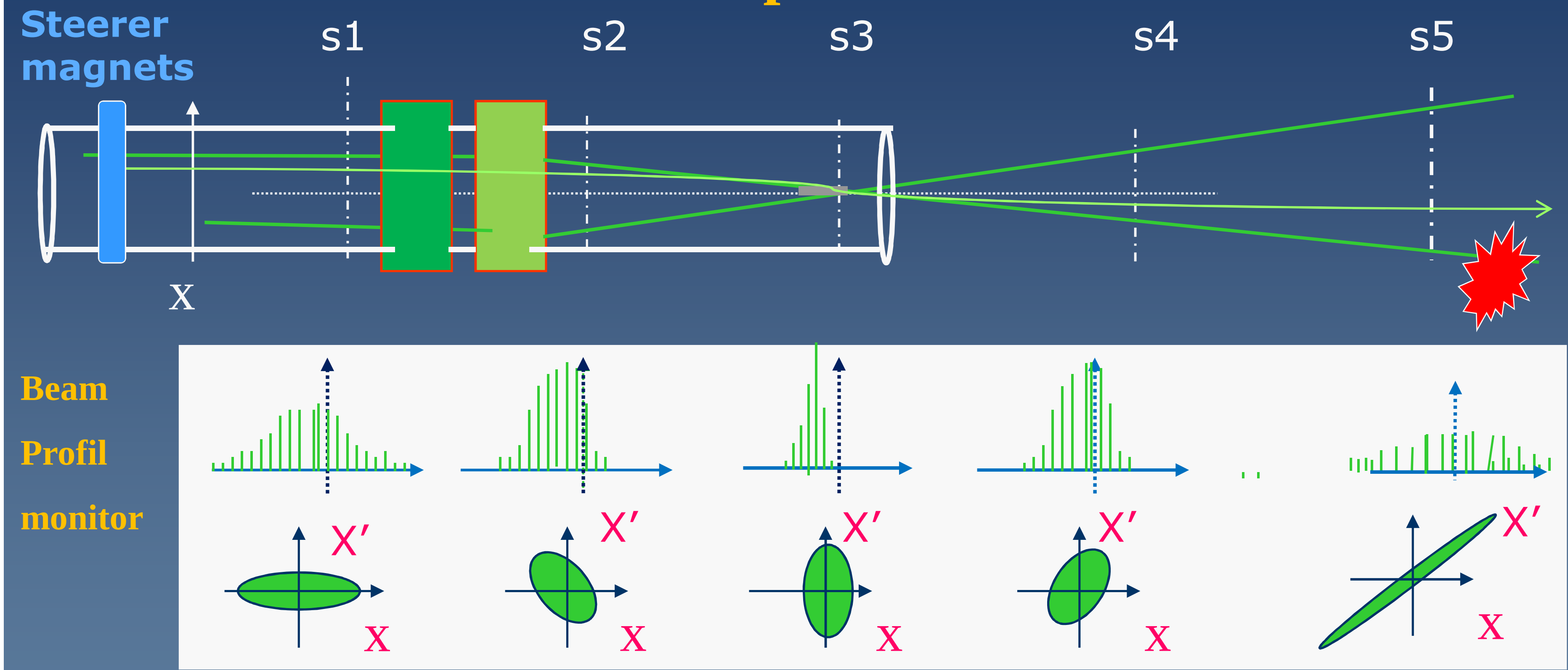
Proportional counter

Specific technologies
adapted for ≠(intensities, Energies)



TUNING

Checking size and alignement with profil monitor



ellipsoid area = $\pi\ \Delta x\ .\ \Delta x'$ = Emittance

Emittance = constant if Energy=constant

B.Jacquot// Ganil

SPECTROMETER TUNING : check the intensity

Beam diagnostics : **Faraday cup**

Intensity measurement

Particle per second **Npps = IA/Qe**

$= I\mu A\ 10^6/[Q\ 1.6\ 10^{-19}]$

SPECTROMETER TUNING

Adjusting field in dipoles and quadrupoles

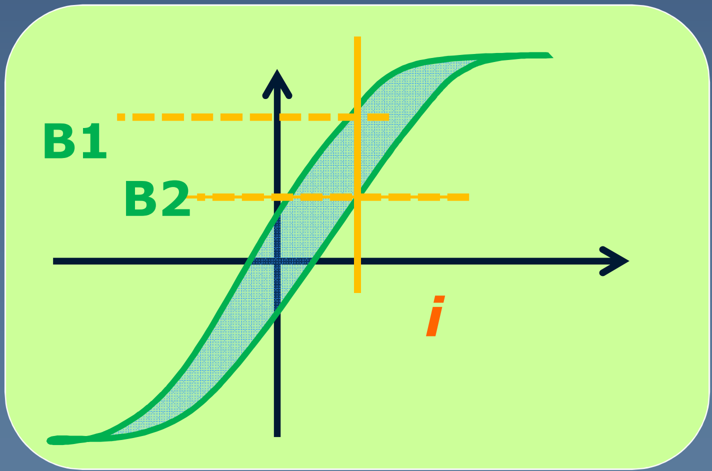
For adjusting dipole field (B) or quad Gradient (G)
adjust *i* in the coils

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



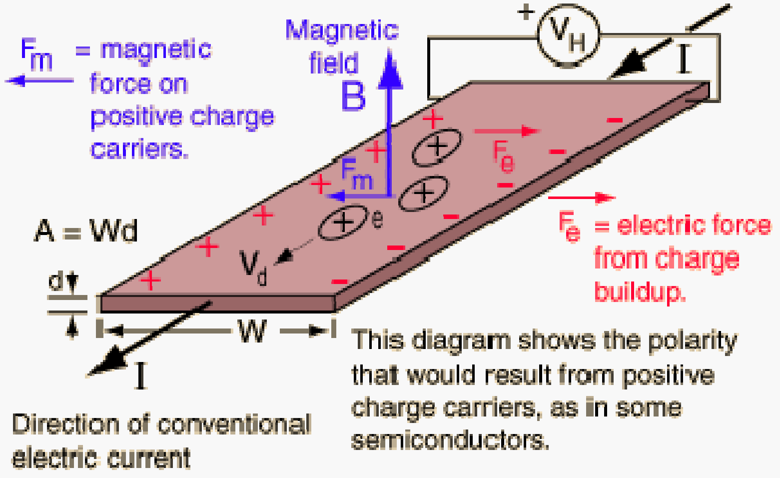
but for one i ,
2 possibilities
B1 and B2

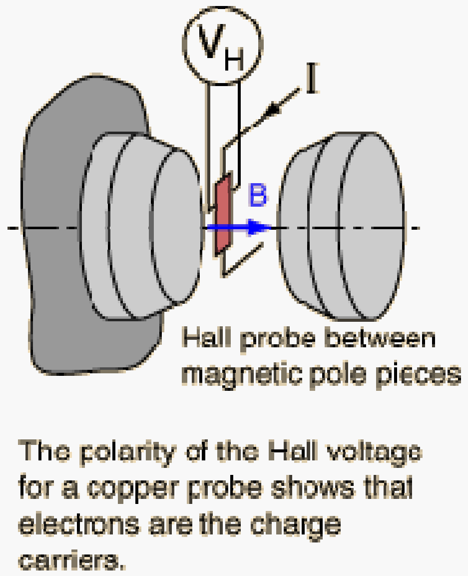
Solutions

- **Raise the current to imax, then get down & adjust i : for reproducibility**
- **Measure B with Hall probe or NMR probes (dipole)**

SPECTROMETER TUNING

Hall Probes : measuring field in dipole





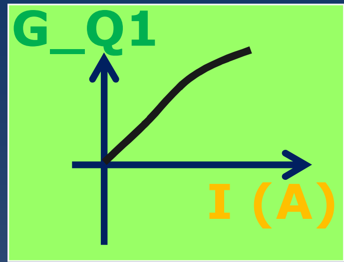
Hyperphysics (gsu)

LOW COST , But not very precise

NMR probes are more precise (Resolution=10^{-5})

Spectrometer tuning : before experiments

Quad Gradient : By=G($i$coil) . X



G_Q1(i*coil*) given by constructor

B_dipole(i*coil*) measured on test bench

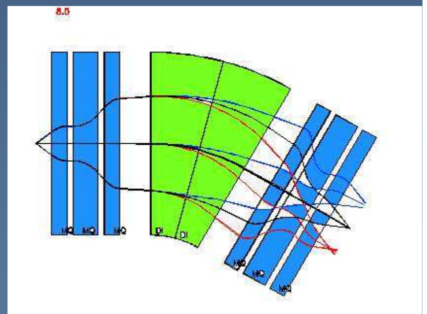
Rdipole has to be known (curvature of the ideal trajectory $R_{dipole}=L/\theta$)

Beam optics (Design step)

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

Compute G_Q1 ,G_Q2... For Bρref=1 Tm (simulation)

to get the right focus on the detectors

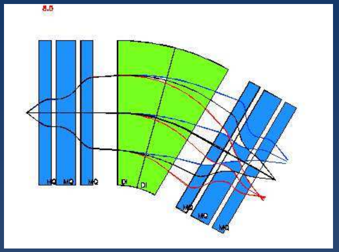


Experiment preparation : step 0

-Evaluate the Bρ of the desired Ion beam

-Which beam optics to be used ? (detector location?,...)

Spectrometer tuning : during the experiment



Step 1 : Check the beam alignement

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 Bρ0 of the desired ions : **B= Bρ0 /R**

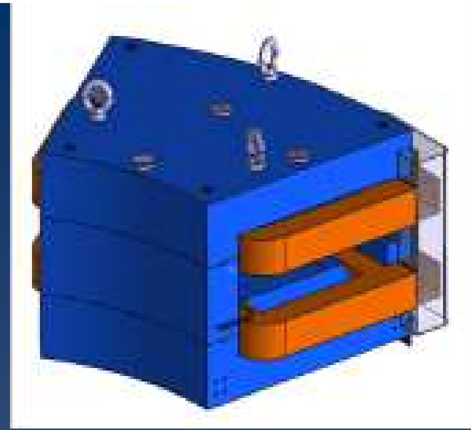
The Software Computes the fields by scaling:

G_Q1= G_Q1* **B**ρ0 /BρRef (beam optics N°xxx)

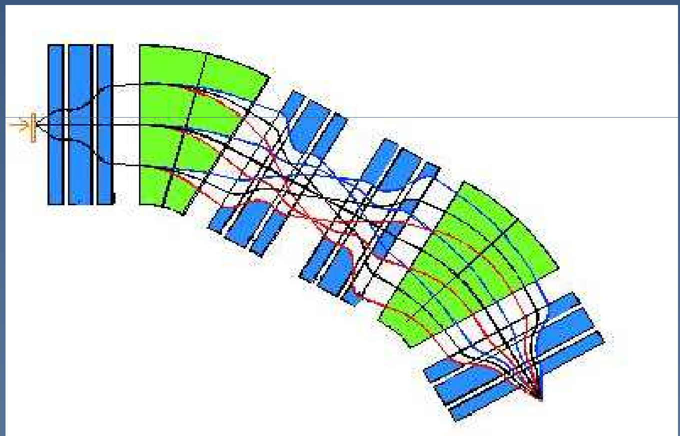
Bdipole= Bρ0 /Rdipole

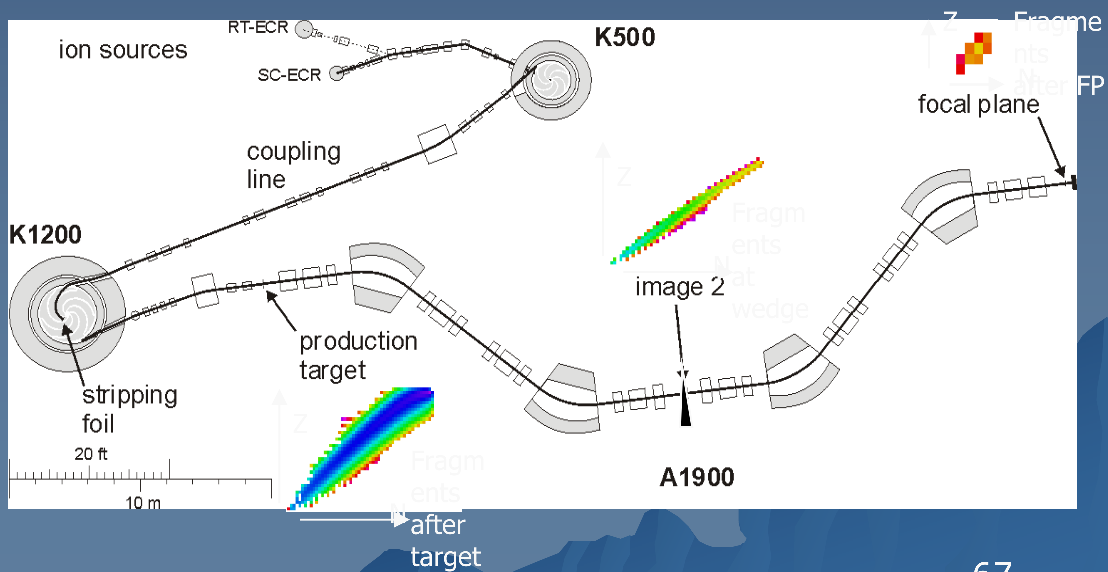
The **software computes the currents *icoils*** For the quads & dipoles coils

then, **check the dipole field Bdipole** with probes



End





B.Jacquot// Ganil

References:

The historitical paper for fragment separators:
[1] R.Anne, D.Bazin, A.C.Mueller, J.C.Jacmart and M.Langevin, "The achromatic spectrometer LISE at GANIL", NIM A257 (1987) 215-232.

More on wedge (degrador)
[1] H.Geissel, G.Munzenberg, K.Riisager, "Secondary exotic nuclear beams", Annu. Rev. Nucl. Part. Sci. 45 (1995) 163-203.

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 collegues from Riken, GSI,NSCL, Jyvaskyla, Triumf, Dubna,Legnaro, and Ganil

Back-up slides

- More on matrices
- Real Perfomance 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 s1 & s2 :

x=x(s) y=y(s) ???????

$x2 = x1 + \tan(\theta 1)(s1 - s2)$

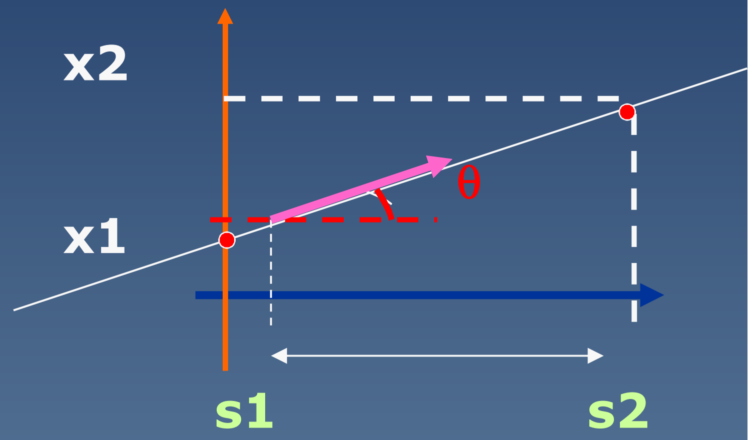
$\theta 1 = \theta 2$

$y2 = y1 + \tan(\varphi 1)(s1 - s2)$

$\varphi 1 = \varphi 2$

nota: $\tan(\theta 1) = dx1/ds = x1'$

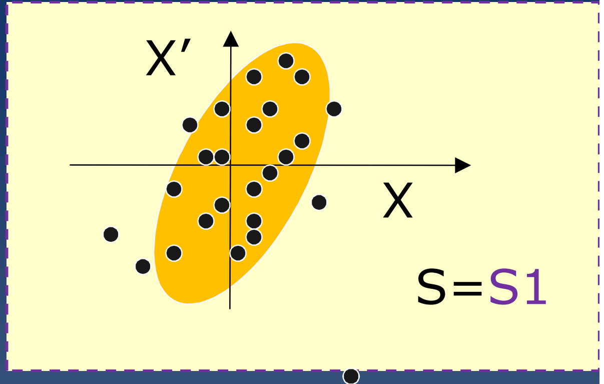
and $(s2 - s1) = L$



$$\begin{pmatrix} x2 \\ x2' \\ y2 \\ y2' \end{pmatrix} = \begin{pmatrix} 1 & L & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} x1 \\ x1' \\ y1 \\ y1' \end{pmatrix}$$

$$R_{d1} = \begin{bmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & L/\gamma^2 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The beam : N particles in a 6D ellipsoid



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

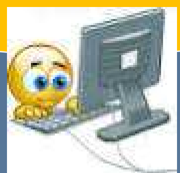
$$\sigma_{x\,x'} = \sigma_{12} = \frac{1}{N} \sum_{\alpha=1,..N} (x_\alpha - \bar{x}).(x'_\alpha - \bar{x}')$$

1) σ_{ij} is a statistical definition of the beam

2) An optical code

Computes σFinal with the R matrix at the end of the spectrometer

$$\sigma_{final} = R^T.\sigma.R$$



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 = εdetector x 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

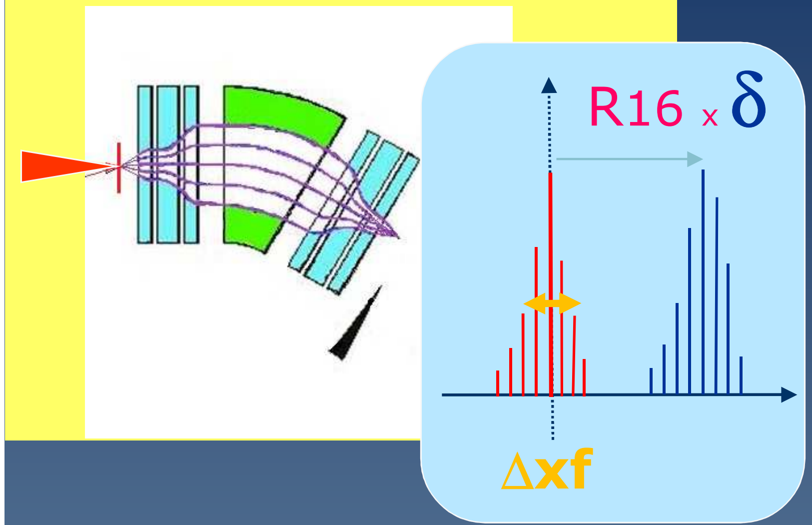
Maximal intensity of incident primary beam

- thermal limit on target (rotative or not,….)
- maximal intensity on detection sytem
- beam losses in spectro (electrostatic sparking,….)
- radioprotection

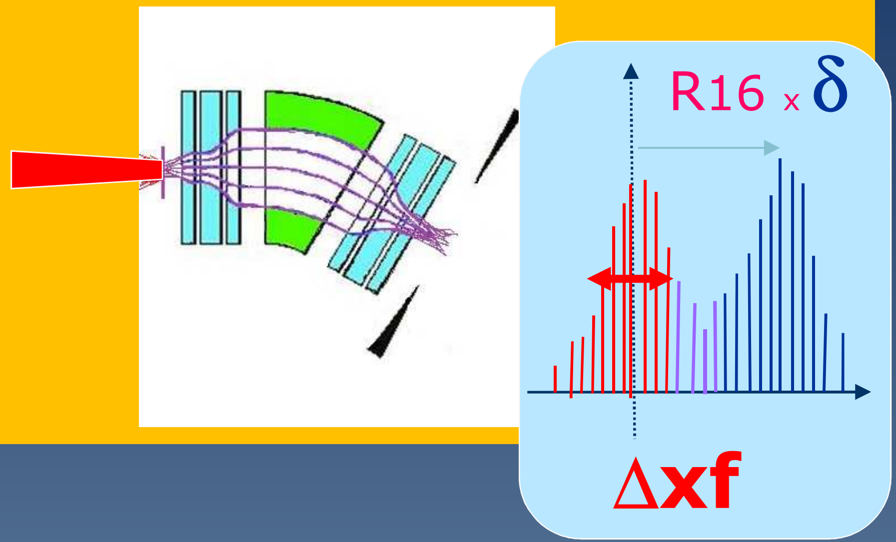
More on Fragment separators

how to optimise selection in separator

Small spot : $\Delta x_0 = \pm 1mm$



big spot : $\Delta x_0 = \pm 5mm$



The spot size Δx_{target} on target defines the beam size at focal plan

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

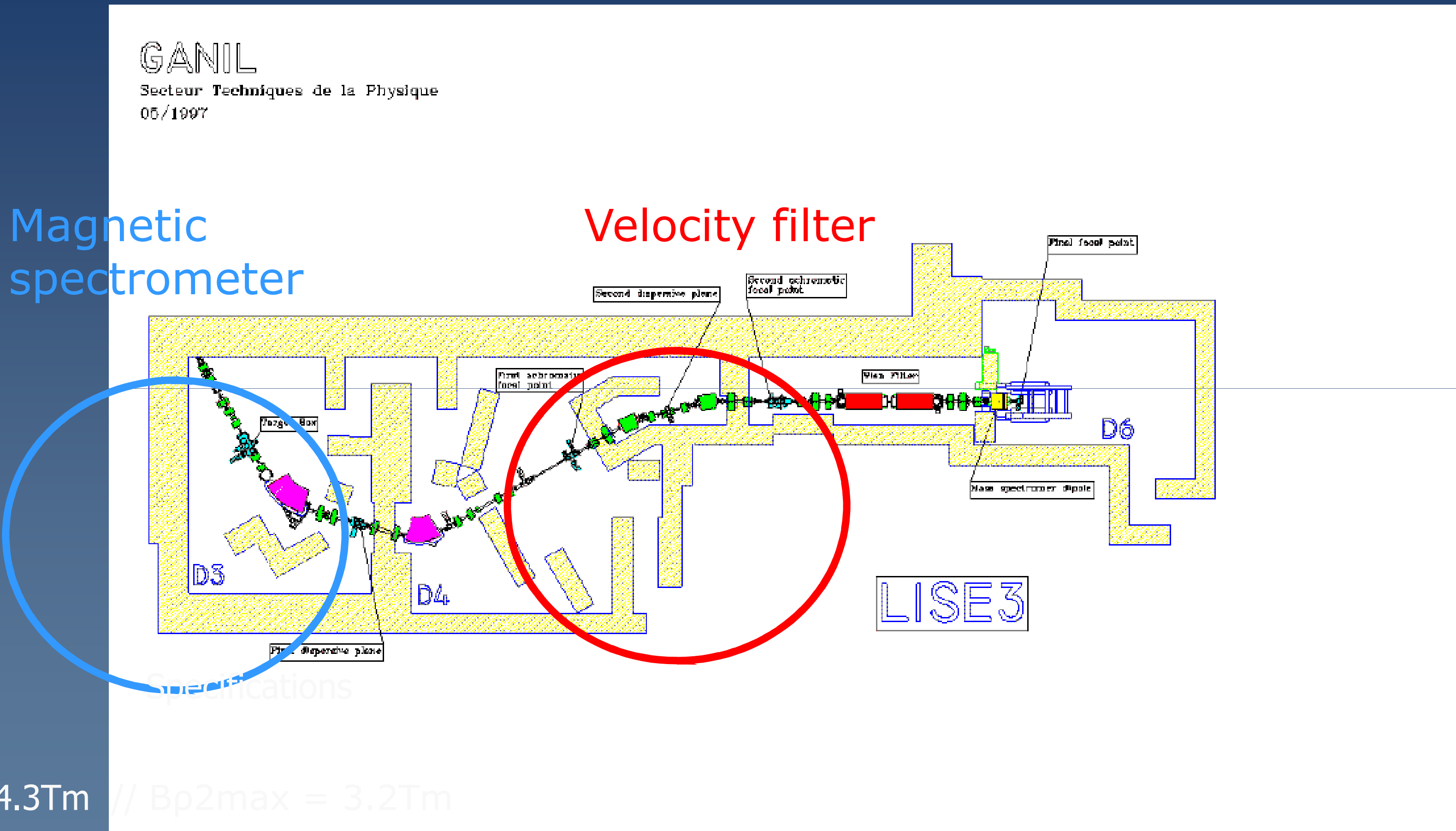
Big spot on Target Decrease the selection (Worse resolution)

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

CHECK FOCUS ON TARGET (Δx_{target} small !!)

More on Fragment separators

LISE separator with Wien filter (ganil)



Specifications

L=35m

$B\rho1_{max}$ = 4.3Tm // $B\rho2_{max}$ = 3.2Tm

$\Delta p/p$ =±2.5%

$\Delta x'$ = ±20mrad

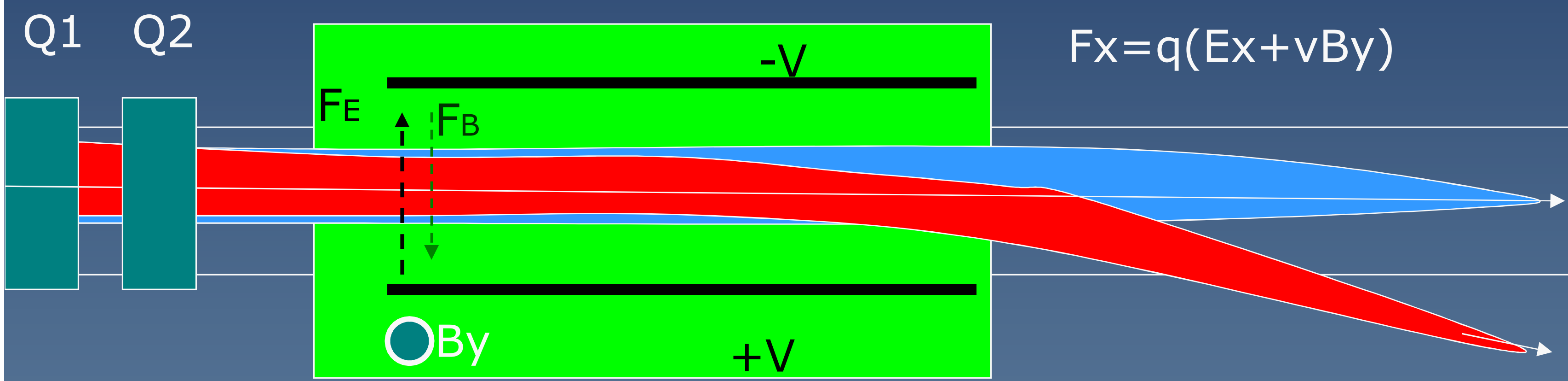
$\Delta y'$ = ±20mrad

B.Jacquot// Ganil

The velocity filter (so-called **Wien filter**)

The wien filter use Electric field
+ magnetic field

$$F = F_E + F_B = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$



$F_x = q(E_x + vB_y)$

The particles with $v_0 = -E_x/B_y$ are not deflected (F=0)

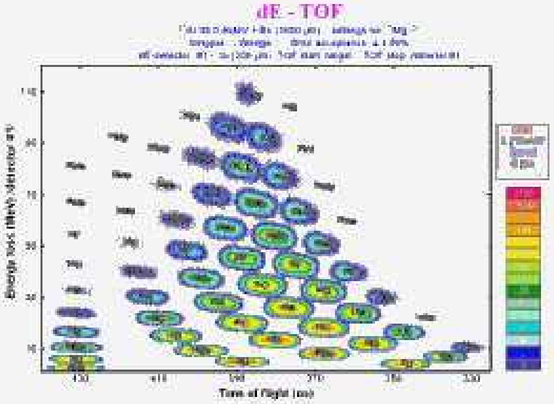
The particles with a Large velocity deviation ($v \neq v_0$) are deflected

Nota : trajectories in Electric field depend on the « electric rigidity « Eρ » of the particles : Eρ= γ MV²/Q

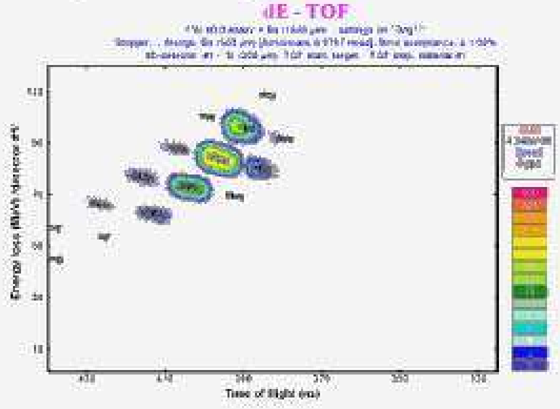
$$\frac{1}{\rho_{trajectrory}} = \frac{Ex}{E\rho} - \frac{By}{B\rho}$$

LISE separator with wien filter

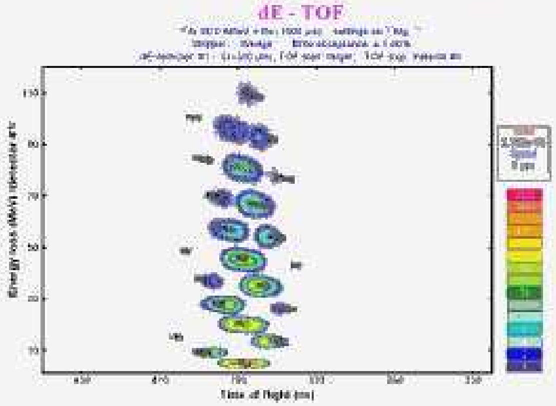
Bρ selection



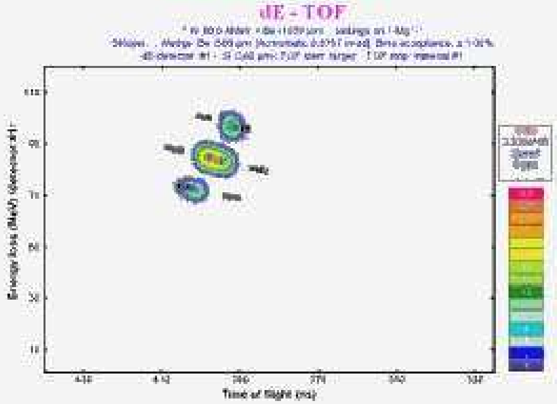
Bρ+wedge selection



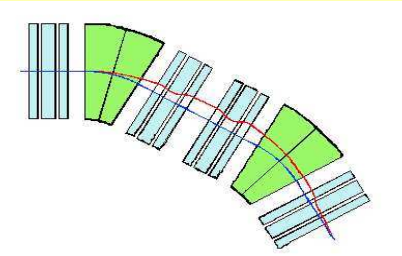
Bρ+velocity filter selection



Bρ+wedge+velocity filter selection



How to get a Fragment separator achromatic



Trajectories are Independant from δ (achromatic)

IF **R**16 (A+B)=0

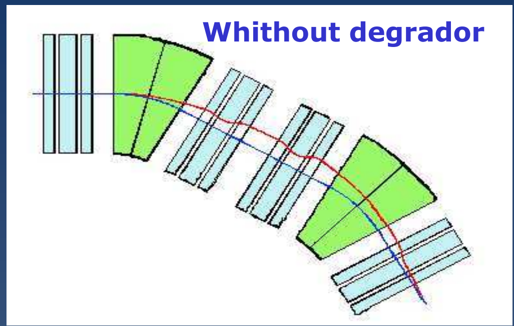
Dipole geometry **and** quad setting are adusted to get **R**16 (A+B)=0

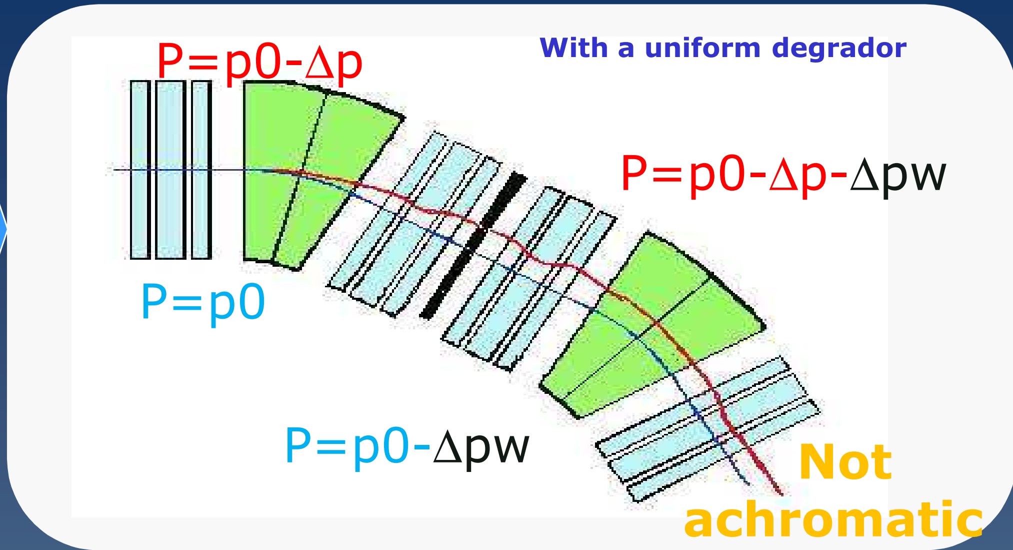
$$\mathbf{R}(A+B) = \mathbf{R}(B)\times\mathbf{R}(A) = \begin{bmatrix} R^B{}_{11} & 0 & 0 & 0 & 0 & R^B{}_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & 0 & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ & & & & & L^B \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} R^A{}_{11} & 0 & 0 & 0 & 0 & R^A{}_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & 0 & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ & & & & & L^A \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Achromaticity if R16 (A+B)= R16 (B)+R16(A) R11(B)= 0

1) Why a degrador (wedge) in not uniform in x :

2 particles
With same
Z, but
different
$B\rho = P/q$





Goal of the degrador :

All the same particles (Z,A) should re-focus at end of the B stage whatever their Bρ (δ) => achromatic degrador (Wedge) : $R_{16}(A+B)=0$

Adding a uniform degrador makes the optics chromatics at the End

Before degrador δ_A, the momentum deviation of the 2 trajectories is $\delta_1 = -\Delta p/p0$

After degrador $\delta_B = [p0-\Delta p- \Delta pw -(p0-\Delta pw)\ ]/[p0-\Delta pw]$

$\delta_B = [-\Delta p\ ]/[p0-\Delta pw]$ $\delta A \neq \delta B$

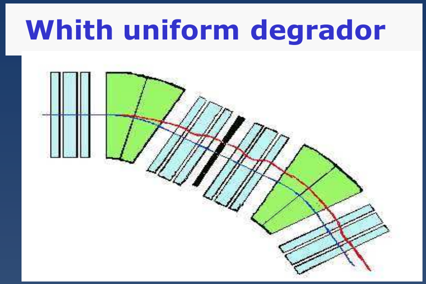
if the Optics is achromatic without degrador ($\delta A=\delta B$)

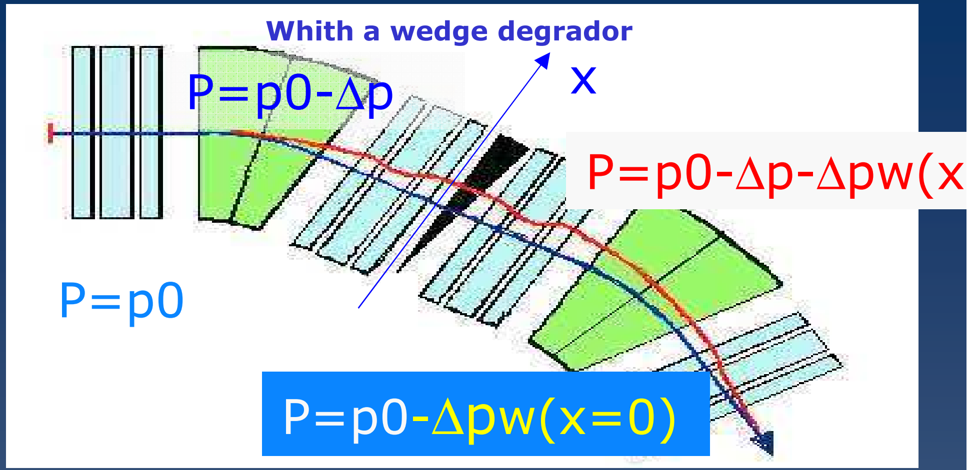
Optics will not be achromatic with a uniform degrador with $\delta A \neq \delta B$

2) Why a degrador (wedge)

in not uniform in x

2 particles
With same Z,
but different
Bρ= P/q





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 Bρ deviation of the 2 trajectories

δ_A= -Δp/p0 = xA/R16 after the wedge (degrador) P=> P-Δpw

After degrador

$$\delta_B=[p0-\Delta p-\Delta pw(xA)-(p0-\Delta pw(xA=0))]/[p0-\Delta pw(xA=0)]$$

$$=[-\Delta p-\Delta pw(xA)+\Delta pw(xA=0))]/[p0-\Delta pw(xA=0)]$$

($\delta_A=\delta_B$) => Δpw(xA) # Δpw(x=0)×[1+ xA /R16(A)]

Thickness of the Wedge # K×[1+ xA /R16(A)]

Beam emittance : (# optical quality)

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

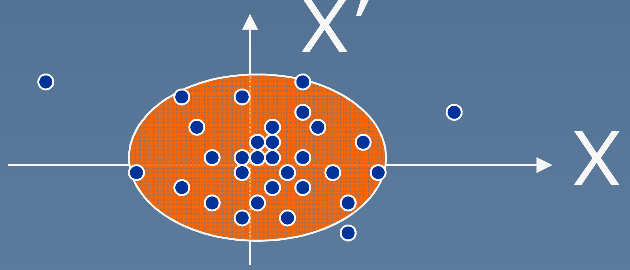
6 Dimensions

For pratical 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)



$\varepsilon_{rms} = 4(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2)^{1/2}$

ε =area of the ellipse ,which correspond to x% particles

Liouville theoreme : 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

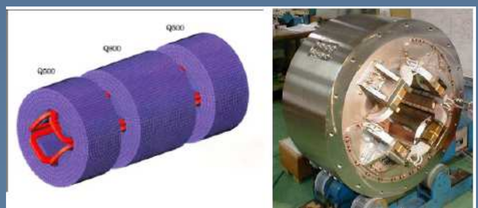
Suppression of the primary beam

(many dipoles, degrador selection)

Help the selection of very rare nuclei

Selection of 4-5 nuclei

Identification (DE-TOF)



Superferric quads

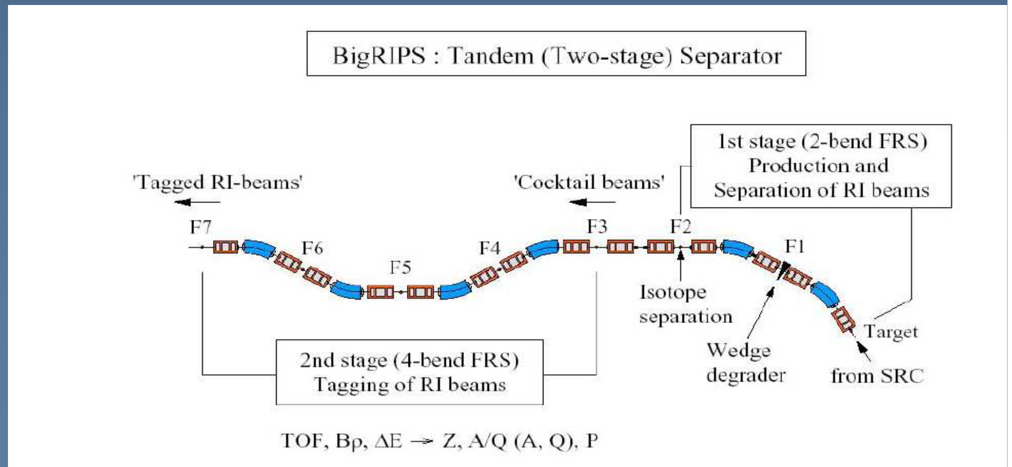


Fig. 2. A schematic diagram of the RI-beam tagging in the BigRIPS separator.

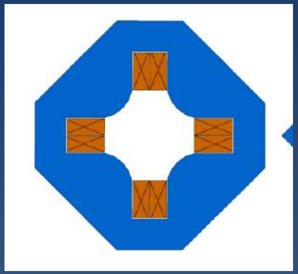
B.Jacquot// Ganil

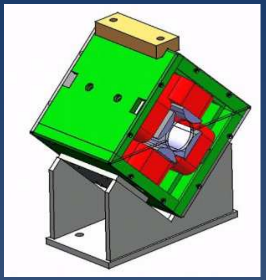
Quadrupole technology

1 :Normal conducting quad

hyperbolic pole (Fe)
coils (Cu)

G~ 10 Tesla/m





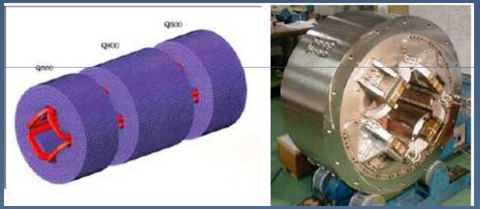
Larger Aperture

or/and

Higher strength

2 : Superferric quad

hyperbolic pole (Fe)
coils (NbTi)



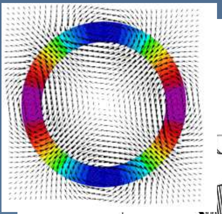
Higher Gradient , larger aperture possible (A1900, BigRips, Synchro.)

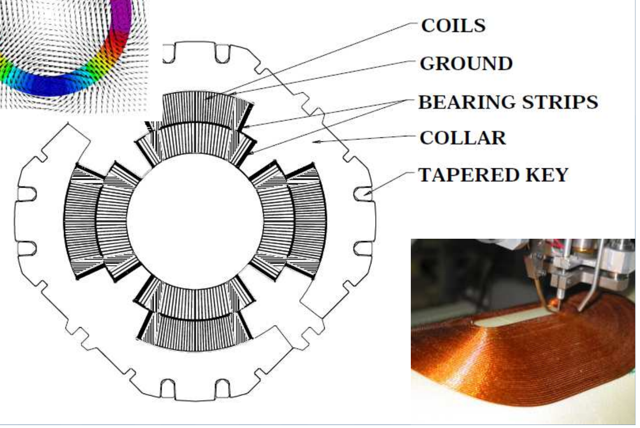
G~ 20-30 Tesla/m

3 : Superconducting quad

No pole !!!!!!
cos(2θ) coils (NbTi)

G~ 40-200 Tesla/m (Cern LHC...)





Example n°2: VAMOS Spectrometer

L=8 meters, 1 dipole, rotative platform

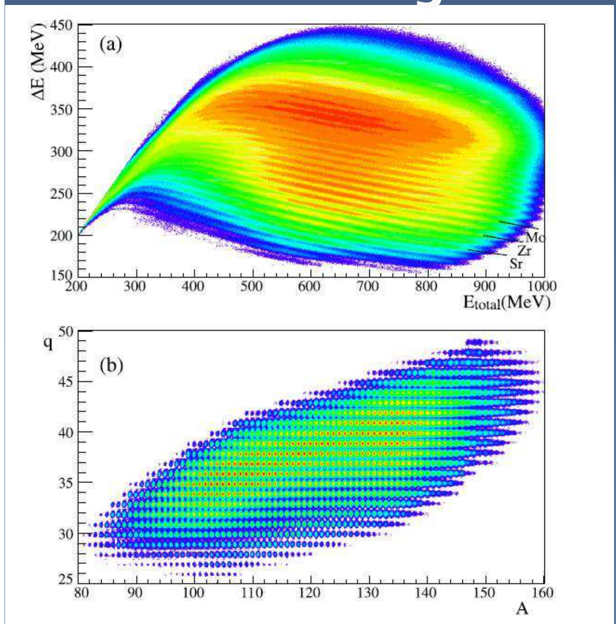
Suppression of the primary beam

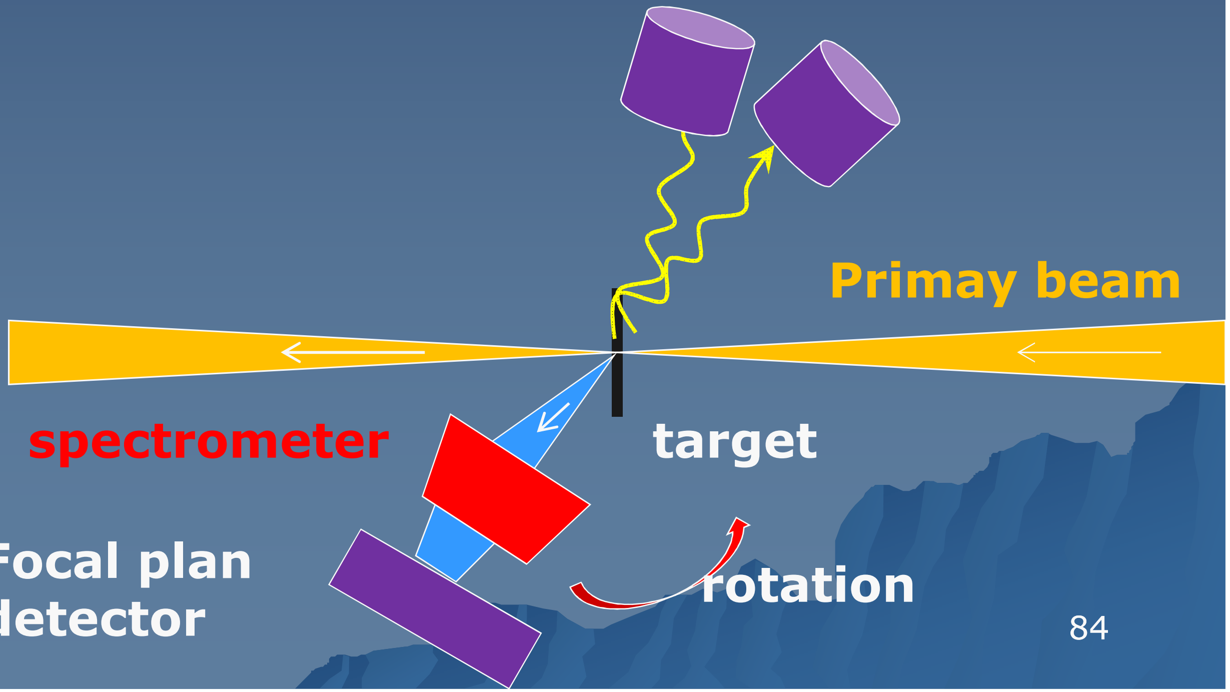
(by rotation)

Selection of 20-300 nuclei

Help Identification (ΔE-TOF, position and angle measurements)

300 fission fragments id.





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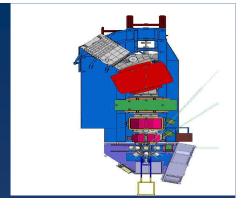
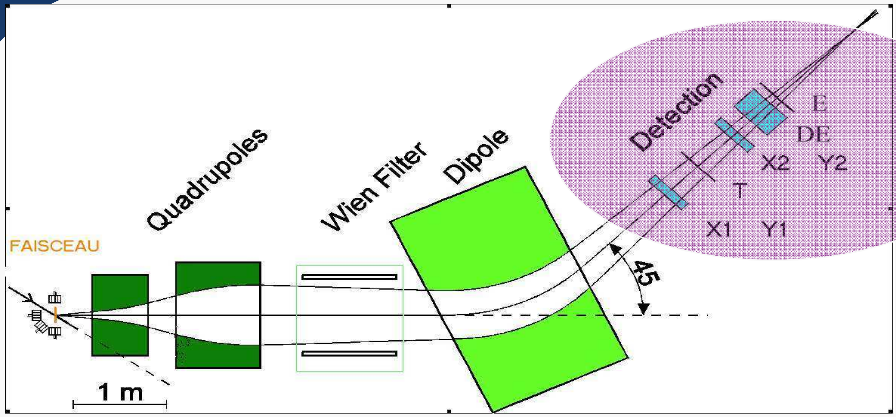
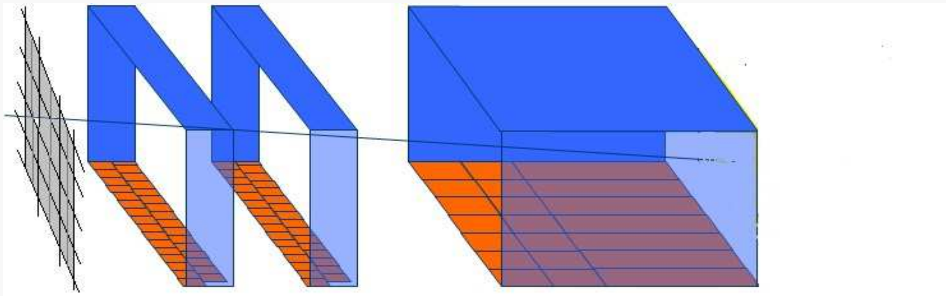
Example n°2: VAMOS Identification







MWPPAC
(Tof)

Drift Ch.
(X,X',Y,Y').

Ionis. Ch.
(ΔE,E)

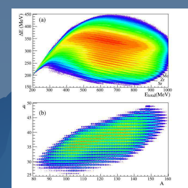
In the focal plane, 7 quantities are measured :
T, x1, y1, x2, y2, ΔE, E

T : Multi Wire PPAC

x1,y1
x2,y2 :

$$x' = (x_1 - x_2)/d \quad = \tan(\theta)$$
$$y' = (y_1 - y_2)/d \quad = \tan(\phi)$$

ΔE,E : ionisation CHAMBER



$$B\rho = B\rho_0 \,(1 + x/R_{16} + a\,x'^2 + b\,x^2 + c\,x^3 + \ldots)$$

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

B.Jacquot// Ganil

Non linear effects in optical system

1rst order

$$\overrightarrow{Z_2} = R.\overrightarrow{Z_2} + \dots \varepsilon$$

Linear Approximation holds for small angle, small Bρ deviation… (#30mrad,δ<2%)

$$Z1 = (x, x', y, y', l, \delta)_1$$

for large angle, large Bρ deviation 2nd order, third order is required.

$$Z2_i = \sum_{j=1}^{6} R_{ij} \; .Z1_j + \sum_{k=1}^{6} \sum_{j=1}^{6} T_{ijk} \; Z1_j . Z1_k + \dots$$

1rst order 2nd order

Effects of second order :

-Inclination of focal plane

-the Focusing strenght of quads is bρ dependant

-Large angle particles are not well focused

Non linearities (ABERRATIONS) come

- with large acceptance (large x' and large δ)
- but also, with field defects in quads and dipoles

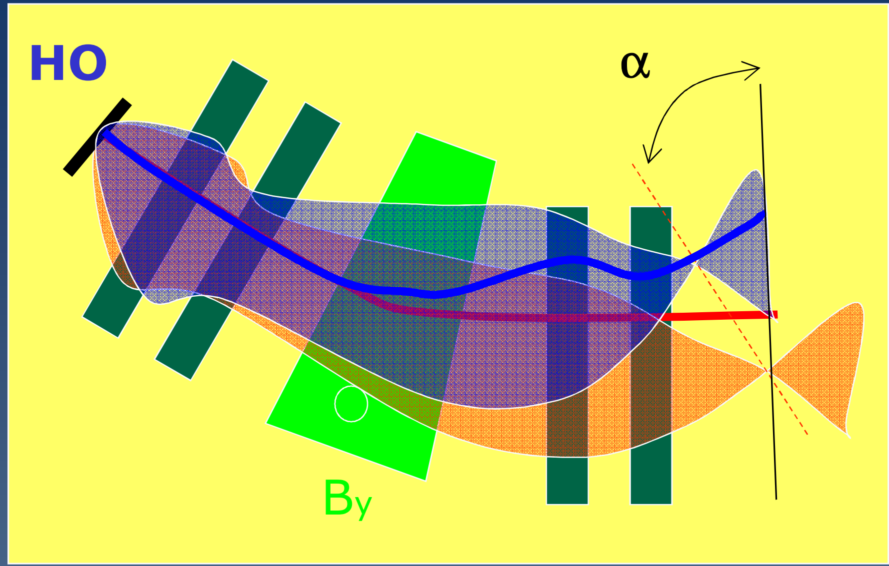
Non linear effects in optical system

Ex1: Inclination α of the focal in a spectrometer

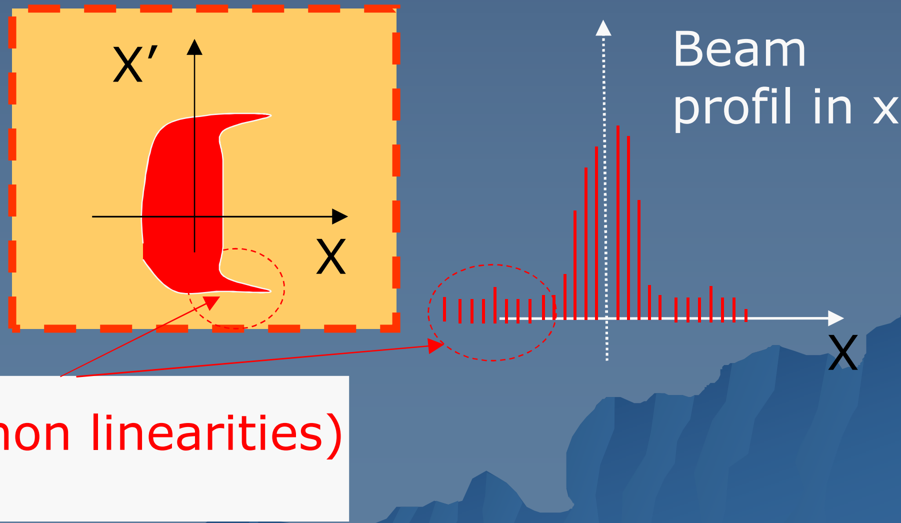
$tg(\alpha) = R_{16} / T_{126}.R_{11}$

-Choice of the dipole Angle

-Magnetic sextupole has to be used for correction



Ex2: distorsion of beam ellipse In phase space Inducing Distribution wings



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Non linear effects in optical system

Beam optics is linear when x < 5cm

x'<30mrad

δ<2%

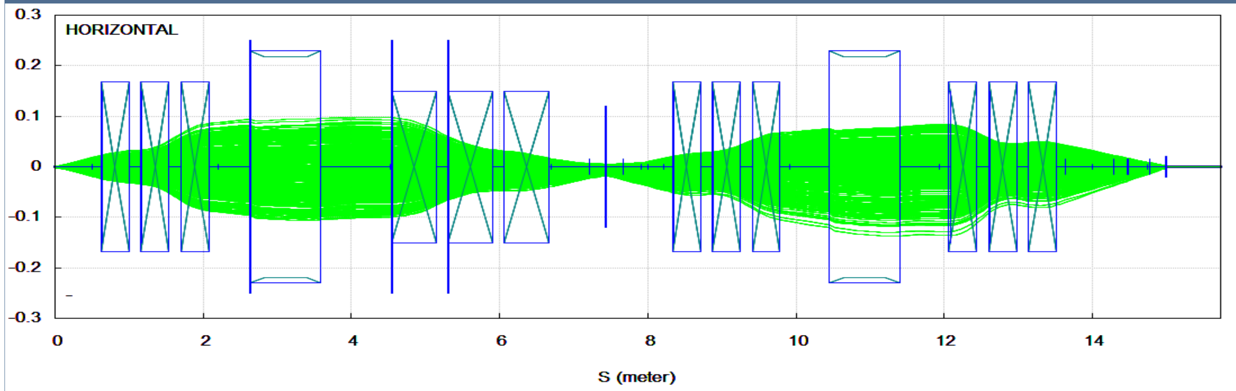
Beam is a nice ellipse in phase space, R matrix is sufficient

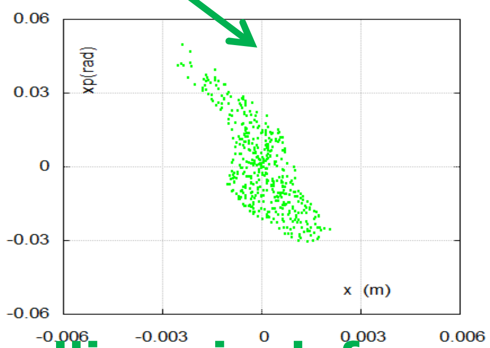
If |X'| > 30mrad or |δ| > 2%

Beam are not well represented by an ellipse

R matrix is not sufficient for the calculation

(field maps + tracking with « Runge kutta » simulation needed)

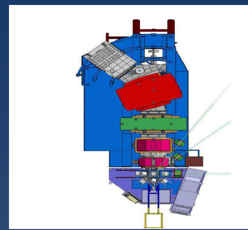




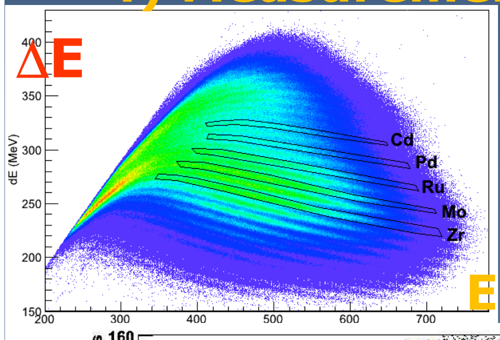
ellipse is deformed

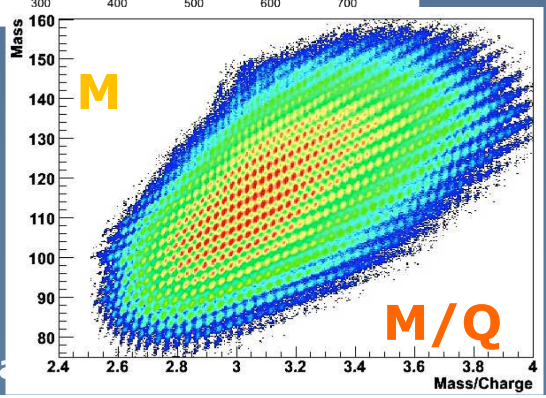
Example n°2: VAMOS Spectrometer

Particle identification Method (M,q,Z)



1) Measurement of the time of flight (TOF) => velocity
2) Measurement of the position x_{focal} after the spectrometer
   => $B\rho = B \times$ Rdipole $(1 + x / R_{16} + \ldots)$
3) Measurement of the energy loss ΔE in a thin detector (Ionization Chamber)
4) Measurement of residual energy Er (Ekinetic= $(\gamma-1) M c^2$]





v	$v = T$ fligth $/ L_0$
M/q	$M/q = B\rho / \gamma v$
Z	Z# k ΔE .....
M_1	$M_1 = (Er + \Delta E) / [c^2 (\gamma - 1)]$

finally

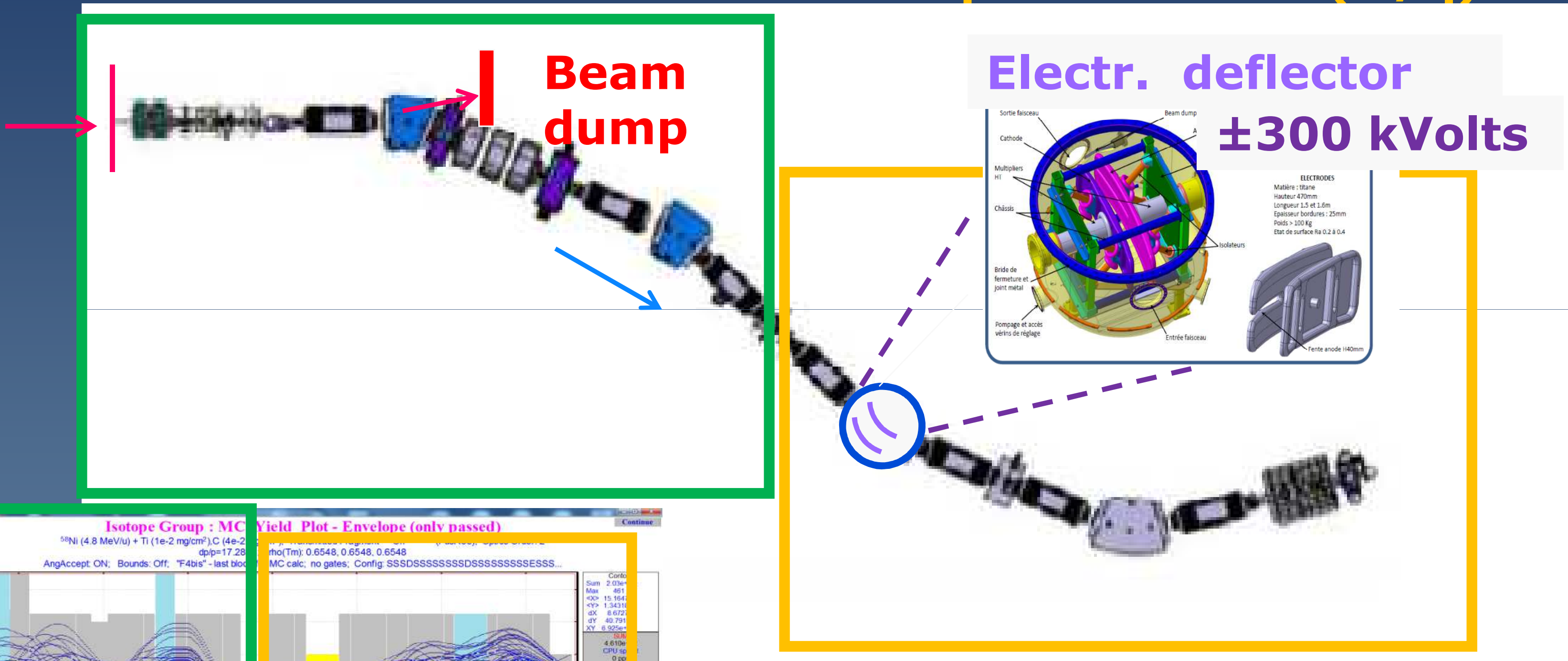
$Q = M_1 / [M/q]$
$M = [M/q] . Q$
$Z \# k(E) \Delta E$

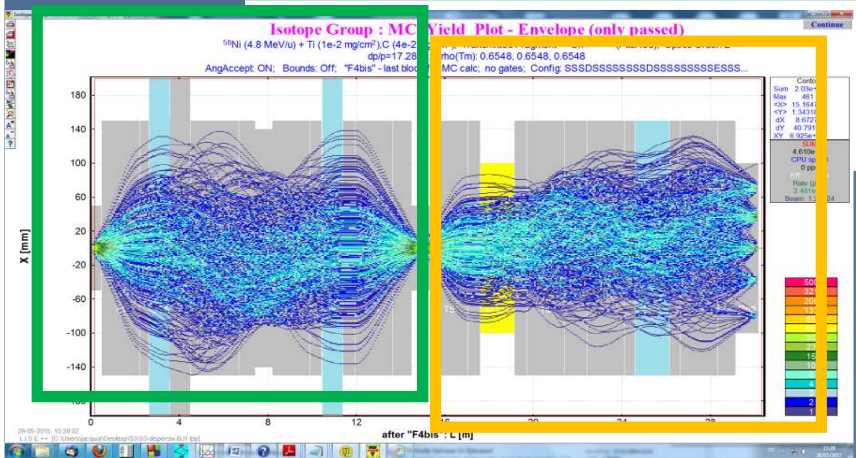
Example : S3 spectrometer @Ganil

S3 :

1 Magnetic achromatic separator (2 dipoles)

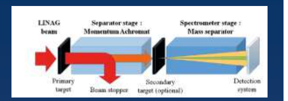
+ 1 mass spectrometer (M/q)



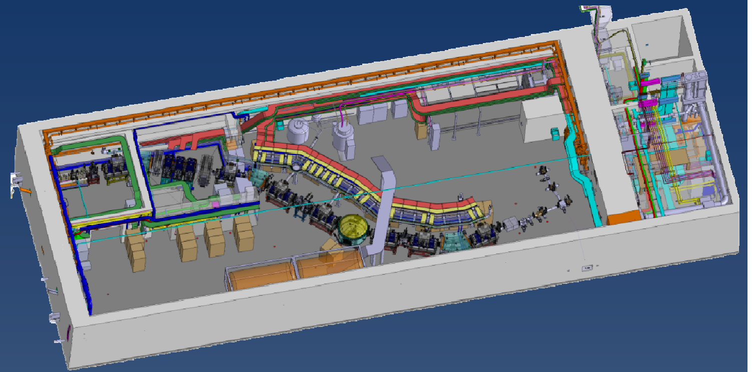


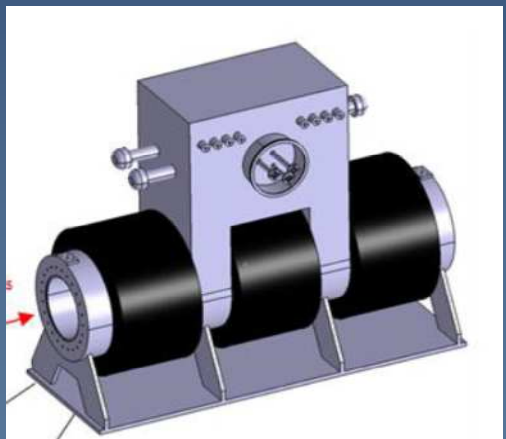
Lise++ simulation :
fusion reaction , 5 charge states (horizontal plane)

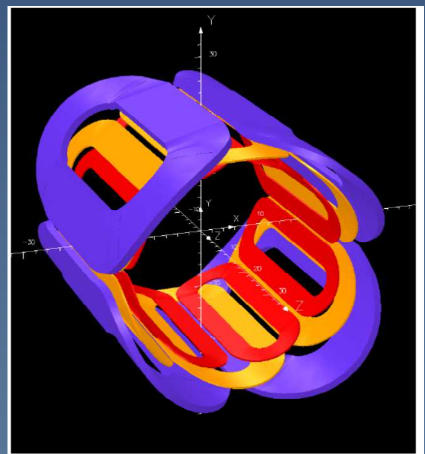
Example : S3 spectrometer @Ganil



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 ;