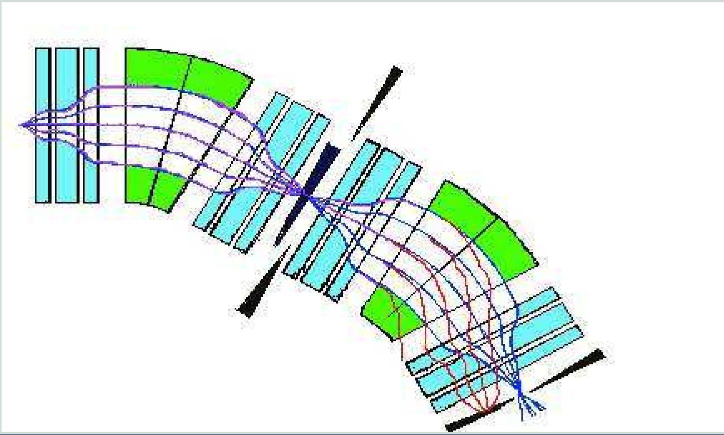
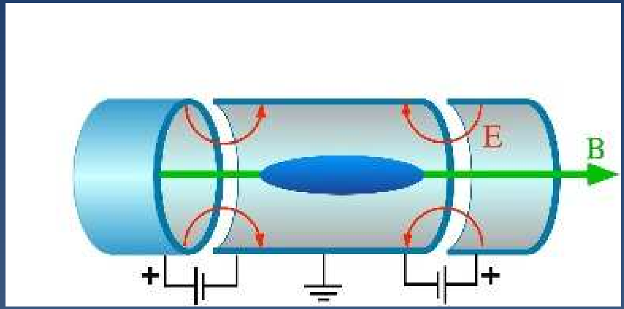
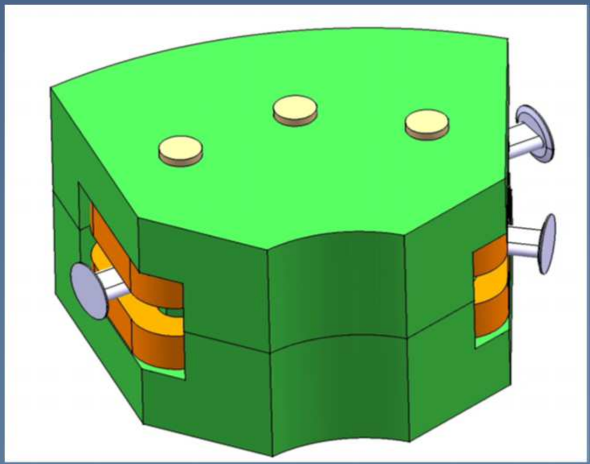
Electromagnetic Spectrometers







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Summary

- I) History and evolution of the spectrometers

- II) Magnetics spectro/separators with accelerator's beams

technical devices : quads, dipoles

Beam optics concept

- III) Spectrometers without accelerator
- 1 exemple for Astroparticle
- Penning Traps

I) History/evolution of the electromagnetic spectrometers

1) Thomson (1897): cathode rays measurement

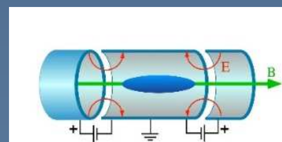
Noble prize in 1906 for discovery of the electron (measurement of m_e/q_e ratio with E+ B selection)

2) Aston (1919) : **E+ B selection**

identification of isotopes Ne,Cl & mass measurement

3) 40's :Manhattan project U_{235}/U238 enrichment (B selection)

4) Dehmelt (1955) :Penning Traps



5) « Commercial » mass analyzer : (Tof ,Maldi,Esi,…)

Small size tools commercially available for many applications

….

Magnetic selection : the basic things

Ion Equations in a transverse magnetic field

$$\frac{d\mathrm{p}}{dt} = \mathrm{F} = q\,(\mathrm{v} \times \mathrm{B})$$

Lorentz force : $(\mathbf{v} \perp \mathbf{F})$ so $\mathbf{v}.\, d\mathbf{v}/dt = d\mathbf{v}^2/dt = 0$

hence the modulus $|\mathbf{v}|$ =Constant and γ = constant

The motion is circular and uniform:

$$\frac{d\mathbf{v}}{dt} = \frac{|\mathrm{v}|^2}{R}\, e_r$$

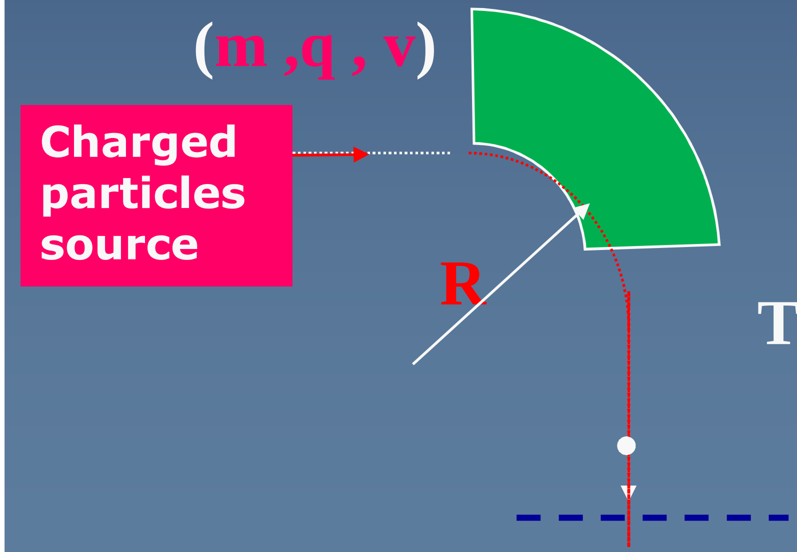
$$\gamma\, m\, \mathrm{v}^2 / R = q\, |\mathrm{v}|\, |\mathrm{B}|$$

trajectory Radius R

$$R = \gamma\, \frac{m\mathrm{v}}{\mathrm{q\,B}}$$

We define the particle rigidity : Bρ [Tesla.m]

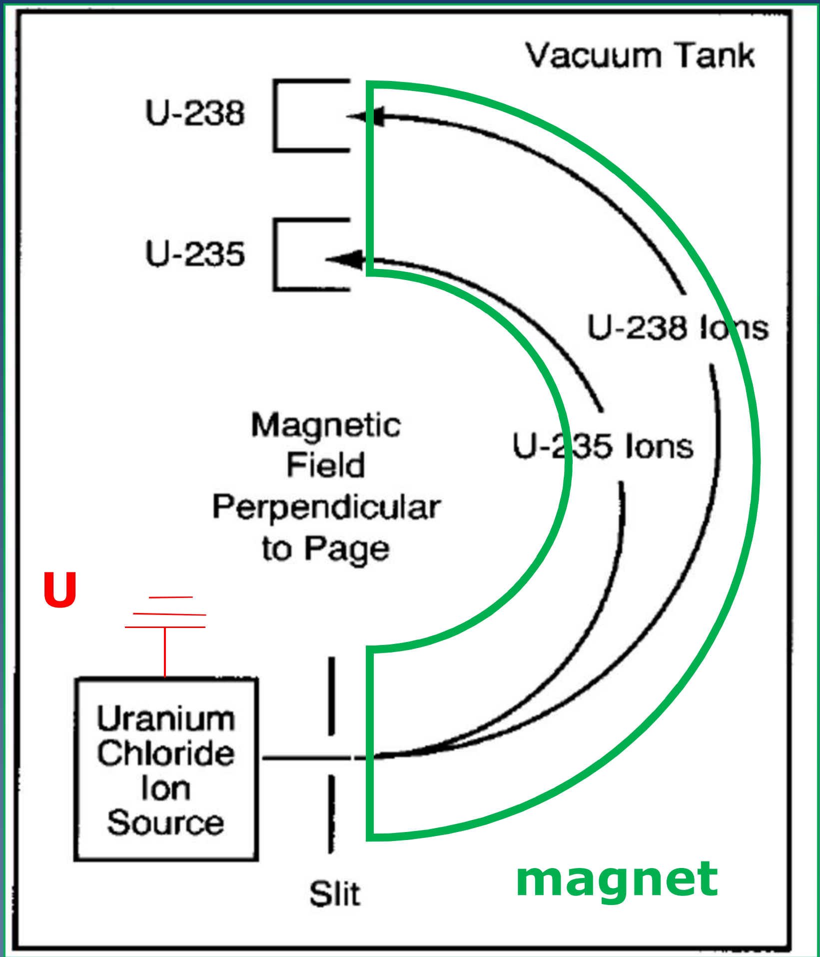
$$B\rho \overset{def}{=} \gamma\, \frac{m\mathrm{v}}{\mathrm{q}}$$



The trajectory radius given By R= Bρ /B

$$R = \frac{B\rho}{B} = \gamma\, \frac{m\mathrm{v}}{\mathrm{q\,B}}$$

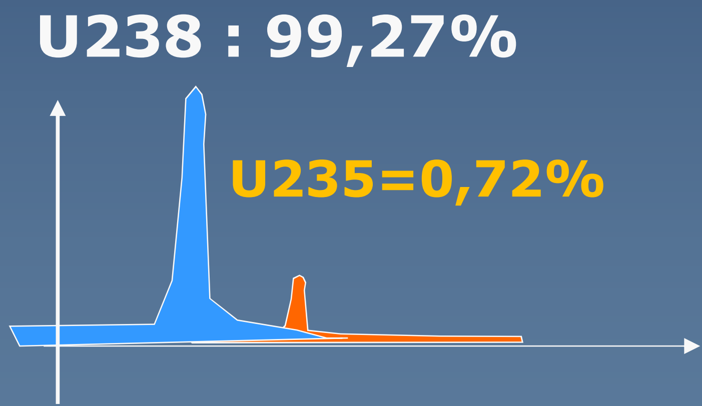
Isotope separator for atomic bomb (1942)



$$R = \frac{B\rho}{B} = \gamma \frac{mv}{qB}$$

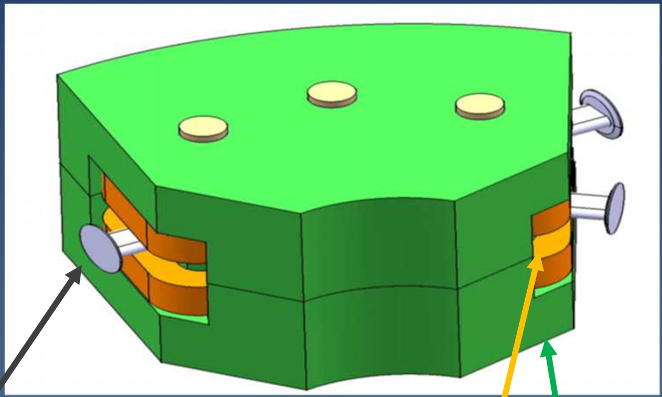
V= (2 q U /m) ½

$$R_{235}/R_{238} = (235/238)^{1/2}$$

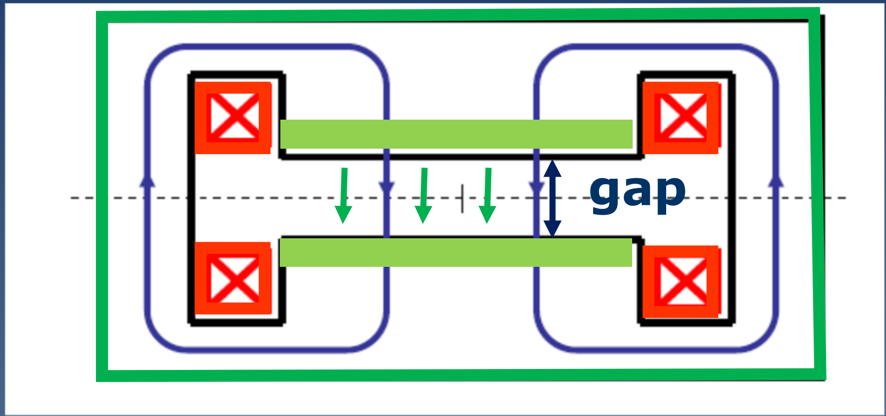


1152 isotope magnetic separators at Oak Ridge (USA) in The 1940's for ^{235}U bomb

Magnetic dipole : technical details



H type magnetic dipole

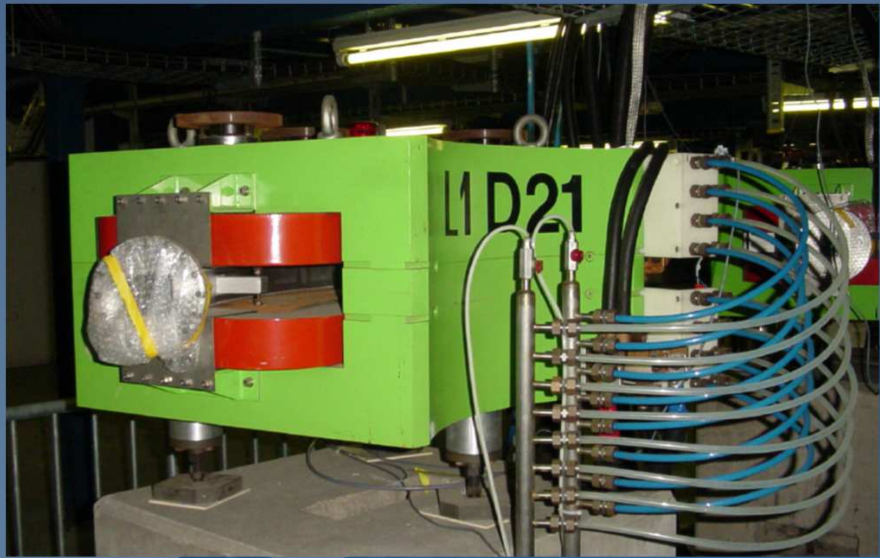


Beam pipe (vacuum)
Coils (copper)

***Yoke* & Poles (N & S)**

Poles saturates at 1,6-2Tesla
Bz ~ Ipower supply/gap

Power supply (100-1000A)



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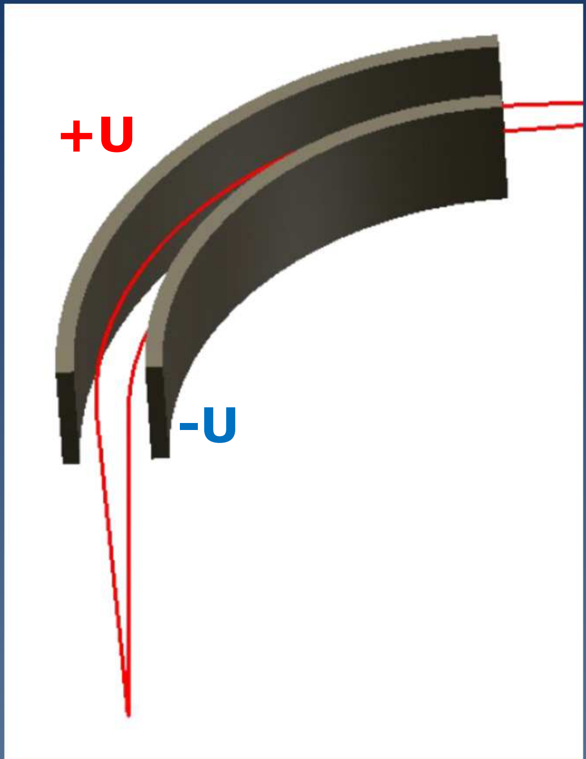
Electrostatic selection :*



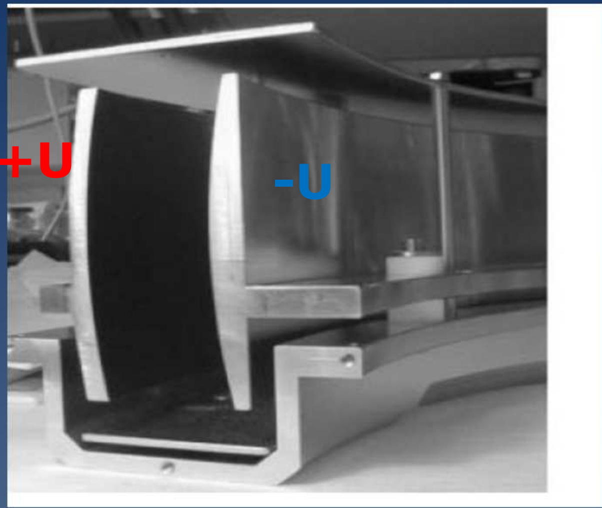
F= $q\,E$

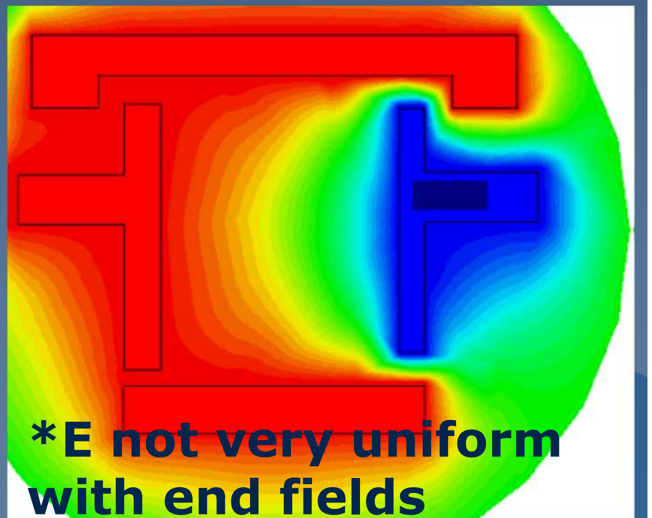
R=γ m V² /qE

$$R=\gamma m V^2/qE$$

***Difficult to bend energetic particle With raisonnable E.field**

***sparking**





E not very efficient

Electric force ~ q E

low energy particles keV ion/electron

Magnetic force ~ q V B

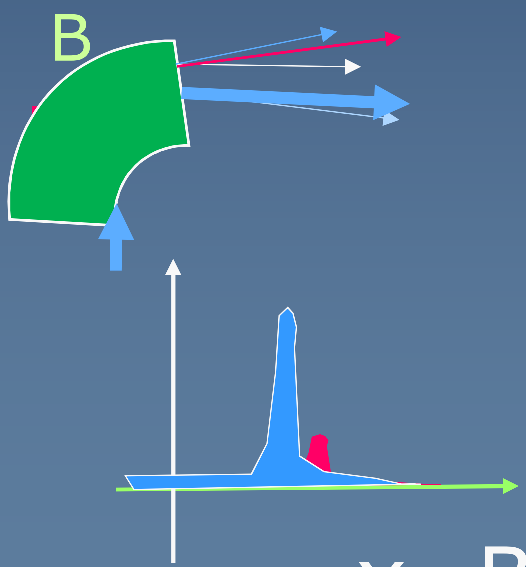
adapted to high energy particle

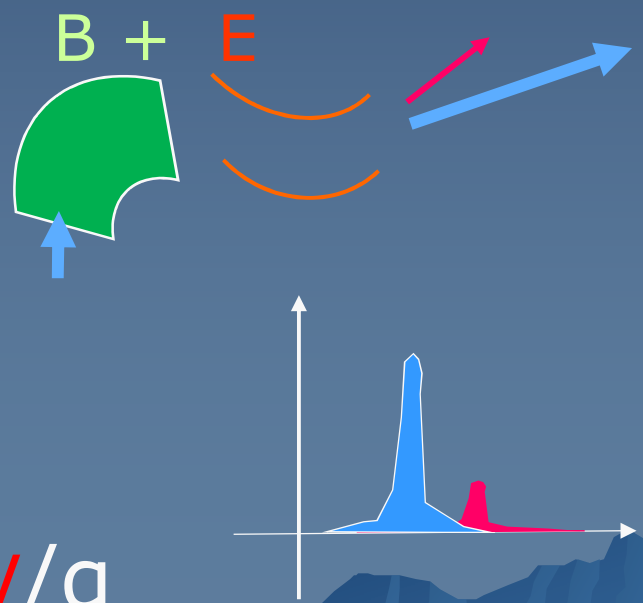
Electrostatic selection : many limitations but …

- Lower weight/cost than electromagnet

- Electric *deflector* can complement Magnet
  (velocity compensation possible $R_E/R_B \sim v$)

F.W. Aston : Nobel prize in 1929 with a
« mass spectrograph »
identification of ^{20}Ne ^{22}Ne



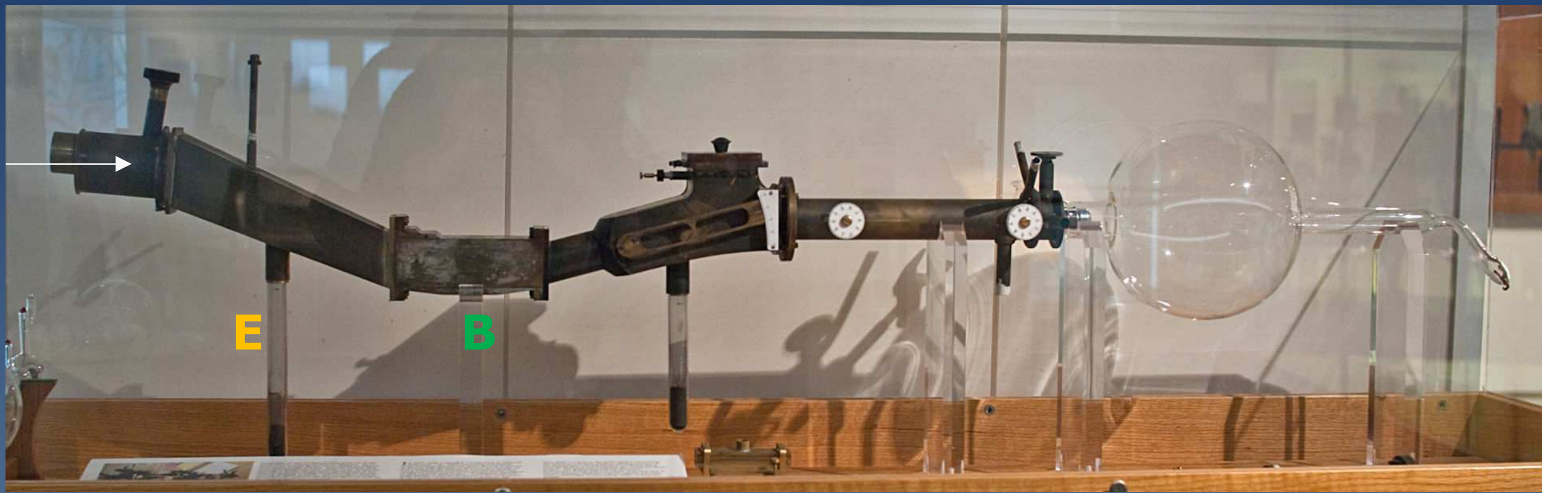


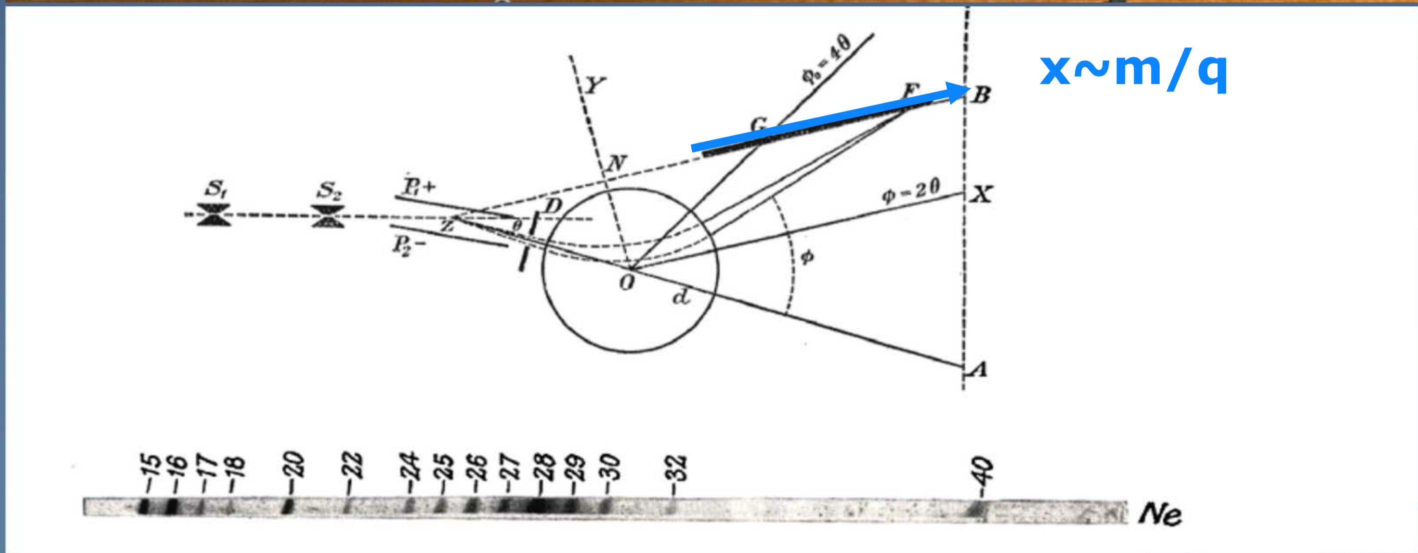
$x \sim B\rho = mv/q$

$x \sim m/q$

F.W Aston Nobel Prize :

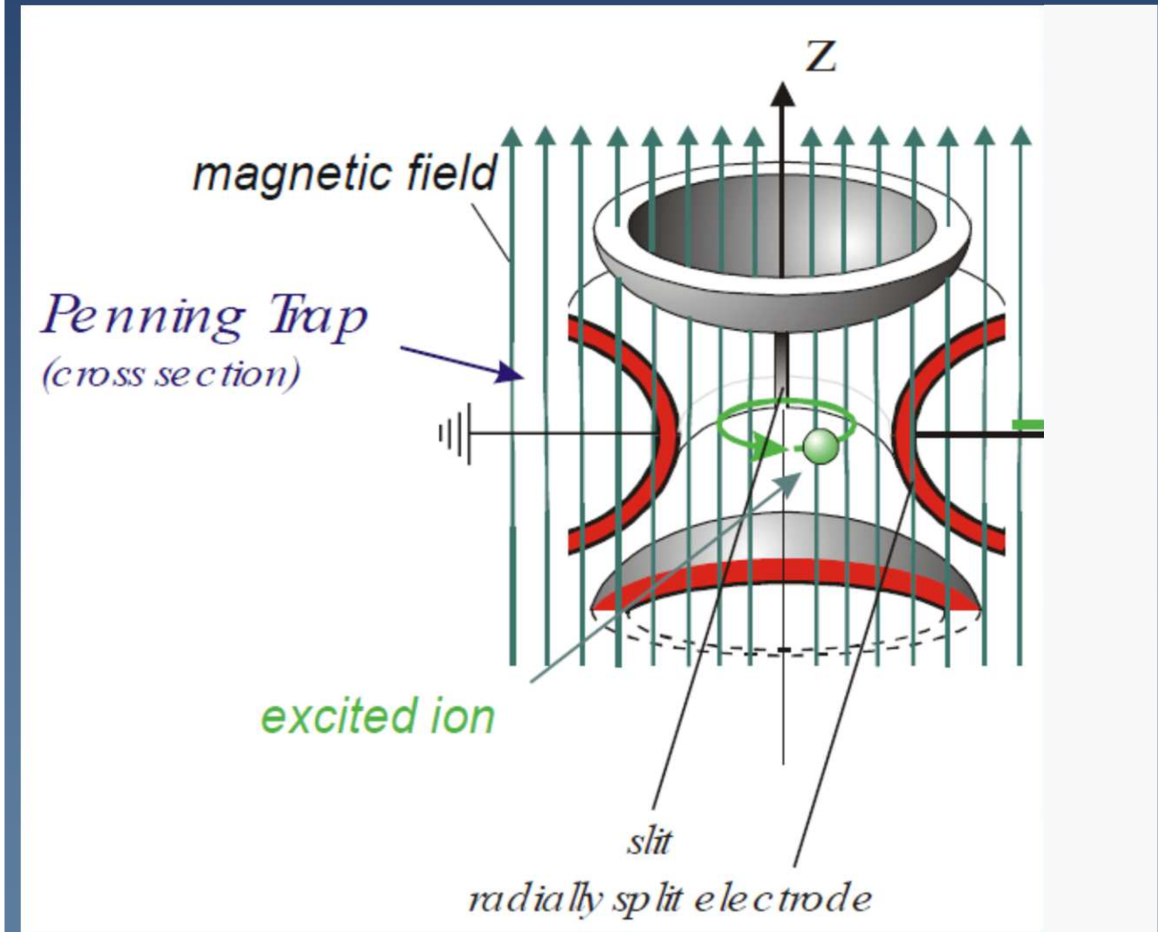
Stable isotopes discovery : $^{20-22}$Ne; $^{35-37}$Cl





Penning Traps : high resolution mass spectroscopy $Rm \sim 10^{-5}-10^{-9}$

Developped in the 50s (Dehlmet)
Used in research but the applications are expending



3 tricks

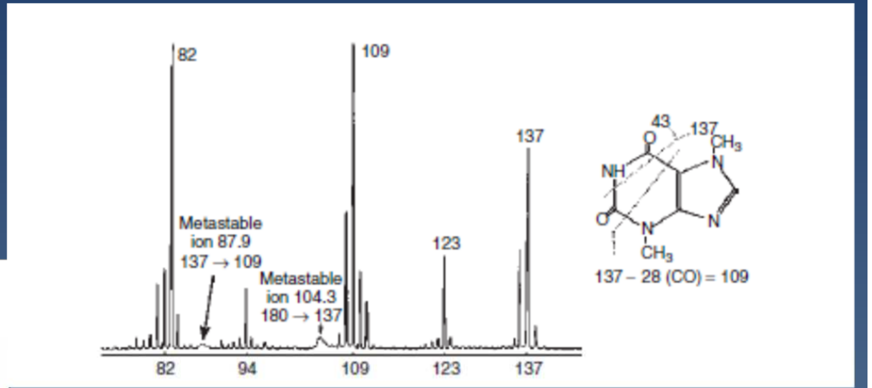
1) Confinement (Bz+Ez) static EMfieds

2) Excitation (RF field)

3) Extraction (Tof measurement)

Commercial Mass analysers

ToF or magnetic & electrostatic deflection
Chemistry, Phamarcy, industry



Molecule identification

Accurate mass measurements

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Quantitation

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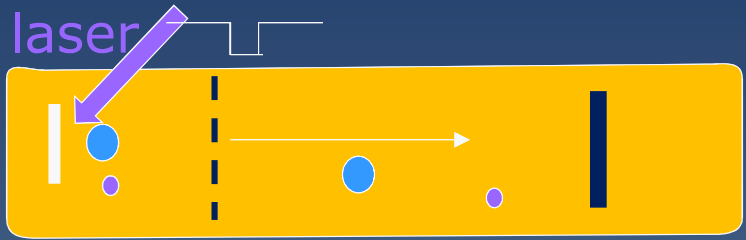
Isotope ratio measurements

« Commercial » tools : Small Tof spectrometer for mass analysis

Time of flight : ionisation (pulsed laser) + acceleration

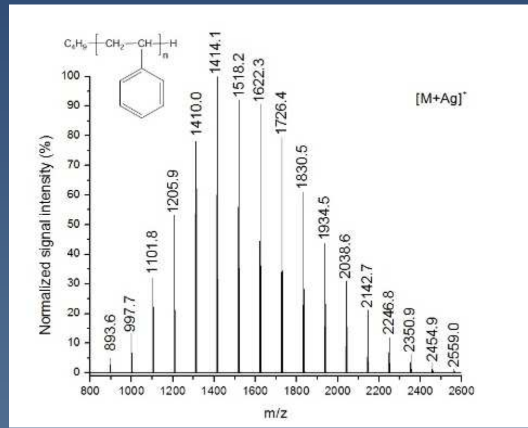
laser



+U   0Volt   Time detector

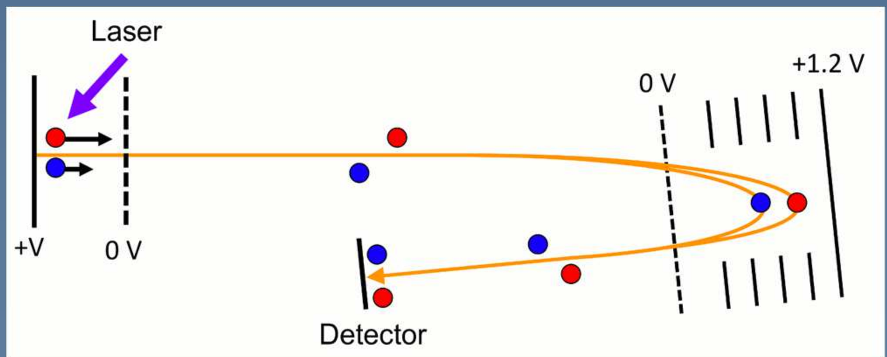
$qU = mV^2/2 = m\,(L/Tof)^2$

$Tof = L\,(m/qU)^{1/2}$



Reflectron (Tof ~ m/q)

: isochronism (Tof non dependant of U)



$Tof = L\,(m/q)^{1/2}$

$L = F(U)$

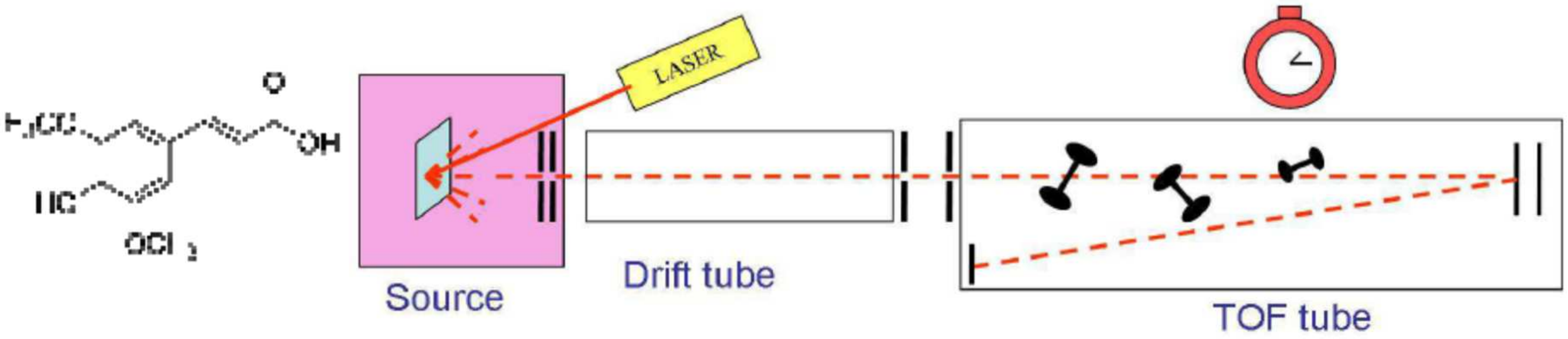
for $U = U0$ **L** $= L0$

for $U = U0 + \Delta U$ **L** $= L0 + \Delta L$

Commercial tools for Mass spectroscopy

Maldi = **M**atrix **A**ssited **L**ASER **d**esorption /**I**onization

MALDI-TOF
matrix assisted laser desorption/ionization TOF

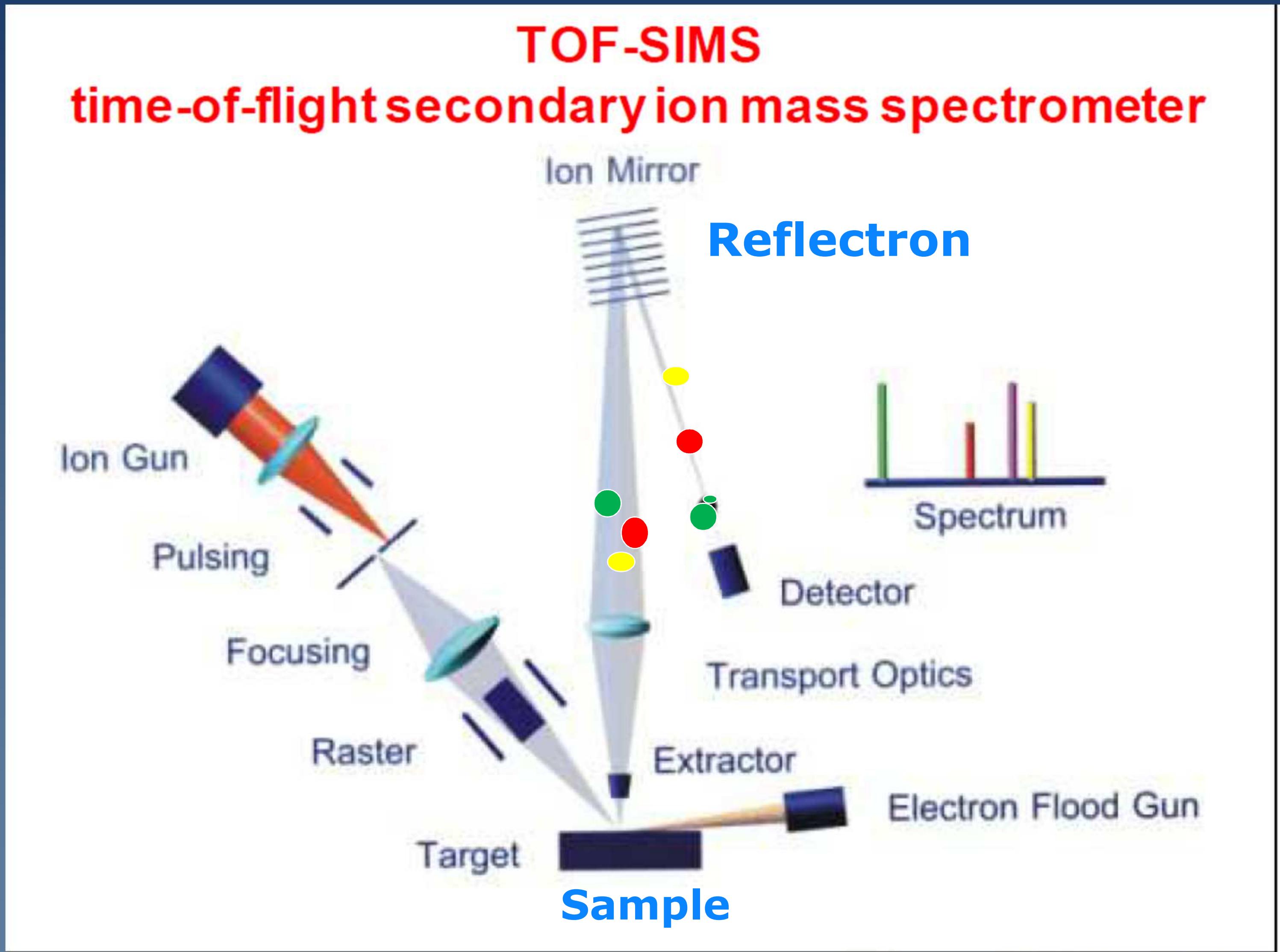


Matrix:

- low vapor pressure for operation at low pressure
- polar groups for use in aqueous solutions
- strong absorption in UV or IR for efficient evaporation by laser
- low molecular weight for easy evaporation
- acidic: provides easily protons for ionization of analyte

Commercial tools for Mass spectroscopy

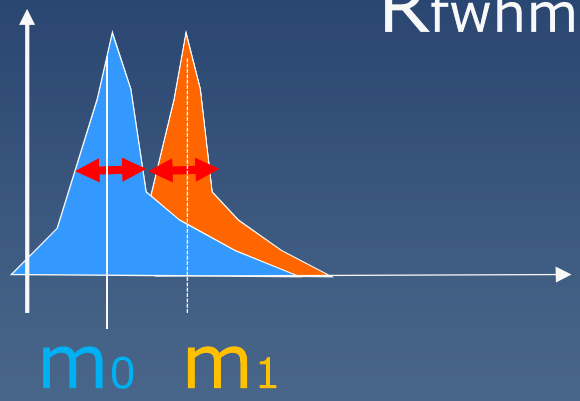
SIMS = ionzation with an ion gun of a sample



Spectrometer measurement :
what are the performances ?

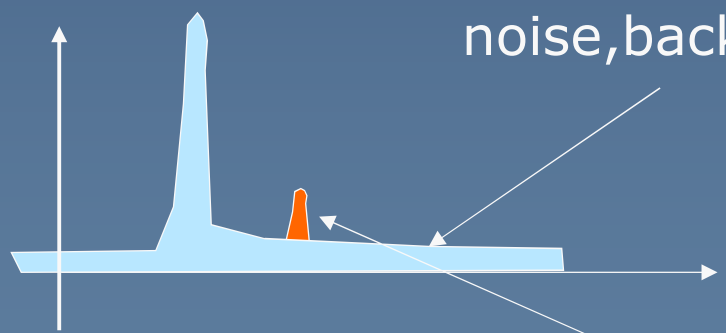
Resolution (closest peak separation)

$$R_{fwhm} = \delta m / m_0 = [m_0 - m_1]/m_0$$



x (position, Tof)

Selectivity (clean or not clean)



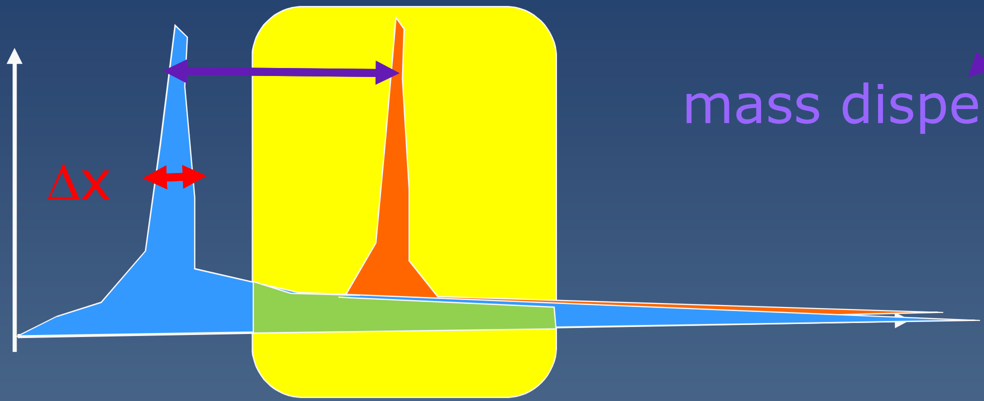
noise,background,distribution tails..

rejection of unwanted particle

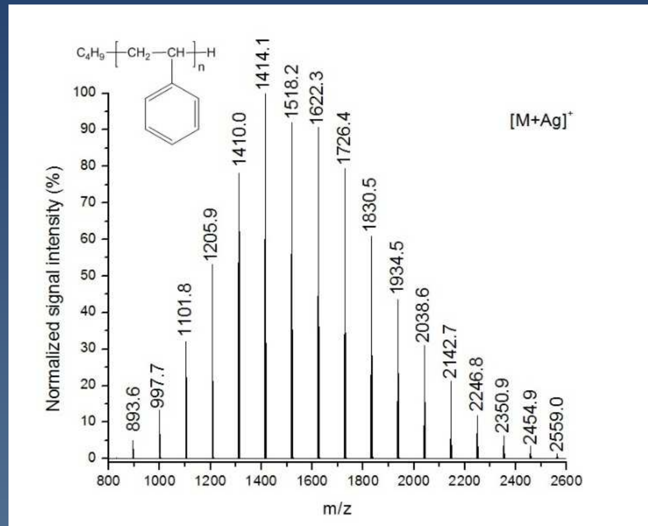
bad selectivity for the particle of interest

Spectrometer measurement : performances

-Resolution $R_{fwhm} = \Delta x_{fwhm} \,/\, dx/dm$



mass dispersion



-Acceptance : -Mass range

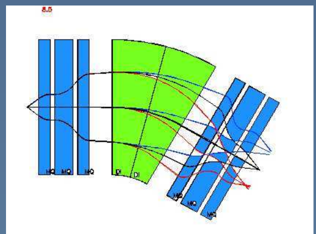
-Angular acceptance

(solid angle: steradian)

Rejection = Nb of unwanted particles (final) / Nb of unwanted particles (initial)

II) Spectrometers & separators

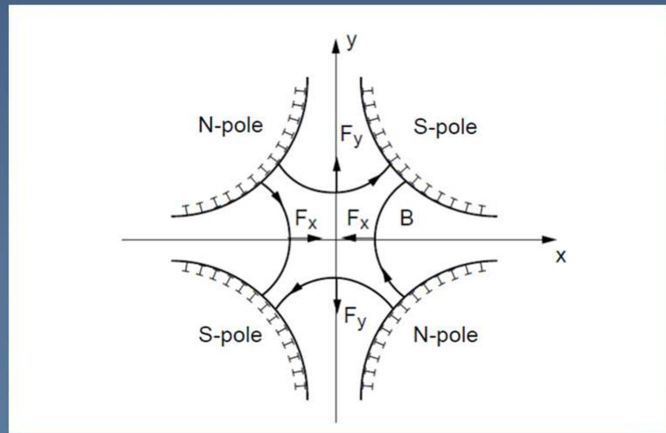
with accelerator's beams



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

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

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



Spectrometers & separators with accelerator beams

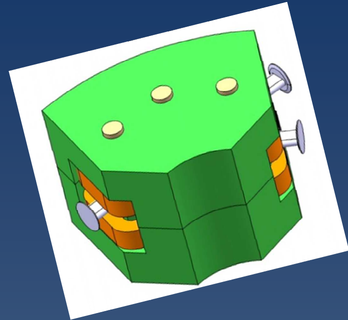
1) Why a spectrometer ? Part 1

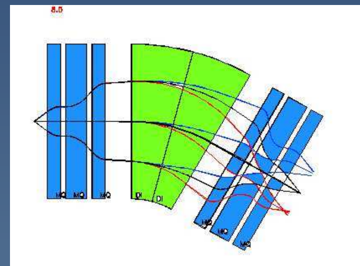
2) Designing a spectrometer (1rst approach)

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

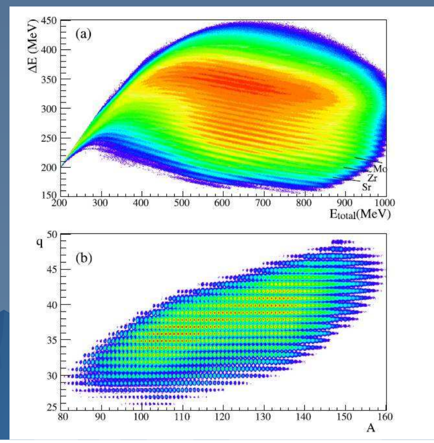
Part 2
5) Fragments separators (100MeV/A-500 MeV/A)

6) Tuning And Diagnostics





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



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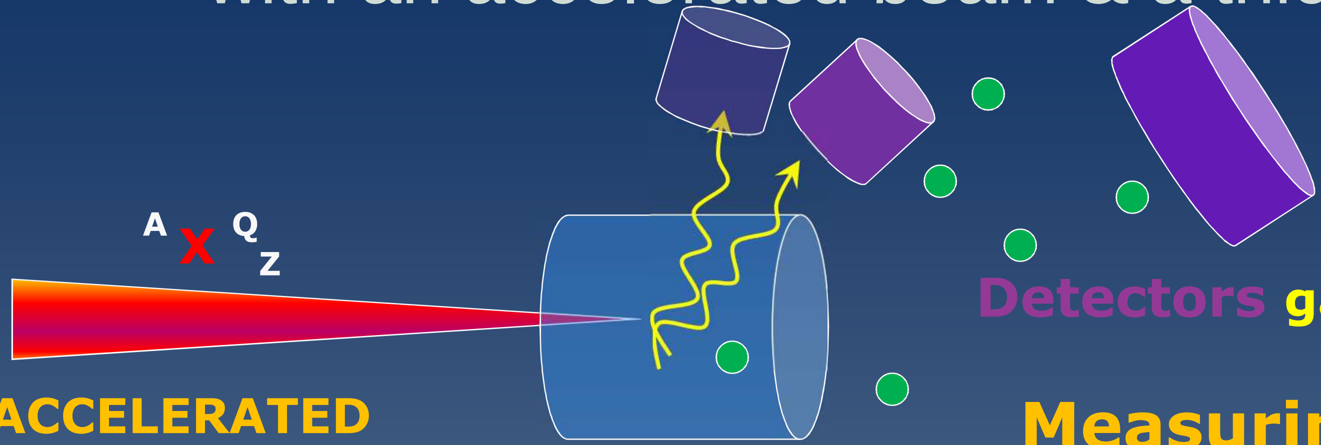
An experiment with an accelerated beam & a thick target



Measuring σ, γ spectroscopy,...

$$^{A}X_{Z} + \text{Target} \rightarrow n + {}^{A-1}X_{Z}^{*} \rightarrow \gamma + {}^{A-1}X_{Z}$$

Reaction of interest, but

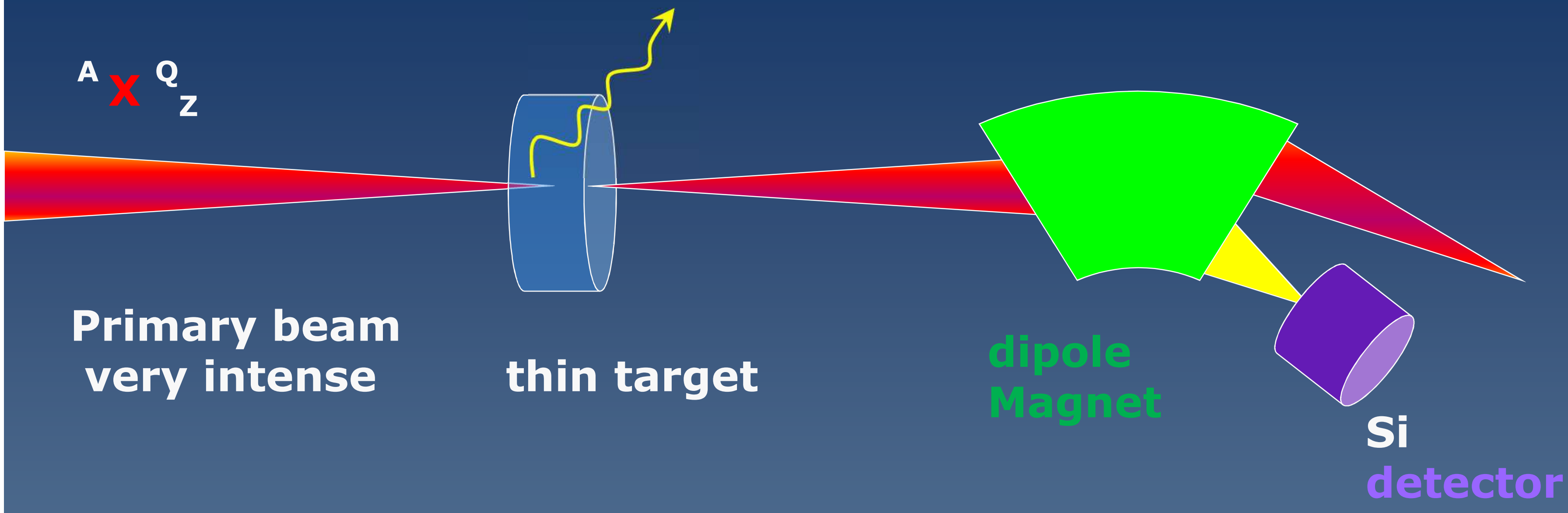
Many reaction channels

$$^{A}X_{Z} + \text{Target} \rightarrow 2n + {}^{A-2}X_{Z}^{*}$$

$$^{A}X_{Z} + \text{Target} \rightarrow 3n + 1p + {}^{A-3}X_{Z-1}$$

Reaction products not identified , ion energy not measured

An other experiment with a thin target & and a spectrometer



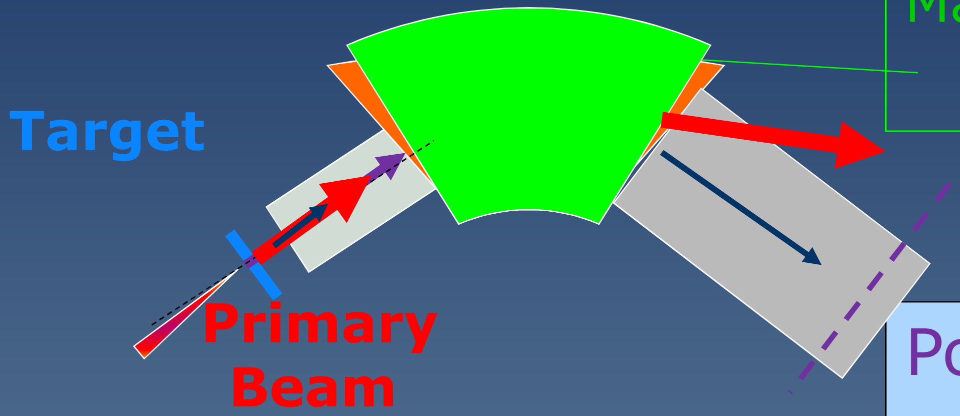
Eletromagnetic spectrometer

- **Eliminate primary beam (~ 10^{11-13} particles per second)**
- **Help to identify the reaction products**

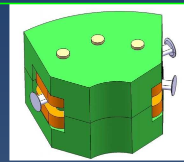
- **Measure Energy with very good resolution**
- **Select very rare events (selectivity)**

Let's design a simple Magnetic spectrometer

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



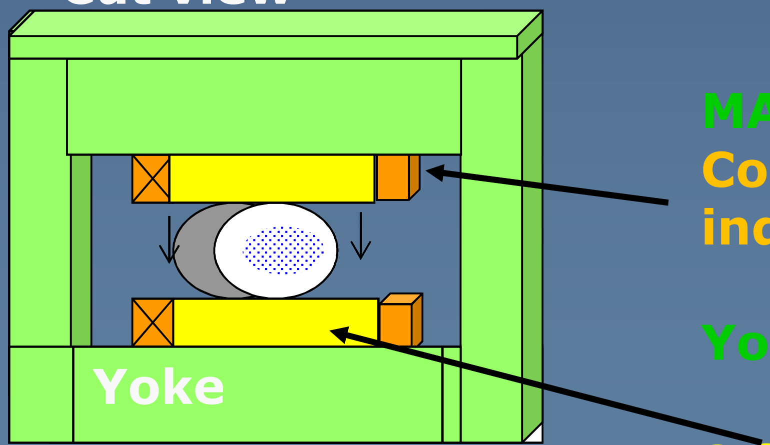
Magnetic dipole



Positions Xfinal ?

Xf=F(Mass of ions,…)

Cut view



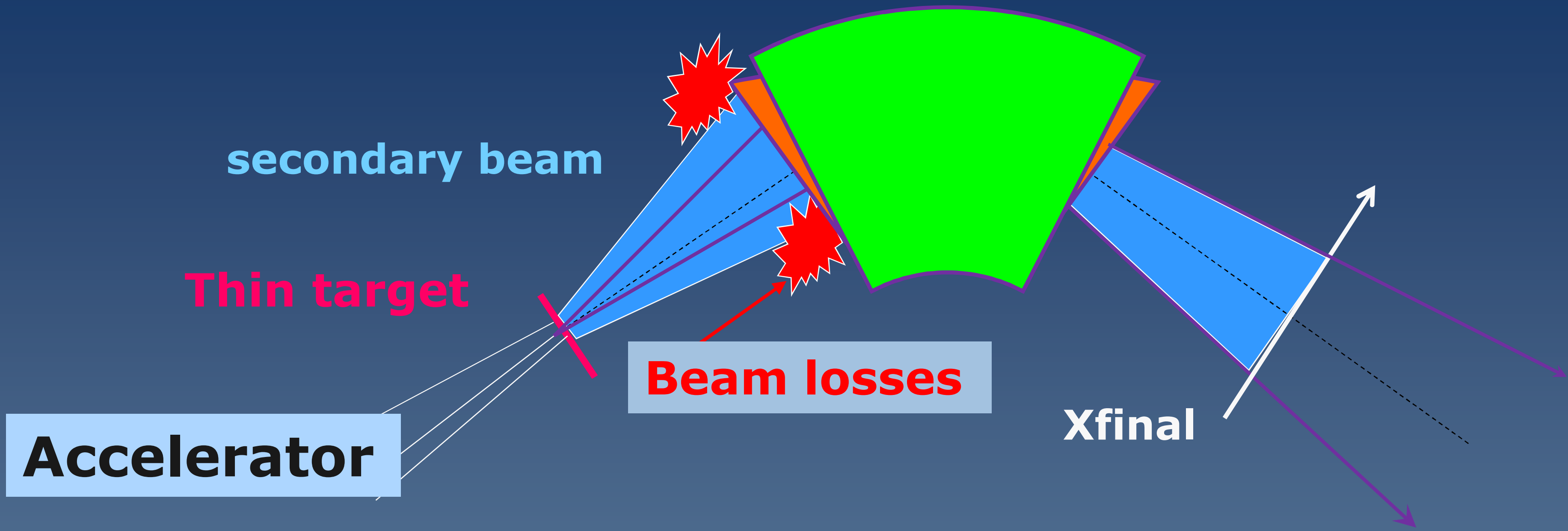
MAGNETIC DIPOLE : By=Constant

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

Yoke (guide the field lines to the pole)

2 flat poles : By=Constant

2 problems with 1 dipole magnet : Acceptance & identification



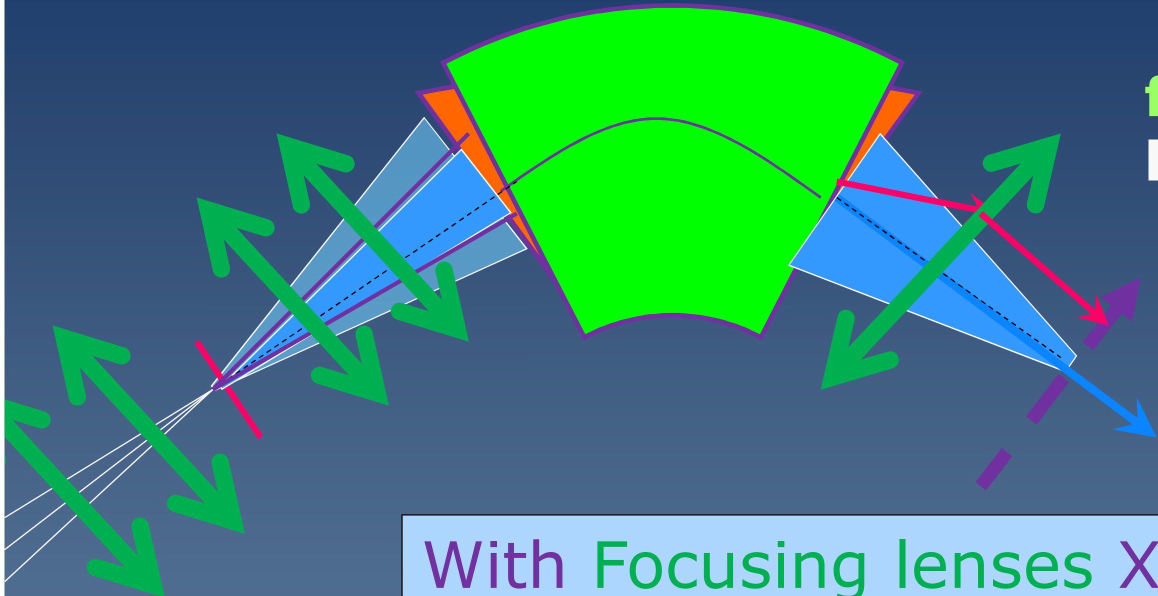
-1: Many particles are lost in the magnet (very bad)

-2: Trajectories are complex (bad)

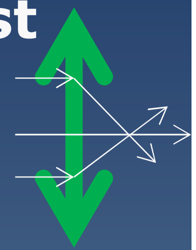
Xfinal =f(Bρ , θi, ϕi , X0,Y0)

- 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



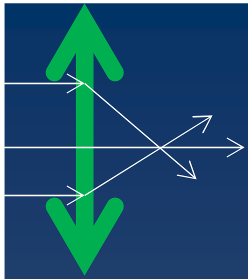
Xf

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

less unknowns ! **Less beam losses**!!

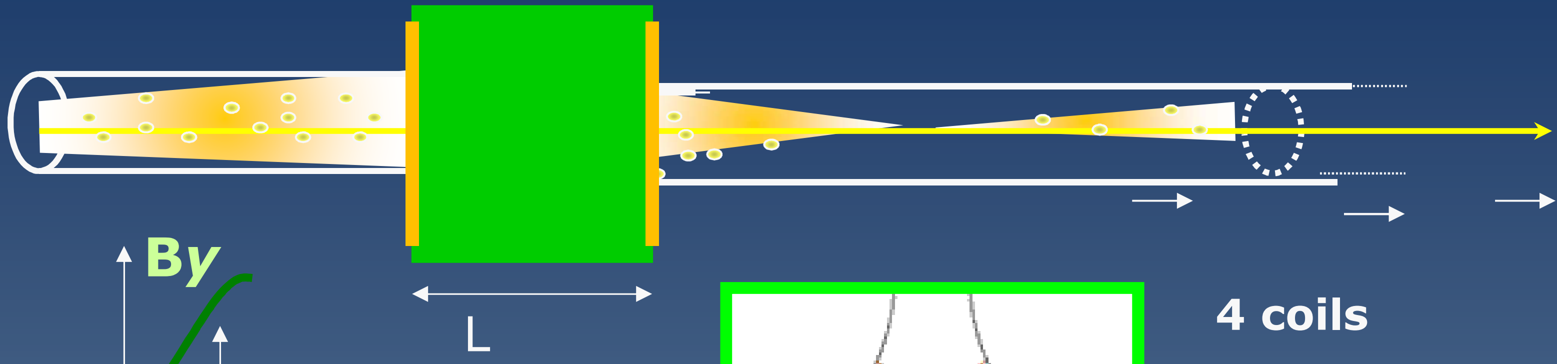
At one location s (the detector location, called focal plan)
The trajectoires are independant of the angles θi, φi
And the initial position is $x_0=0$, $y_0=0$

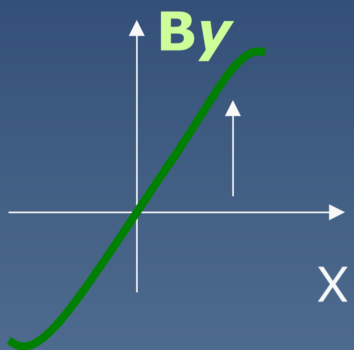
Xf=F(Bρ , ~~θi, φi, X0,Y0~~)



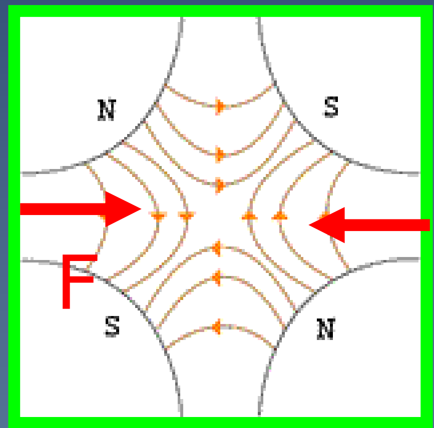
How to construct a Focusing lens for ions :
Magnet with 4 poles (+,-,+,-)

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





G=dBy/dx

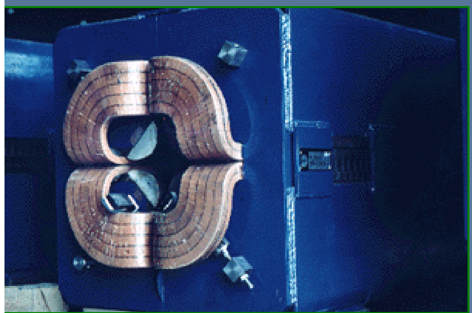


4 coils

+4 hyperbolic poles

By=G.X

G is called GRADIENT [Tesla/m]



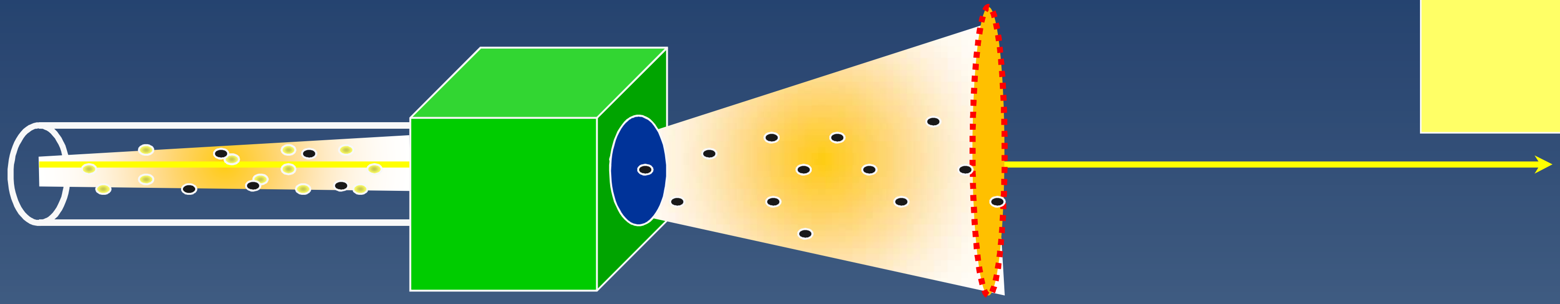
The quadrupole magnet is focusing

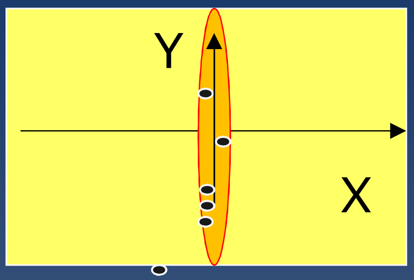
in HORIZONTAL PLAN

Nota: In the center, the force is zero

A quadrupole magnet

Focusing lens in horizontal
But defocusing in vertical





The beam becomes narow in X   and large in Y

$B_x = G.Y$

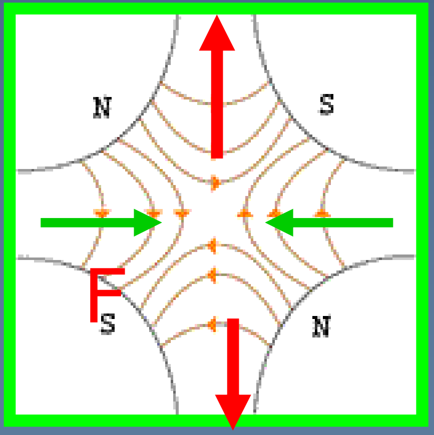
$B_y = G.X$

$B_s = 0$

Focusing in X   (G>0)

Defocusing in Y (G>0)

Since the Force is defocusing in vertical



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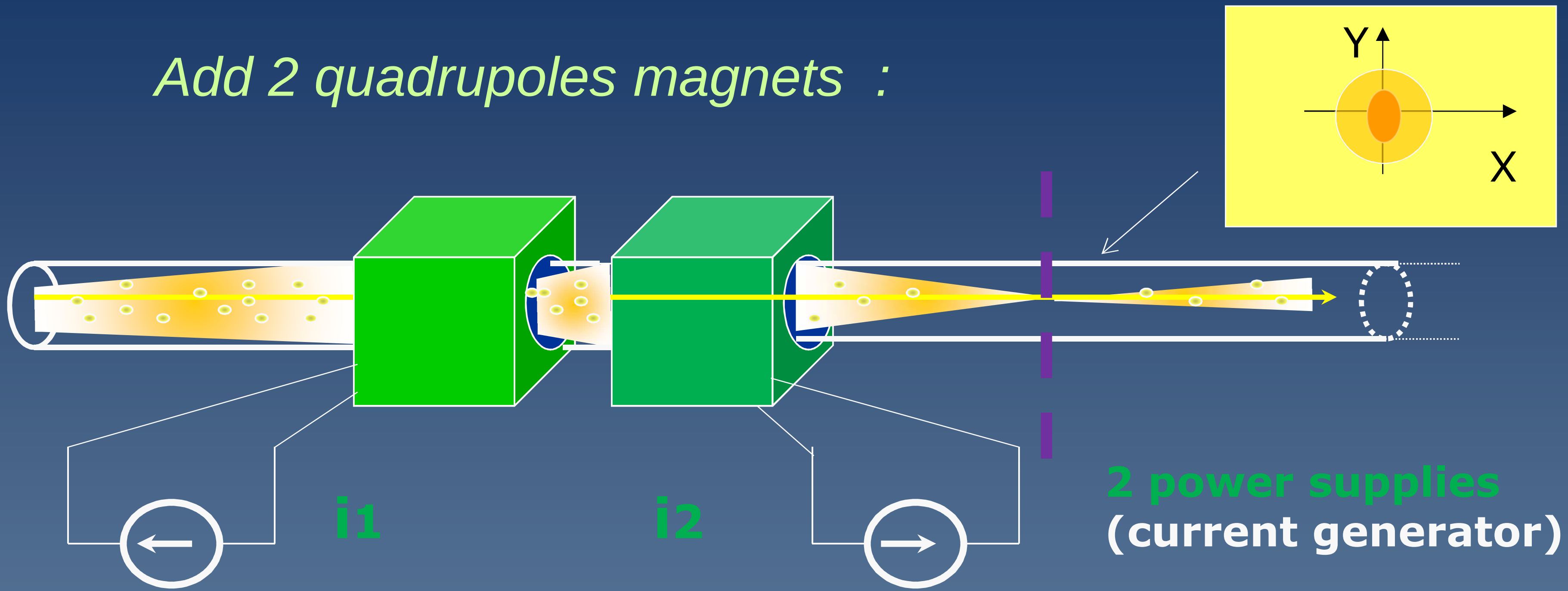
How to construct a Focusing lens System In horizontal AND vertical plan

Add 2 quadrupoles magnets :



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

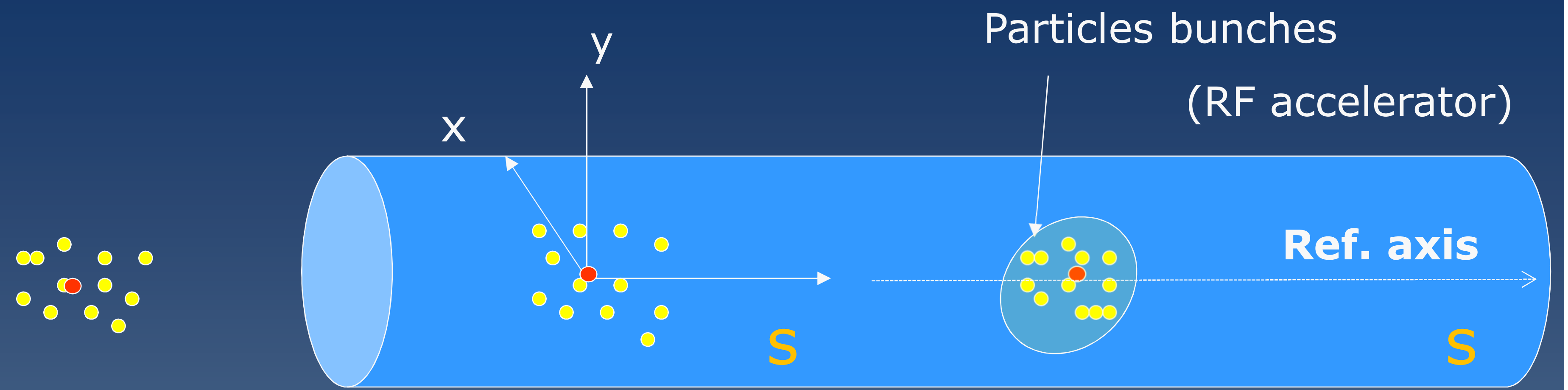
Beam optics (basics)

- 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-X0) ,(Y-Y0)

+ *2 angles* θ, ϕ

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

+*(t –to) 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 $\overrightarrow{Z(S_0)}$

$$\vec{Z} = \begin{pmatrix} z1 \\ z2 \\ z3 \\ z4 \\ z5 \\ z6 \end{pmatrix} = \begin{pmatrix} x \\ x' = \frac{dx}{ds} \\ y \\ y' = \frac{dy}{ds} \\ l = v_0(T - T_0) \\ \delta = \frac{B\rho - B\rho_0}{B\rho_0} \end{pmatrix} = \begin{pmatrix} horizontal\ displacement \\ horizontal\ "angle" \\ vertical\ displacement \\ vertical\ angle \\ longitudinal\ difference \\ "momentun(B\rho)"\ deviation \end{pmatrix}$$

$\vec{Z} = (x, x', y, y', l, \delta)$

6Dim

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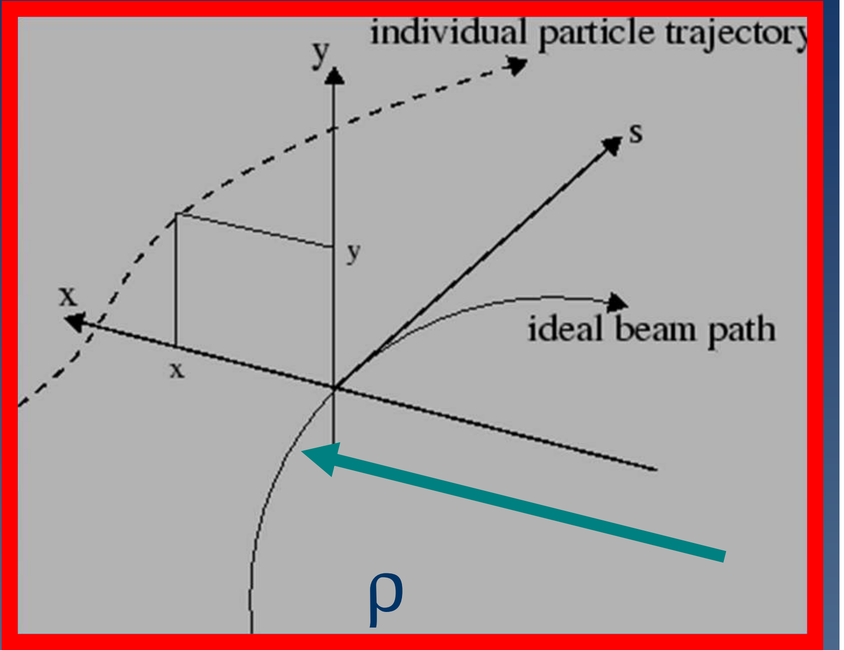
Trajectory equations for 1 particle

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

We use a

curvilinear Reference Frame

which follows the reference particle



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

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

Coordinate change t ⟹ s

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

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

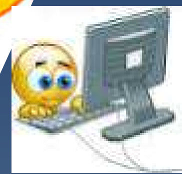
$$\frac{d}{ds}\left[m\gamma\,\mathbf{v}\right] = \ldots$$

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]

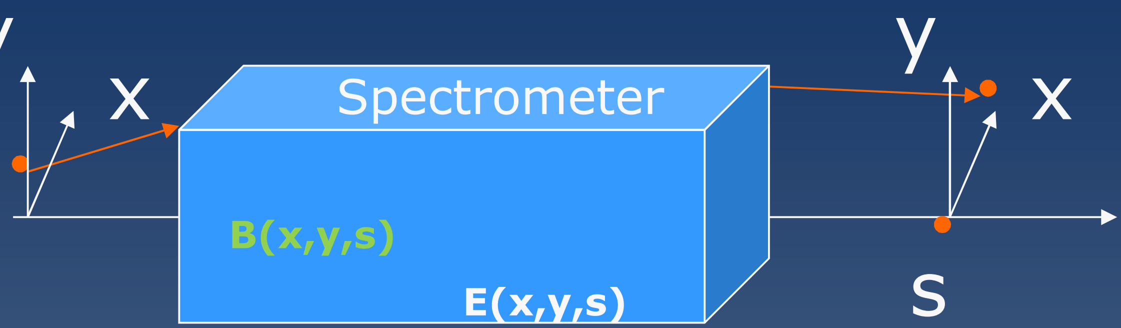
2) Integrate the equations for **ALL the particles**
(computer+ Numerical method: Runge-kutta)

Generally we can do simpler

Matrix approach (1rst order approximation)

Beam optics with Matrices

$$Z_1 = (x, x', y, y', l, \delta)_1$$



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

Exact Dynamic (non linear)

Taylor expansion

(X and Y Are small..)

Linear dynamics

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

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

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The simplest transport Matrice:

Rmatrix for a straight section L (drift)

Particle Evolution in drift length between s1 & s2 :

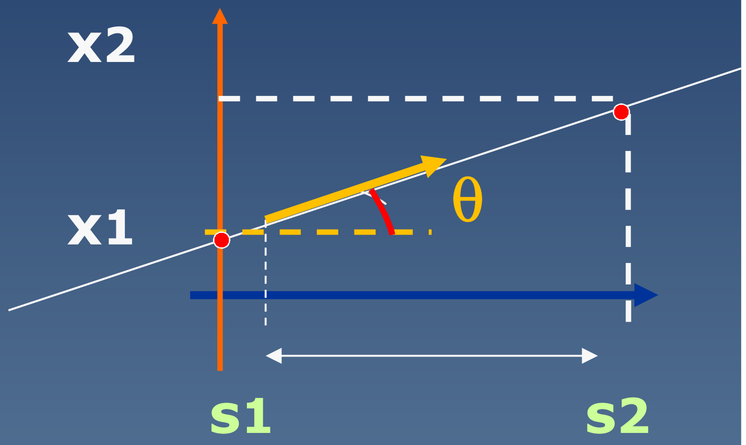
x=x(s) ???????

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

$\theta 1 = \theta 2$

nota: $\tan(\theta 1) = \Delta x1/\Delta s = x1'$

and (s2-s1)=L



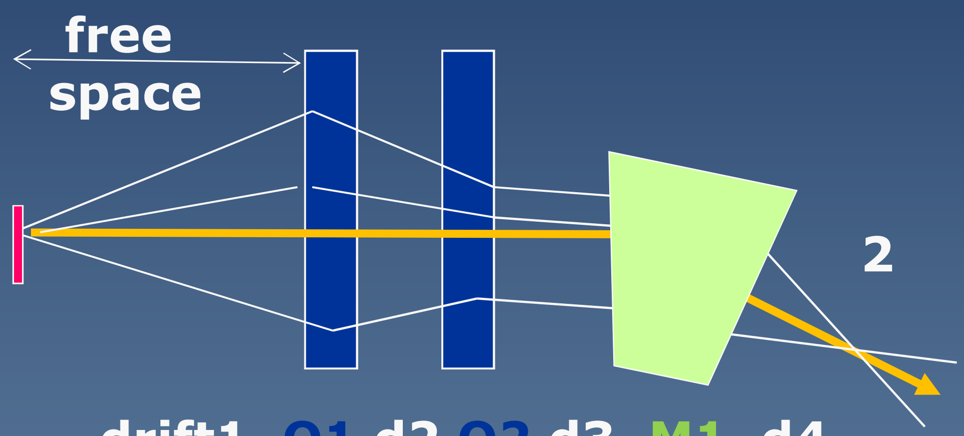
$$\begin{pmatrix} x2 \\ x2' \\ y2 \\ y2' \\ \dots \end{pmatrix} = \begin{pmatrix} 1 & L & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} x1 \\ x1' \\ y1 \\ y1' \end{pmatrix}$$

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

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

The transport Matrix R allows the computation of the coordinates of a particle at the end of a spectrometer

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

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

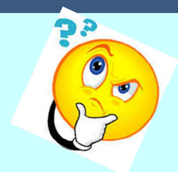
$\vec{Zout} = R.\vec{Zin}$

$$\begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix}_1 = \begin{bmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & R_{55} & R_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{bmatrix}_0$$

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

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

Interpretation of R



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

$ex:$

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

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

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

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

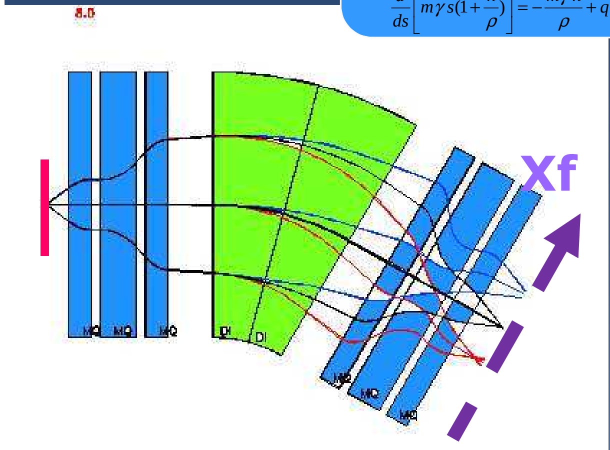
SPECTROMETER TRANSPORT MATRIX R

allow the simulation of 1 trajectory (easily)

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

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

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



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

Typical spectrometer Matrix is simple

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

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

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

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

$B\rho_o$ = **Bdipole**. Rdipole

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The beam size : important for the design

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

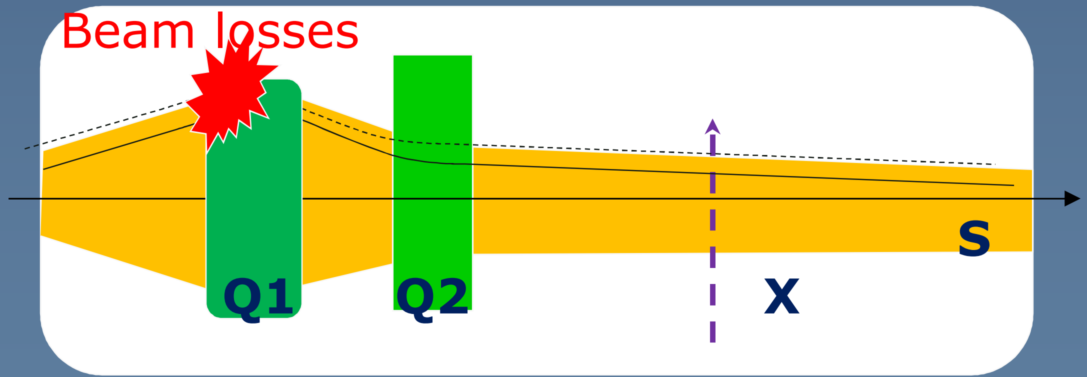
We are not interested by only 1 trajectory/1 particle

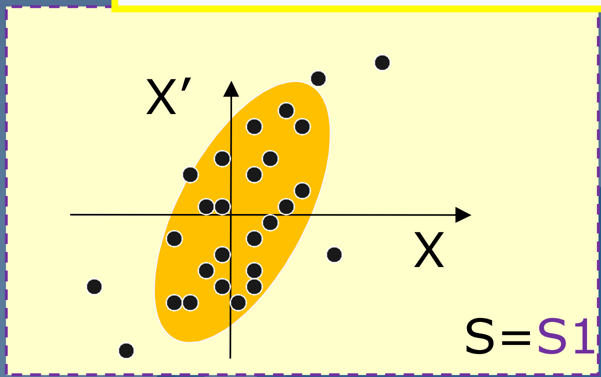
A beam is an ellipsoid in 6D with a given size

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

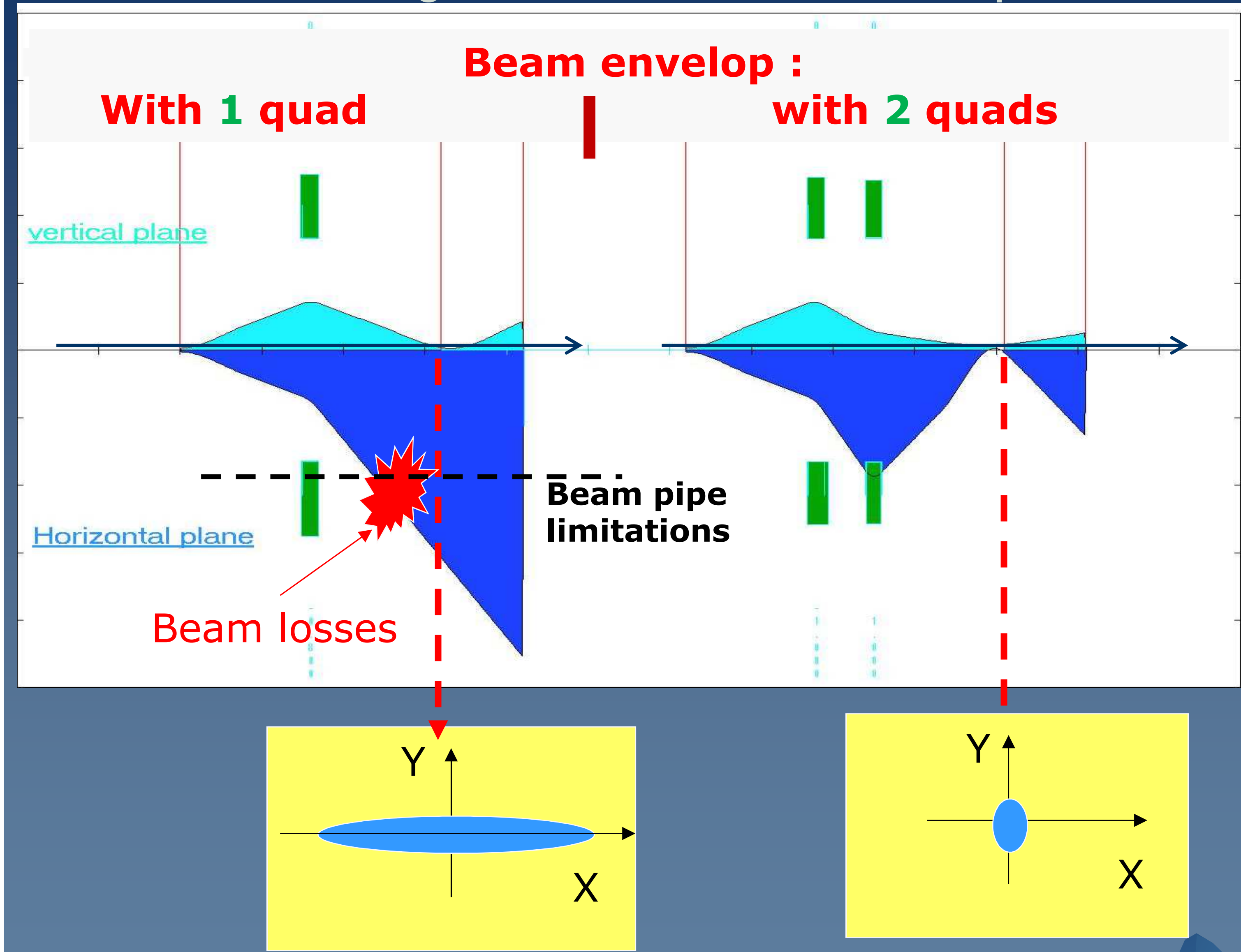
σx (horizontal width) , σy (vertical width)

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





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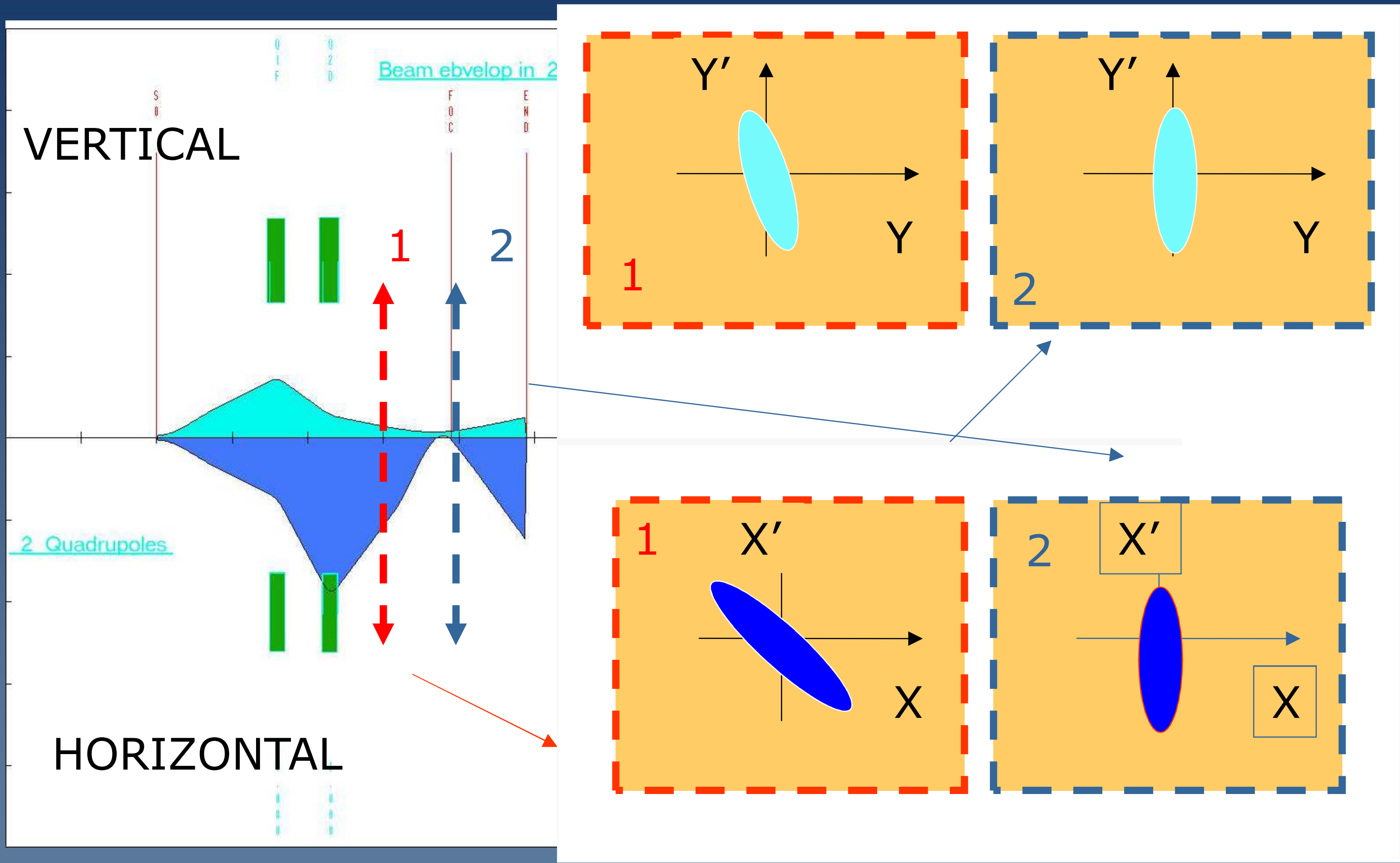
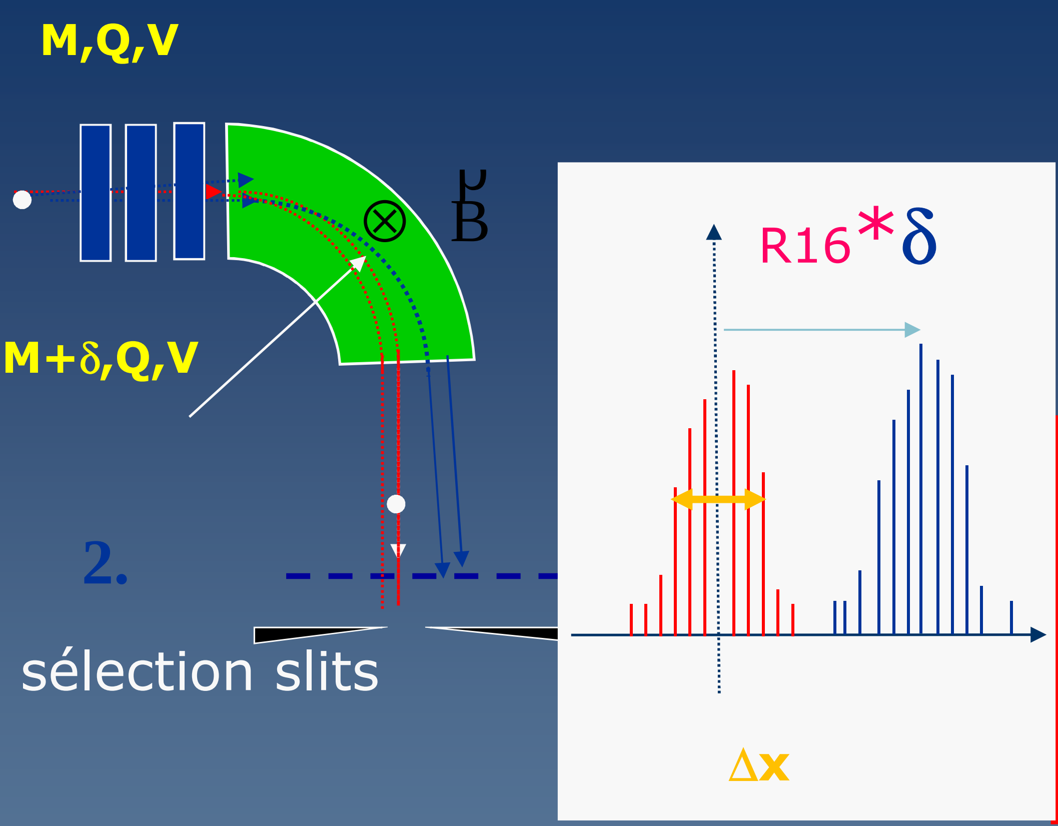
Angular distribution (x') in a beam line ?
The beam ellipse is rotating in (x, x'=dx/ds)



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

Resolution of a magnetic spectrometer



particles are separated

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

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

=Minimal difference in Bρ

for the identification

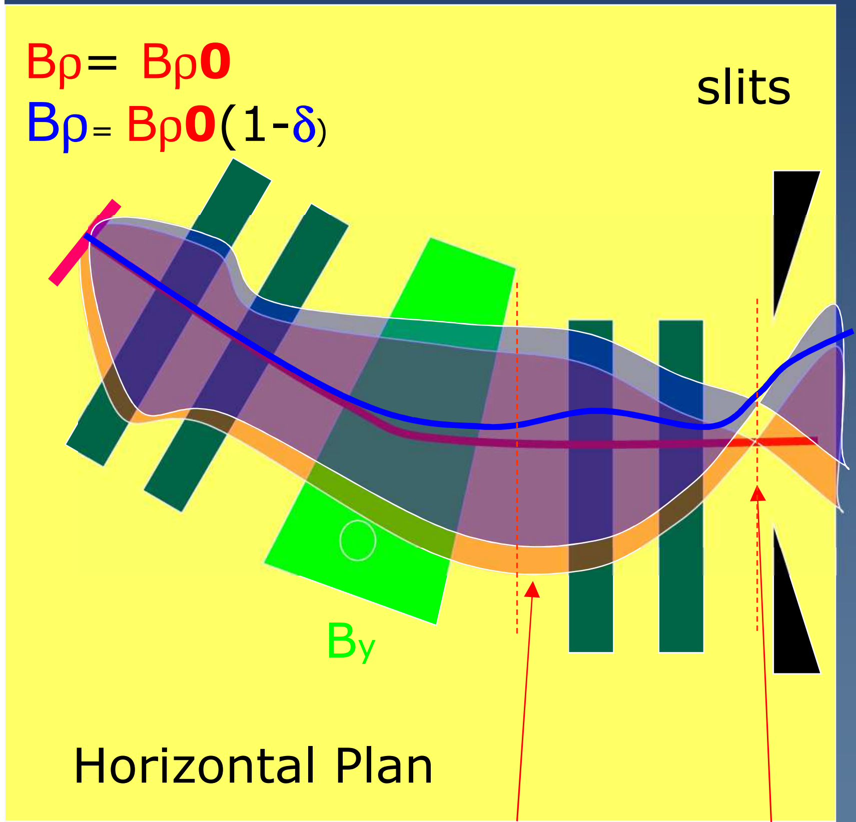
or for separation

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

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

The resolution R (separation)

is optimal at the focus point (size is minimal)



R=1/10

R=1/1000

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/R*16*) is optimal

When σx is small

and R*16*(dispersion) is large

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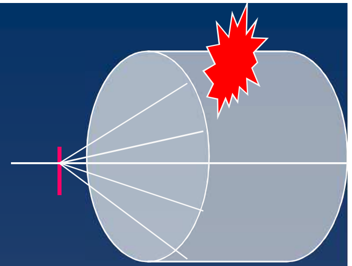
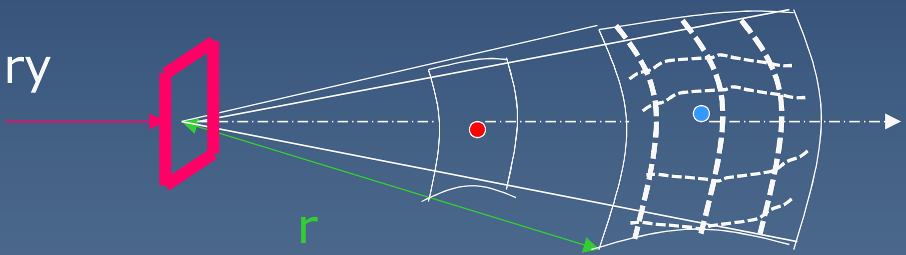
Angular acceptance



The reaction products exit from the target with an

Angular dispersion

Vacuum chamber limitation induces beam losses = less transmission



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

The acceptance

is measured in steradian.

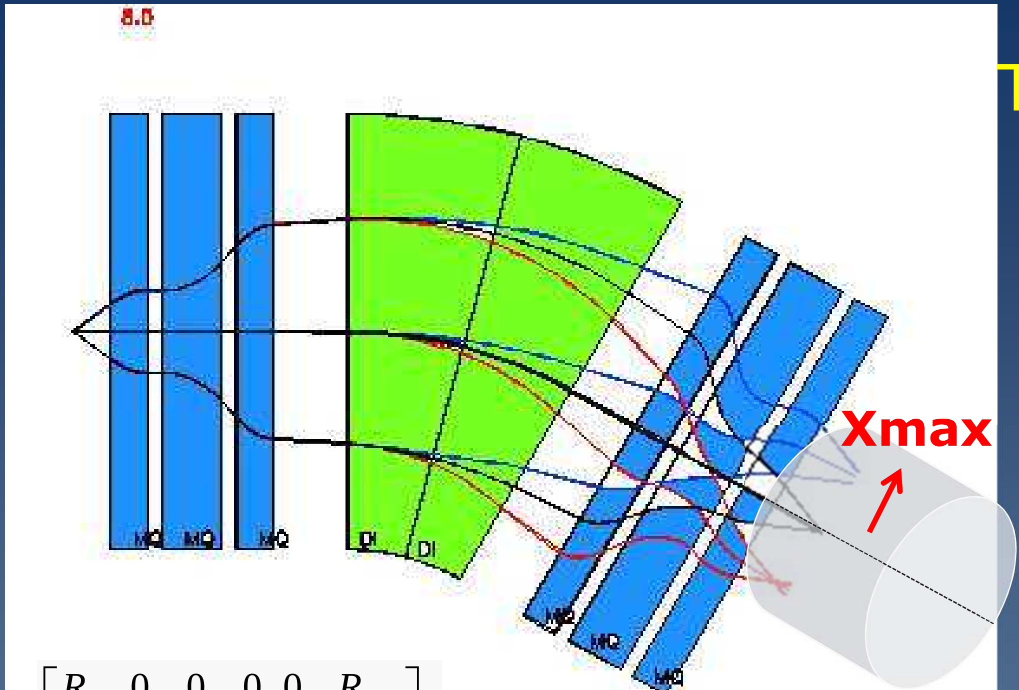
Example: If particles inside **±50mrd** (Horizontal & vertical) are transmitted

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 $\delta = [B\rho - B\rho_0] / B\rho_0$

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

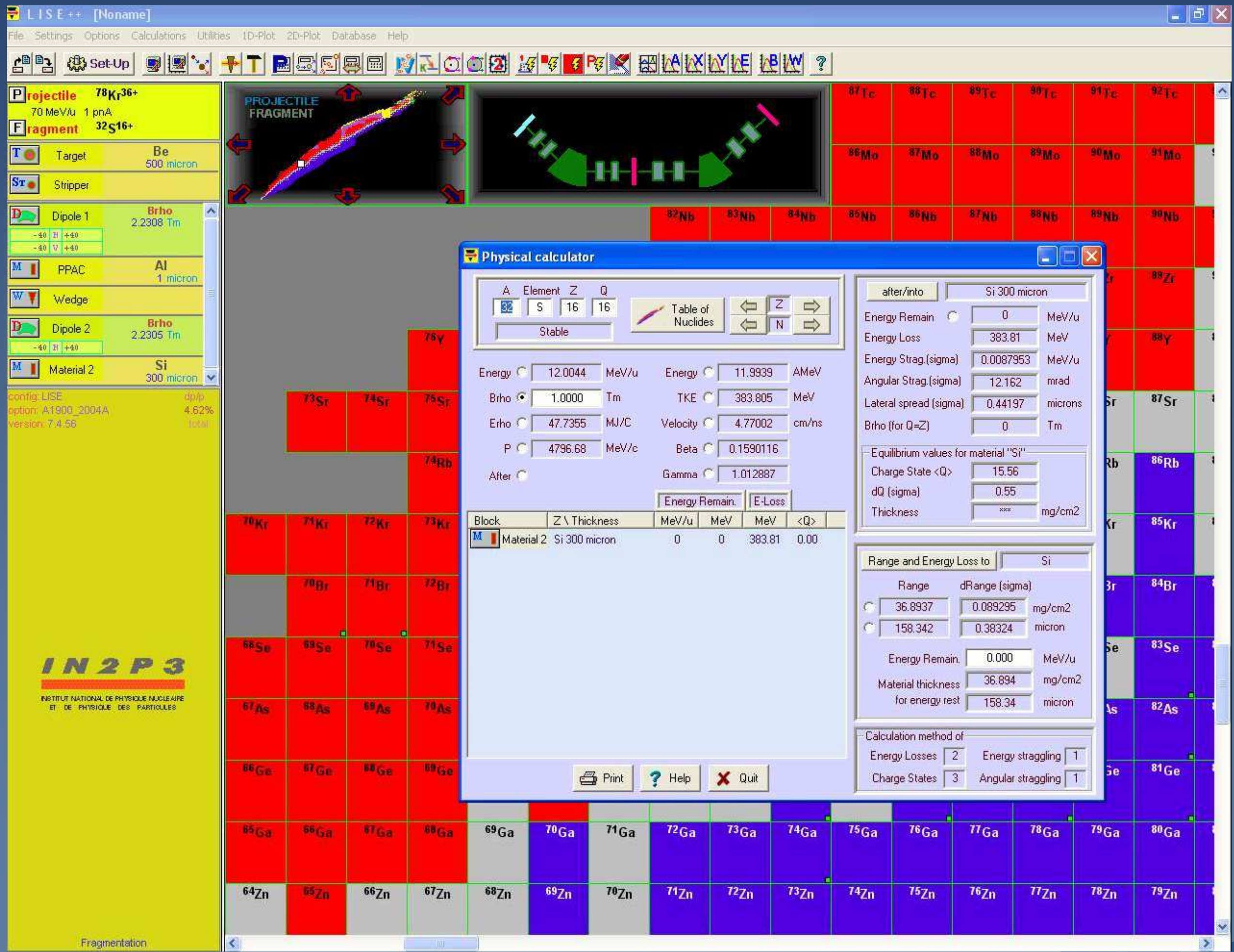
Beam pipe limit: Xmax

$$B\rho \text{ Acceptance} = \pm\, X_{max} / R_{16}$$

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

Bρ Acceptance= ± 2 %

How to simulate an experiment with a spectrometer in nuclear physics

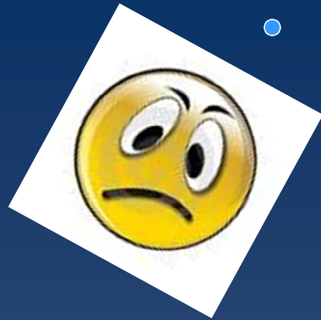


LISE++

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 (R_{16}=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 ?

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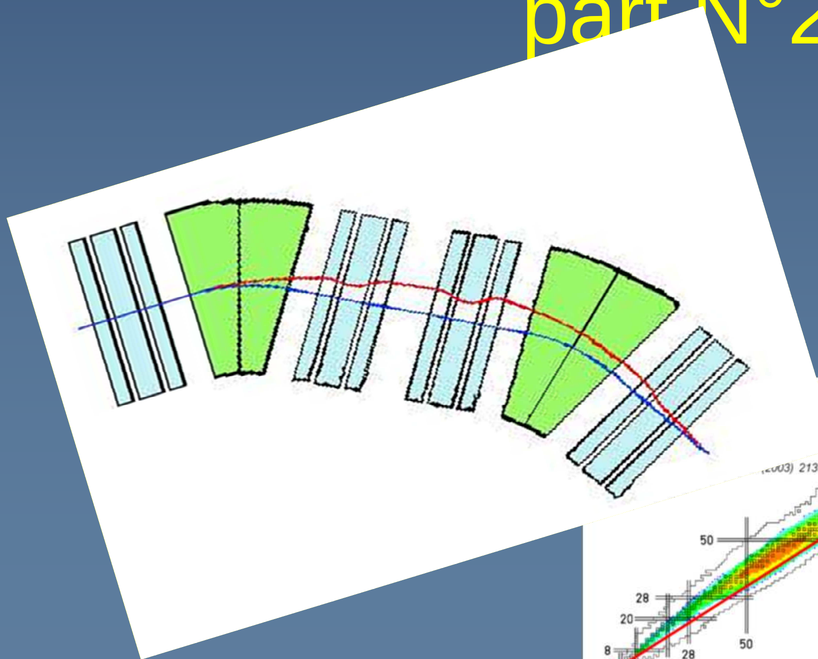
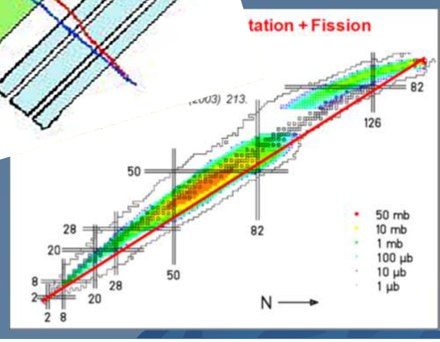
II) Spectrometers

with accelerator beams

part N°2

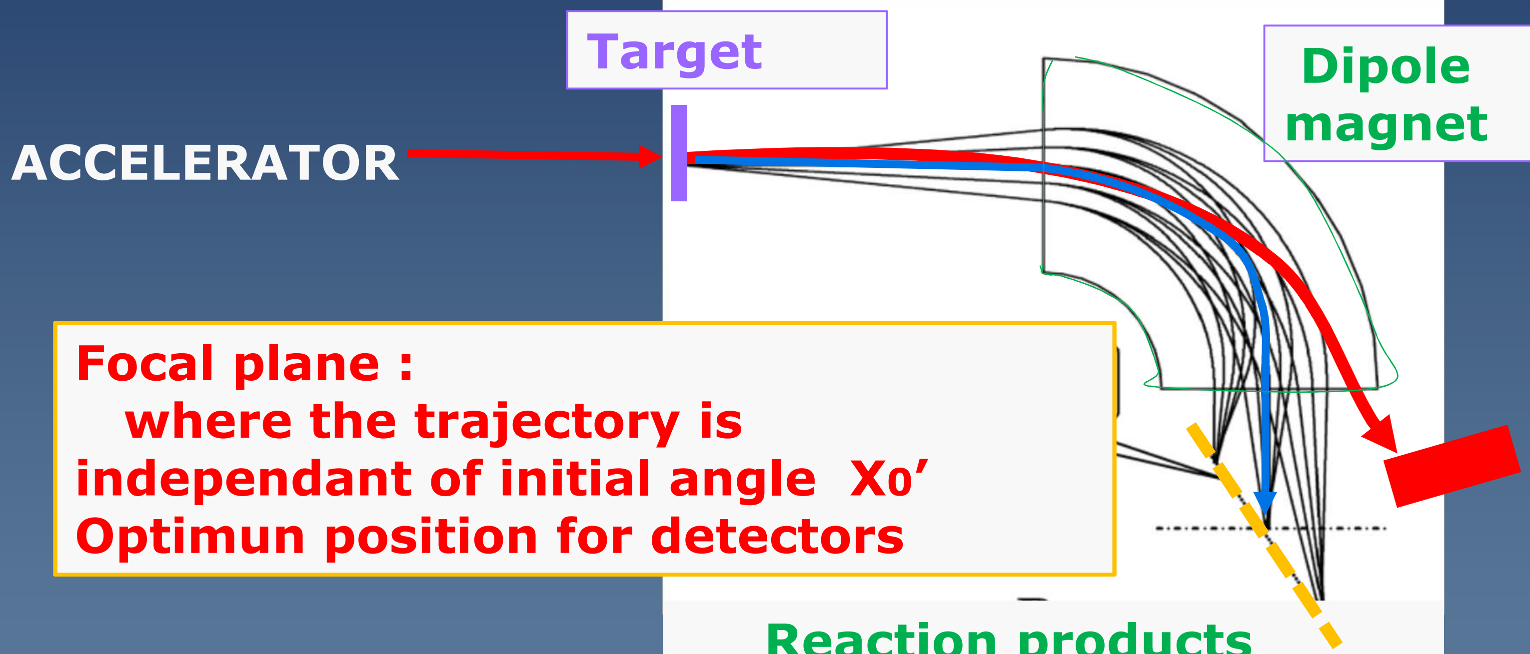




Magnetic Spectrometer recap

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

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



Focal plane :
where the trajectory is independant of initial angle X_0'
Optimun position for detectors

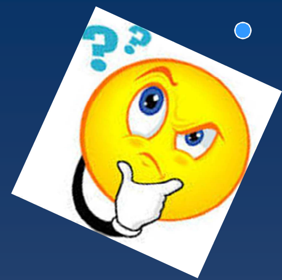
Reaction products

$Xf \sim F(B\rho)$

$Xf = R_{11}\ Xtarget + R_{16}\ \delta$

$\approx R_{16}\ (B\rho - B_0R_0)/\ B_0R_0$

Beam optics coordinates



- At the location S , a particle is represented by a vector ***Z(s) =(x, x’,y,y’, l, δ)***

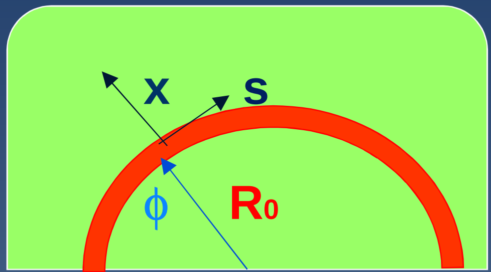
$$\vec{Z} = \begin{pmatrix} z1 \\ z2 \\ z3 \\ z4 \\ z5 \\ z6 \end{pmatrix} = \begin{pmatrix} x \\ x' = \dfrac{dx}{ds} \\ y \\ y' = \dfrac{dx}{ds} \\ l = \mathrm{v}_0 (T - T_0) \\ \delta = \dfrac{B\rho - B\rho_0}{B\rho_0} \end{pmatrix} = \begin{pmatrix} \textit{horizontal displacement} \\ \textit{horizontal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

HORIZONTAL ANGLE

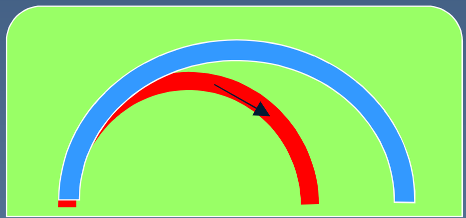
X’= dX/ds=tan(θ) ≈ θ

Rmatrix for a magnet (ϕ=180° exemple)

Frame = attached to the reference particle (circle with R=R0)
S = curvilinear abciss
What is the position of a particle with ($x_0 \neq 0, x_0' \neq 0$, $B\rho \neq B\rho_0$)



*
$x_{ref}(\theta = s/R) = 0$
Reference ($x_0=0, x_0'=0$, $B\rho = B\rho_0 = B_0 R0$)

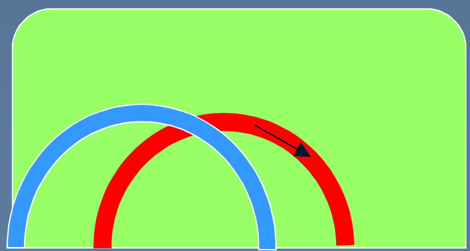


$R \neq R_0$

* **R_{16} : x final pos. if a different rigidity**

$$X(\phi=180°) - x_{ref} = 2\,(R - R_0)$$

$$X(\phi) = (1-\cos(\phi))\,(R-R0)$$
$$= (1-\cos(\phi))\,(B\rho - B\rho_0)/B0 =$$
$$= R_0 (1-\cos(\theta))\,(B\rho_0 - B\rho_0)/B\rho_0$$



$X0 \neq 0$

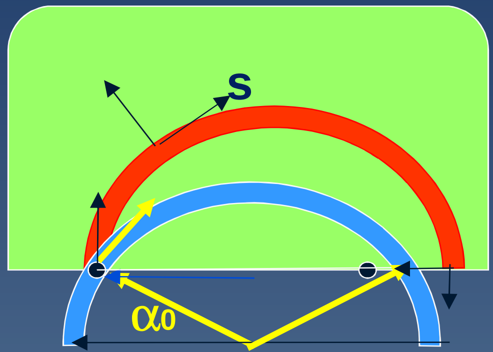
R_{11} : x final pos. if a different initial position

$$X(\phi=180°) = -X(\phi=180°) = -x0$$

$$X(\phi) = \cos(\phi)\, x_0 = R_{11}\, x_0$$

Rmatrix for a magnet (ϕ=180° exemple)

What is the position of a particle starting with an angle ($X'_0 = \tan(\phi_0)$)



R12= Trajectory with initial different angle
Arrive at different position

$X(\phi=180°) = 2R_0\,(1-\cos(\alpha_0))\ \#\ R_0\,X'_0$

$X'_0 = \tan(\alpha_0)$

$X(\phi)\ \#\ R_0 \sin(\phi)\ X'_0$

$$\text{Xfinal} = -R_{11}\,x_0 + R_{12}\,X_0' + R_{16}\,(B\rho_0 - B\rho_0)/B\rho_0$$
$$= -\cos(\phi)\,x_0 + R_0 \sin(\phi)\,X_0' + R_0(1-\cos(\phi))\,\delta$$

$$\mathbf{M}_{dipole} = \begin{pmatrix} \cos\varphi & R\sin\varphi & 0 & 0 & 0 & R(1-\cos\varphi) \\ -1/R\cdot\sin\varphi & \cos\varphi & 0 & 0 & 0 & \sin\varphi \\ 0 & 0 & 1 & R\varphi & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -\sin\varphi & -R(1-\cos\varphi) & 0 & 0 & 1 & R\varphi/\gamma^2 - R(\varphi-\sin\varphi) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Transport matrix For a dipole with angle ϕ

The R matrix of spectrometer

: first order theory

A spectrometer generally

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)

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

$$l = v_0(t - t_0)$$

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

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 : selection and identification of radioactive isotopes (T1/2 ~ 10ms-1s)

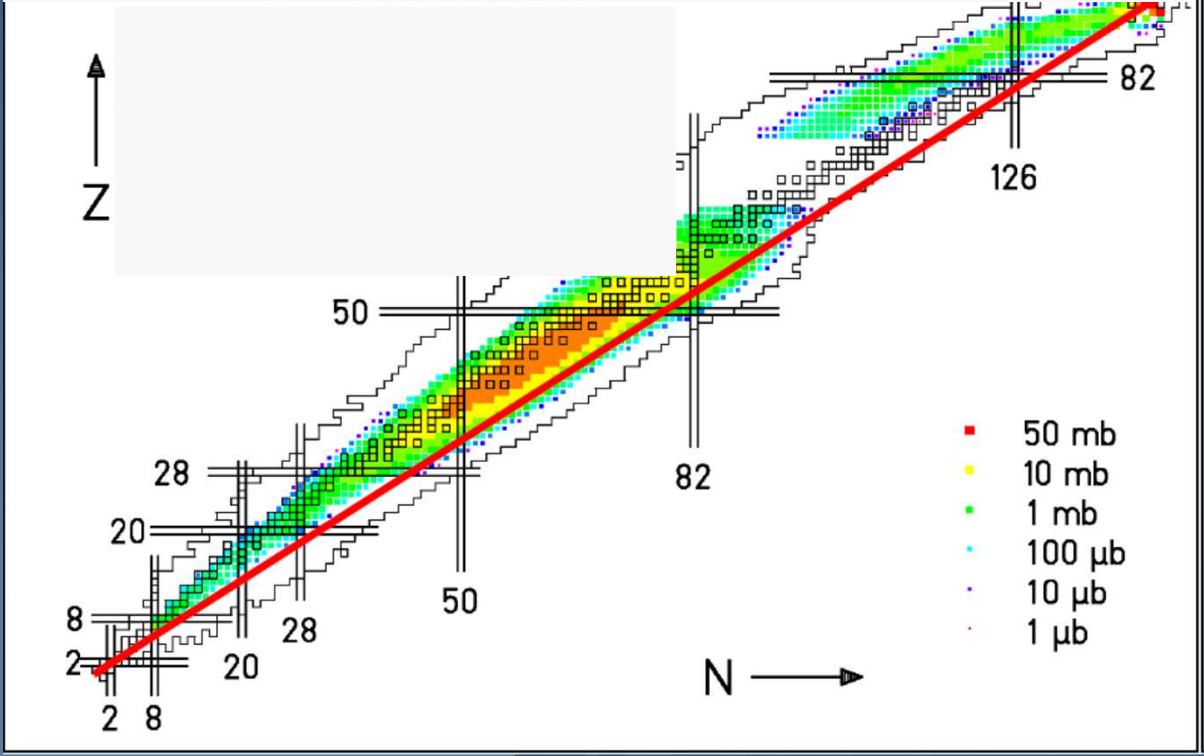
Reaction : fragmentation or U fission

accelerator ion beams at 100-1000 MeV/A

β=0,40 -0,85

GOAL
The production & study of exotic nuclei beyond the region of nuclei known today

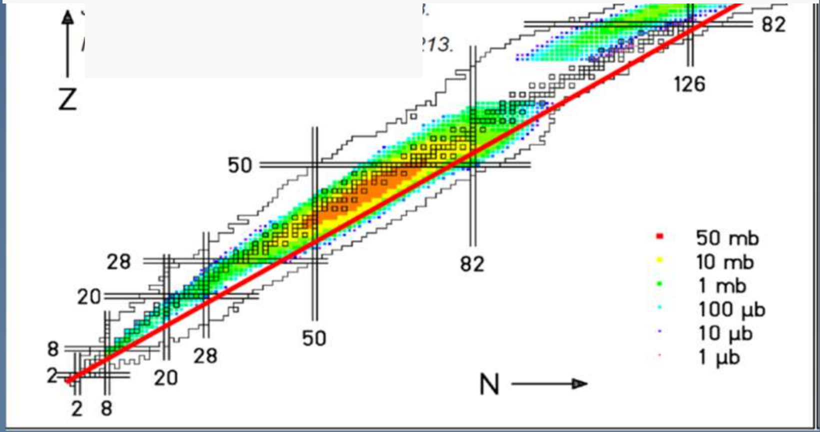
^{238}U beam on Be Target@300MeV/A
Production of many istopes



Fragment Separators : selection of a specific isotopes

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

^{238}U beam on Be Target
Production of many isotopes

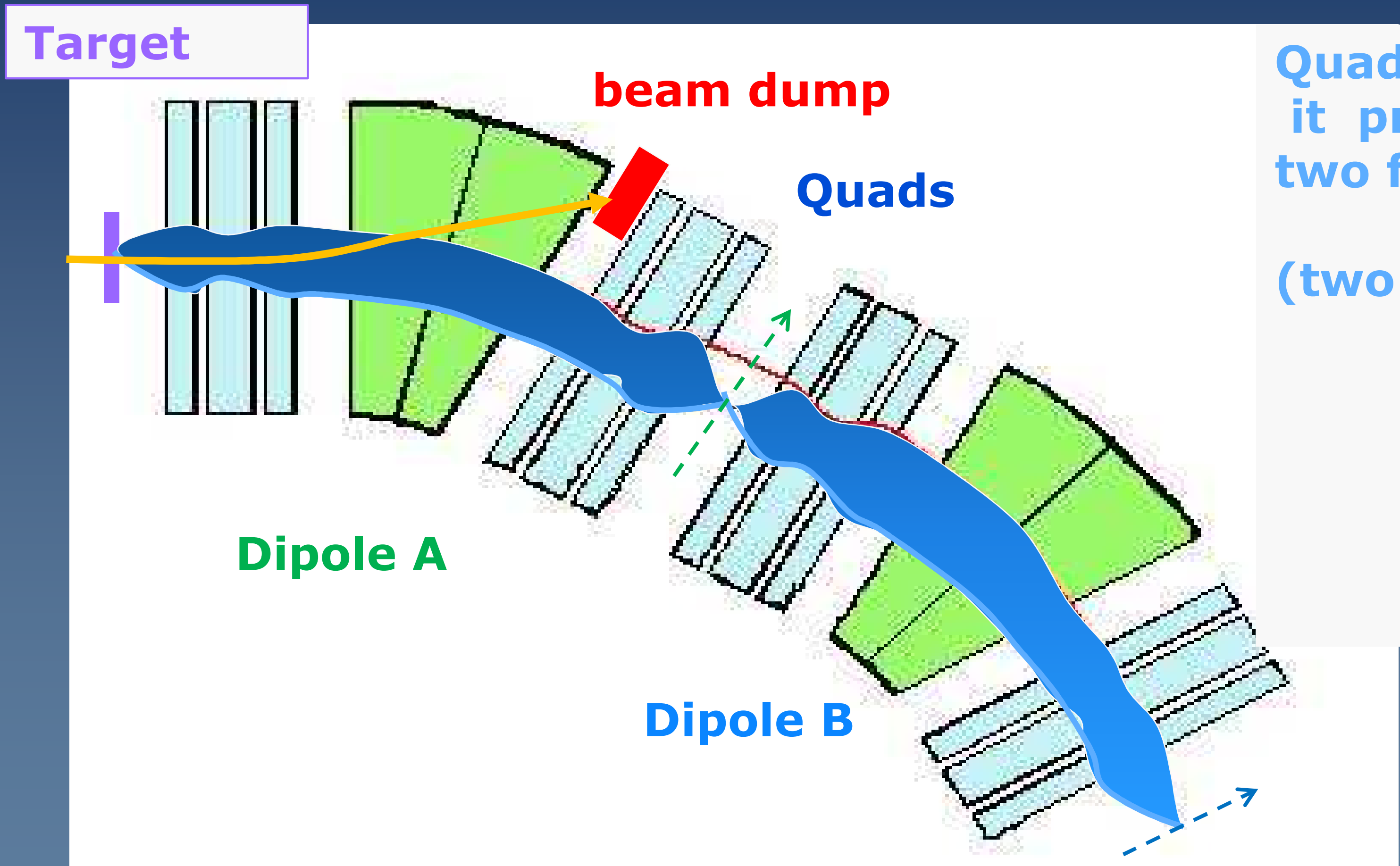


Purification to focus on A specific isotope

Measurement : (Mass; gamma spectroscopy…

Fragment separator

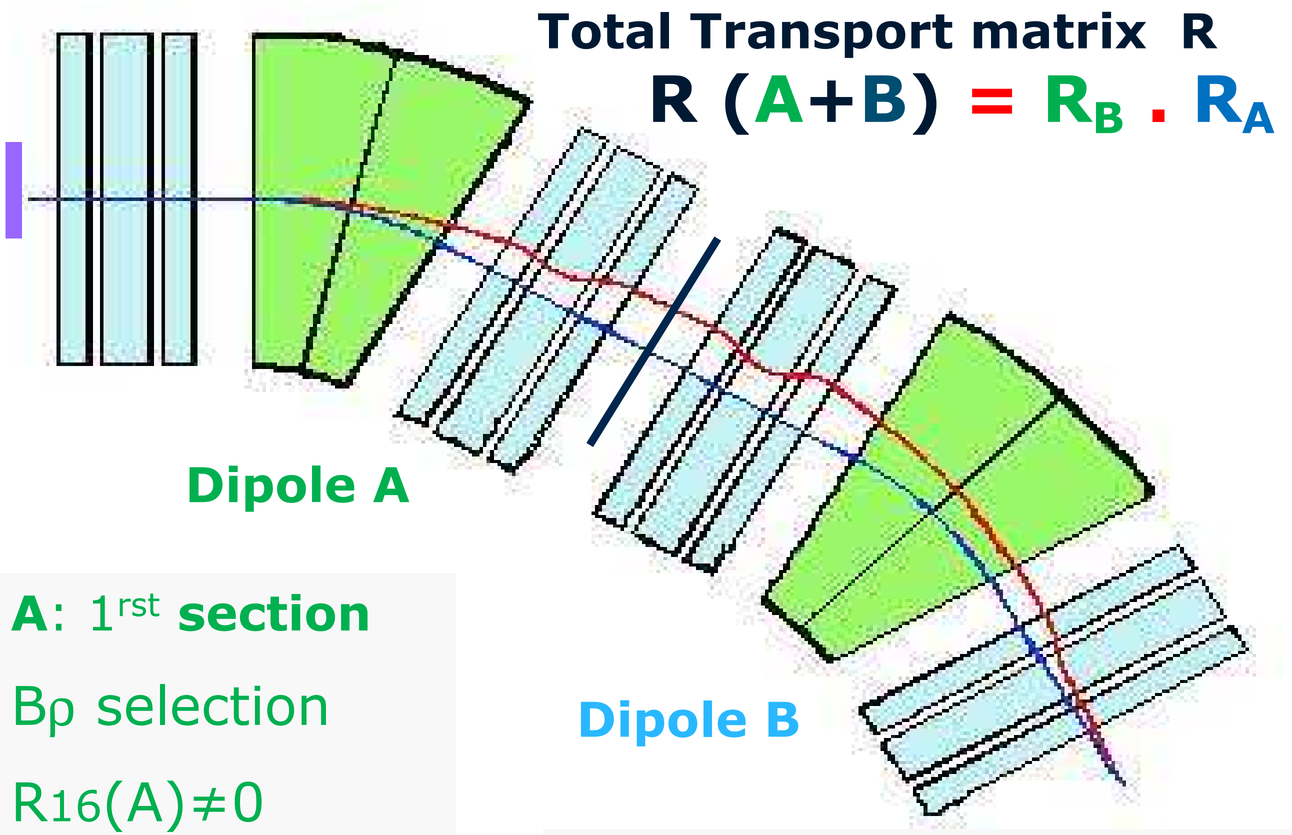
2 symmetric sections : A & B



Quad setting :
it produces two focii

(two focal planes)

Fragment separator :2 symmetric sections



Total Transport matrix R

$$R\,(A+B) = R_B \cdot R_A$$

A: 1rst **section**

Bρ selection

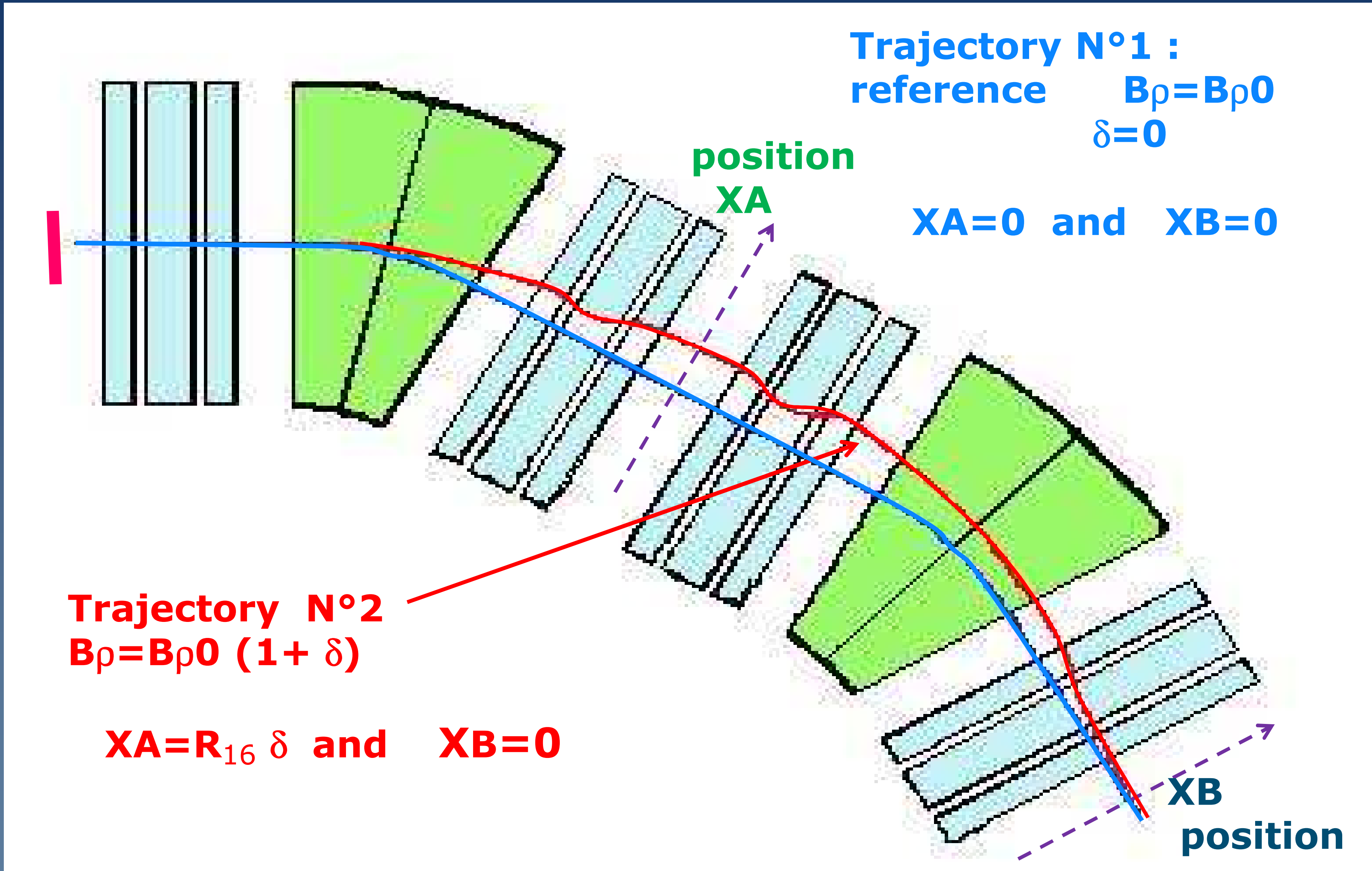
$R_{16}(A) \neq 0$

B: 2nd **section**

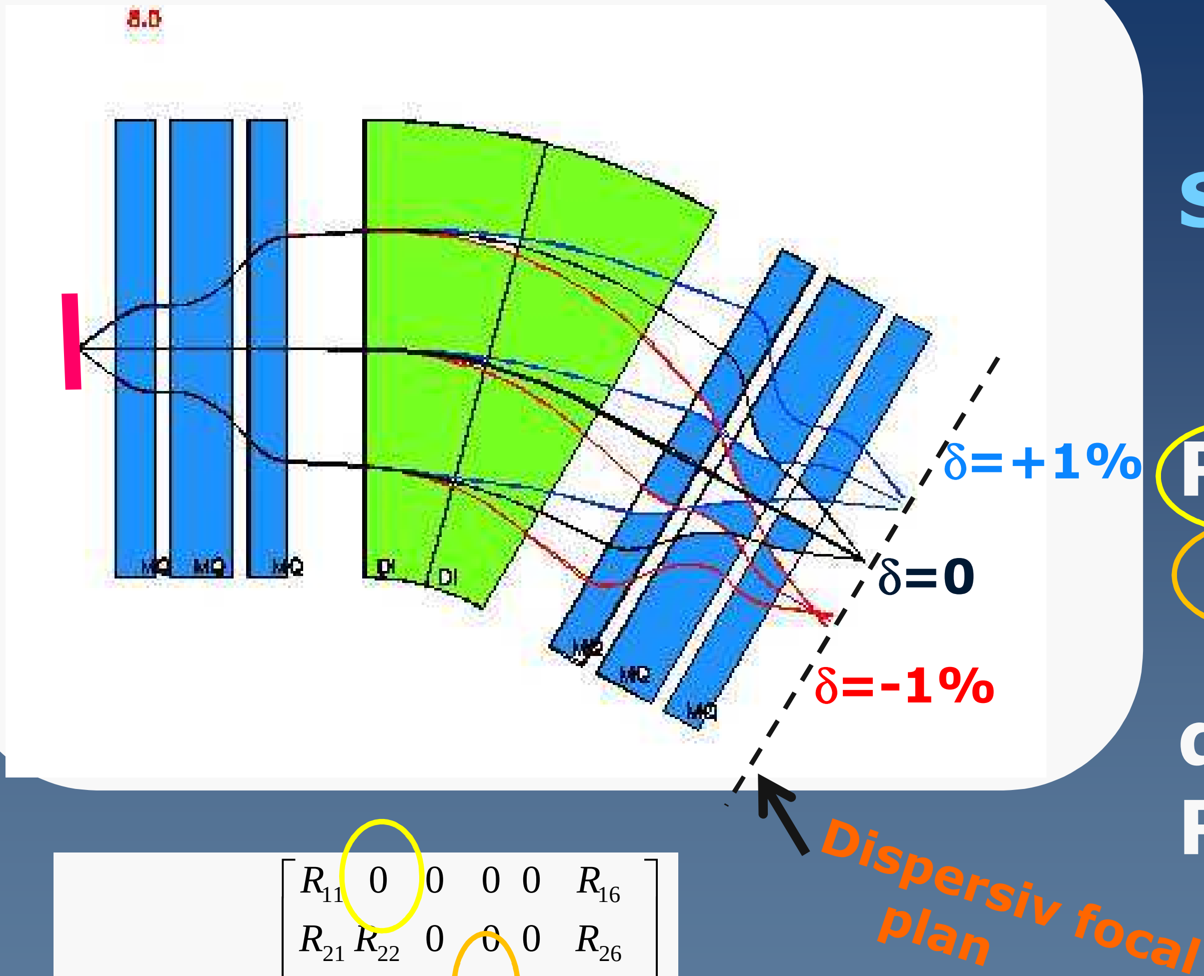
Bρ compensation

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

2 Trajectories in a Fragments separator



Fragments separators : dispersiv section optics



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

Section A :

Focusing

R_{12}=0 (Horizontal)

R_{34}=0 (Vertical)

dispersion

R_{16} (A) ≠ 0

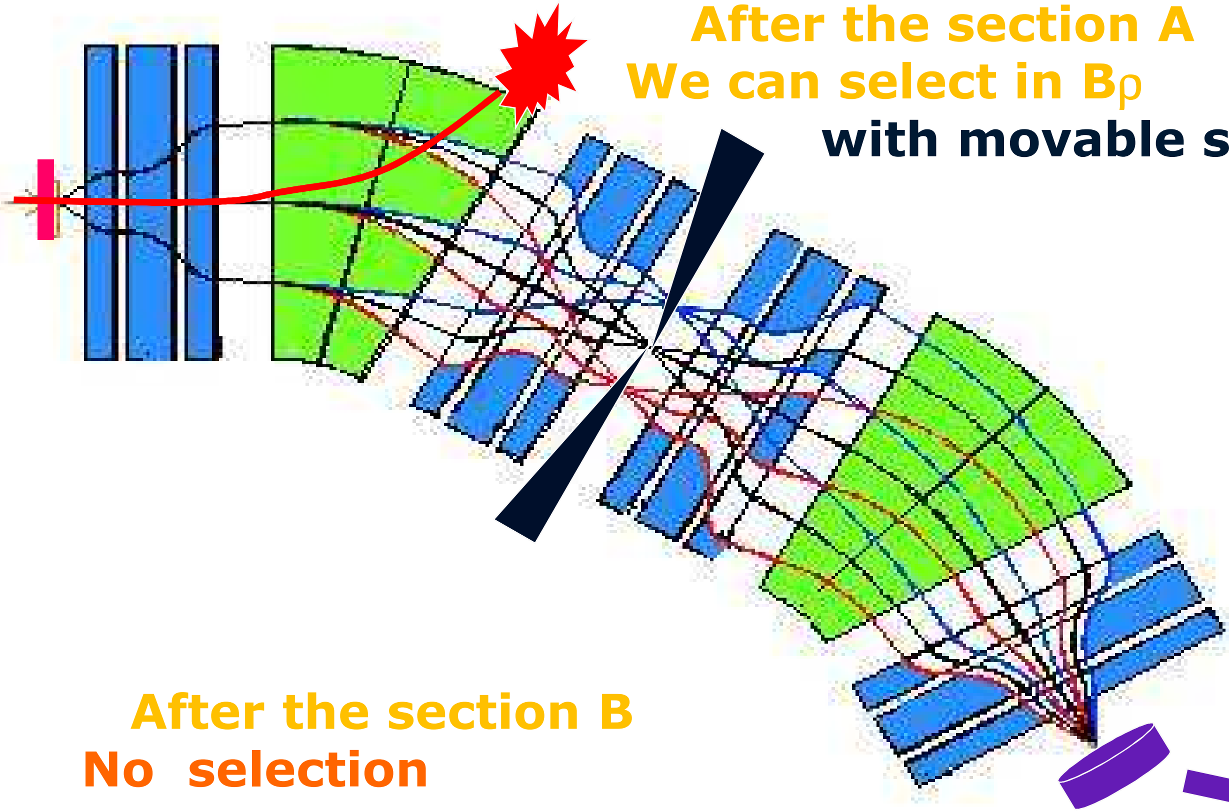
$\delta = (B\rho - B\rho_o) / B\rho_o$

$B\rho_o$ = Bdipole. Rdipole

B.Jacquot// Ganil

1 Selection in Fragments separators is not sufficient

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

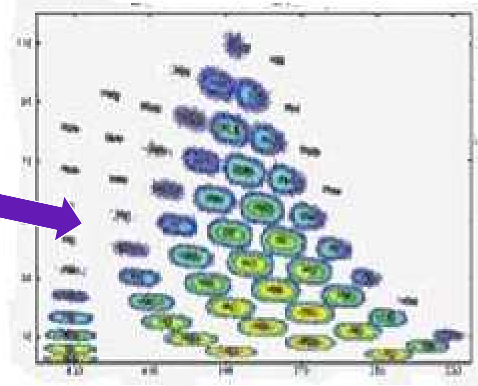


Bρ Selection
Is not
good enough

Bρ selection

identification

ΔE/
TOF



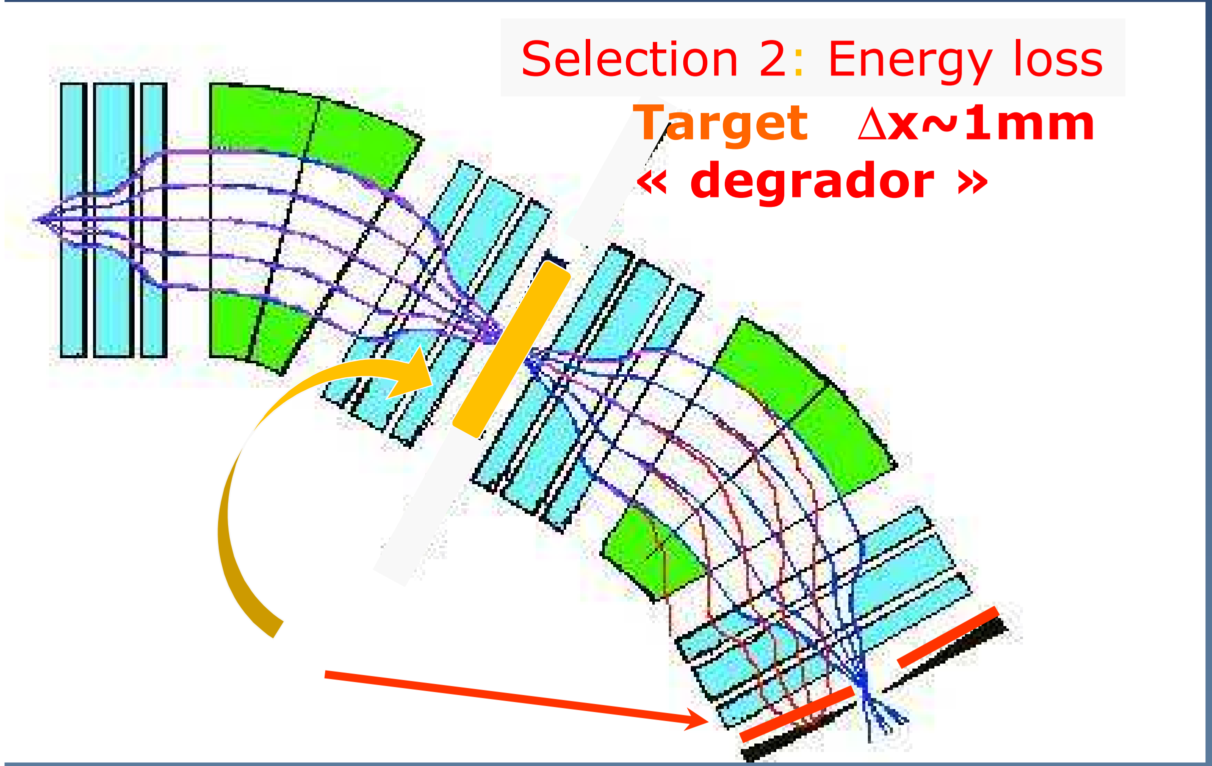
After the section B
No selection

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

B.Jacquot// Ganil

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

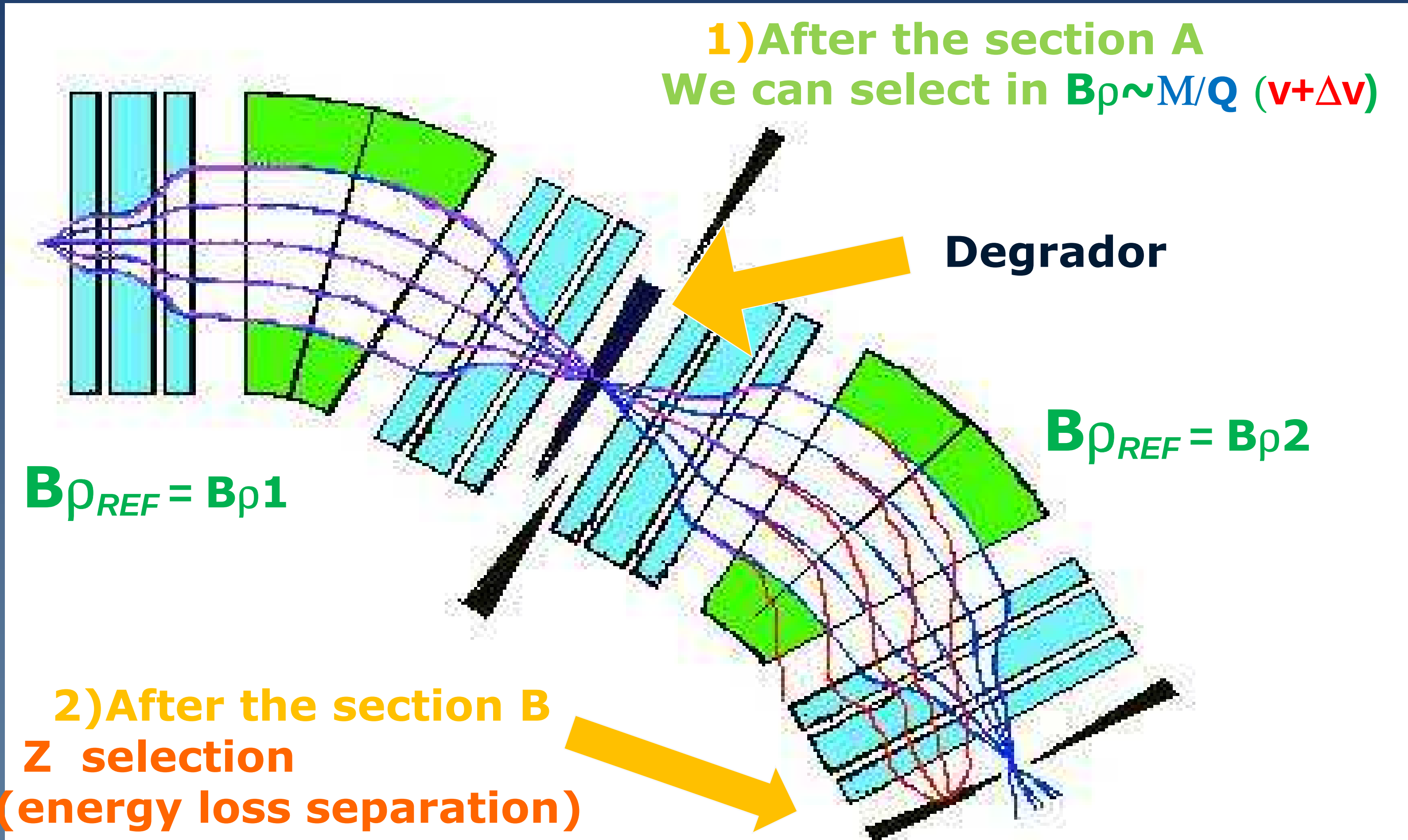
« Z dependant »

Bethe-Bloch formula

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

B.Jacquot// Ganil

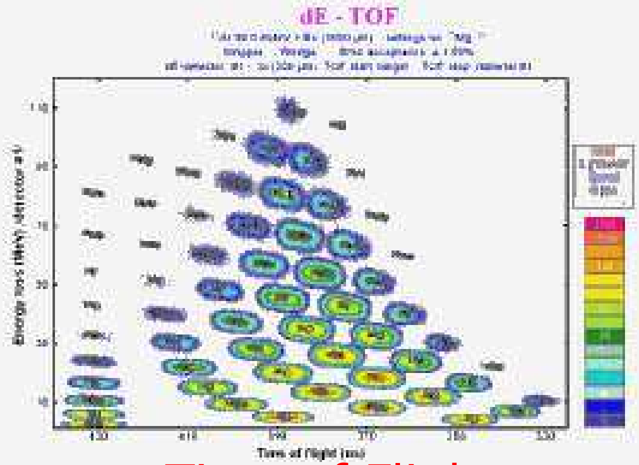
2 Selections in Fragments separators
Bρ + Z (degrador)



B.Jacquot// Ganil

Selection in Fragments separators & identification

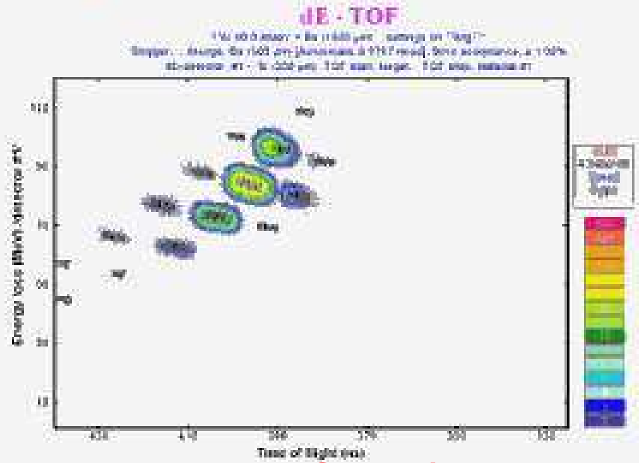
Bρ selection



ΔE
~Z

Time of Flight~M/Q

Bρ +degrador selection

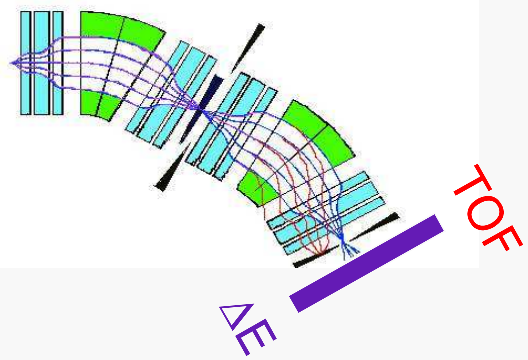


ΔE

Time of Flight

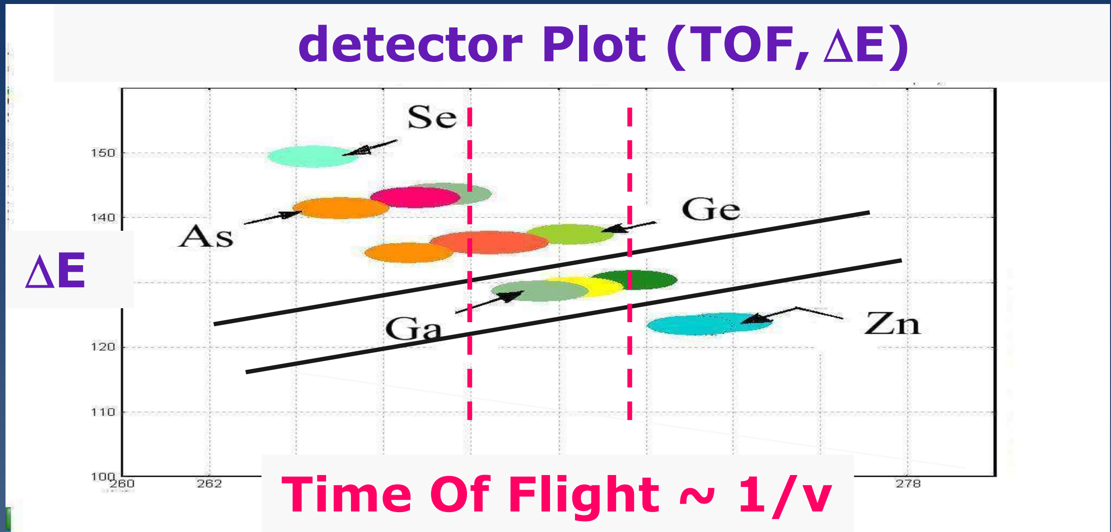
Detector :

Thin Silicone



2 selections Is much better for purety

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



Isotopes

are mixed in TOF

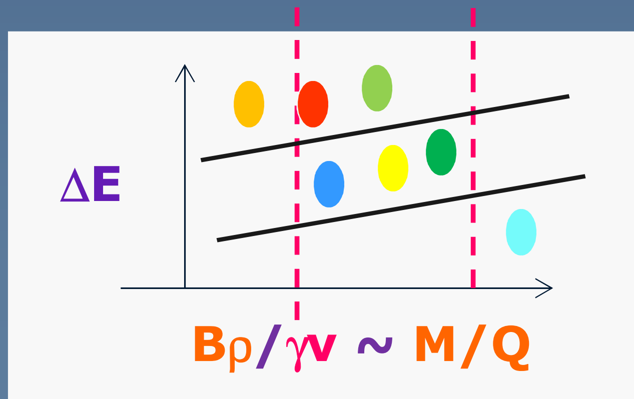
Large velocity distribution Δv

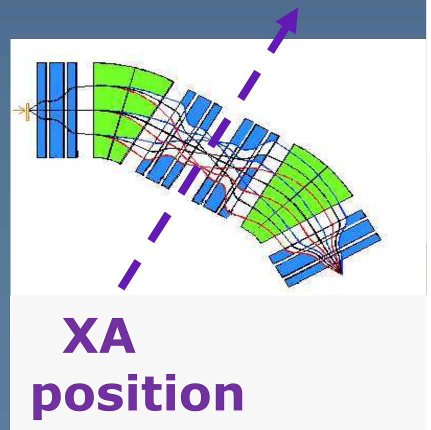
Solution : Measure XA for each ion : $B\rho = B\rho_0\,(1 + XA/R16)$

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

$v = ToF/L$

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





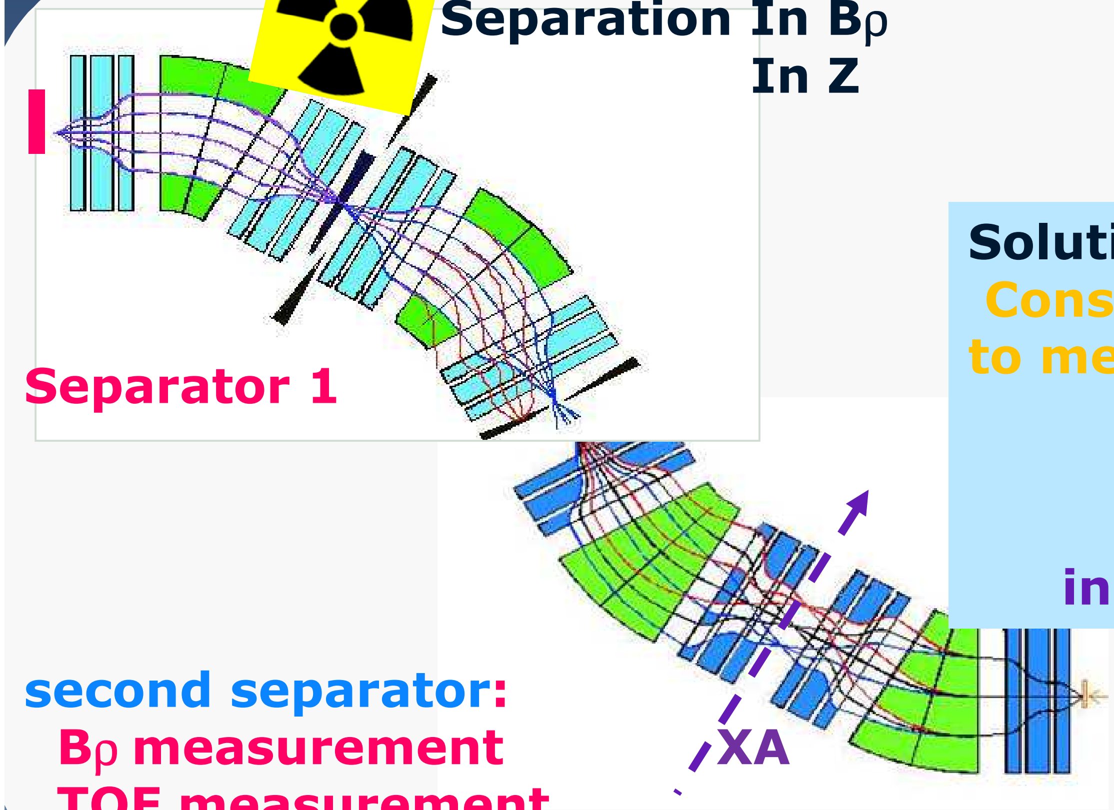
B.Jacquot// Ganil

Isotopes are not well identified with (ΔE,ToF)

Install a Detector position for XA : $B\rho = B\rho_0\,(1+XA/R16)$

NOT POSSIBLE

(too much intensity before Z selection)

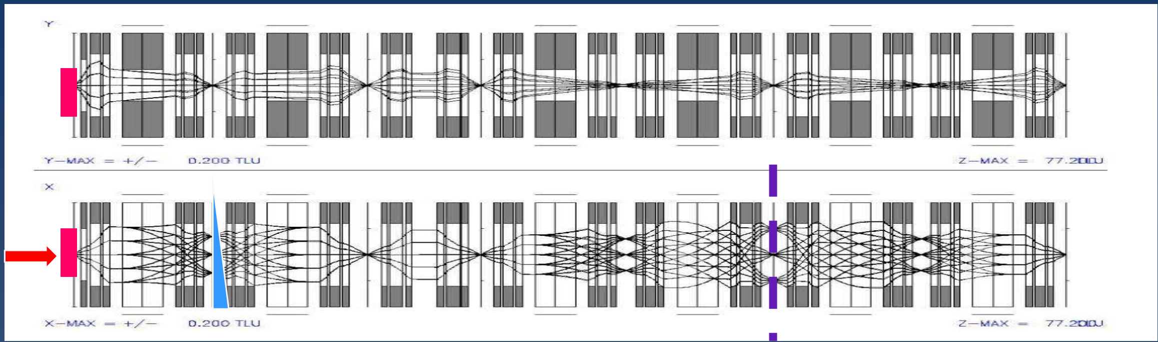


Solution choosen in BigRIPS :
Construct an additiv spectrometer to measure Bρ (€ !!)

Install the position Detector in the second separator

second separator:
Bρ measurement
TOF measurement

1 exemple :BIG RIPS (Tokyo)



Specifications

L=77m

$B\rho_{max}$ = 7 Tm

$\Delta p/p$ = ± 3%

$\Delta\theta = \Delta x'$ = ± 50mrad

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

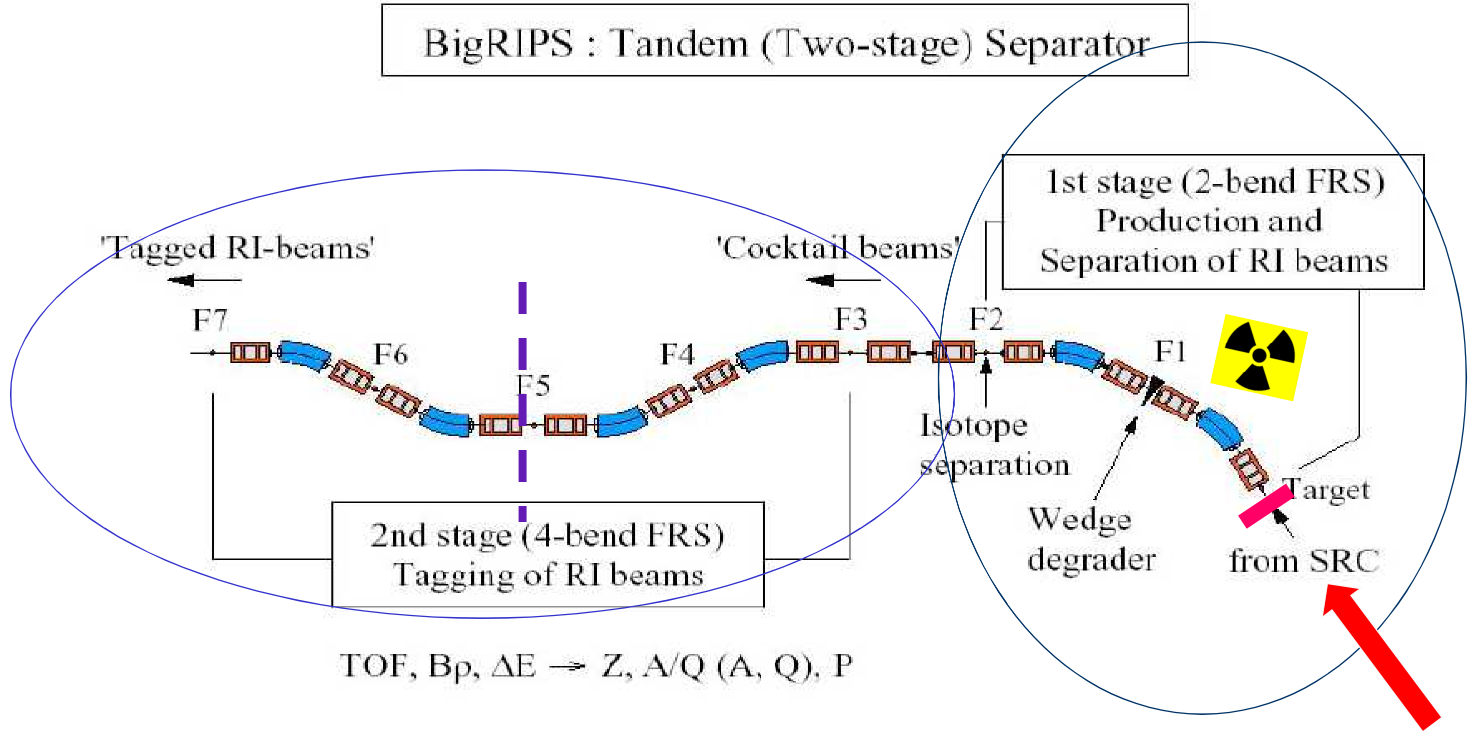


Fig. 2. A schematic diagram of the RI-beam tagging in the BigRIPS separator.

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)

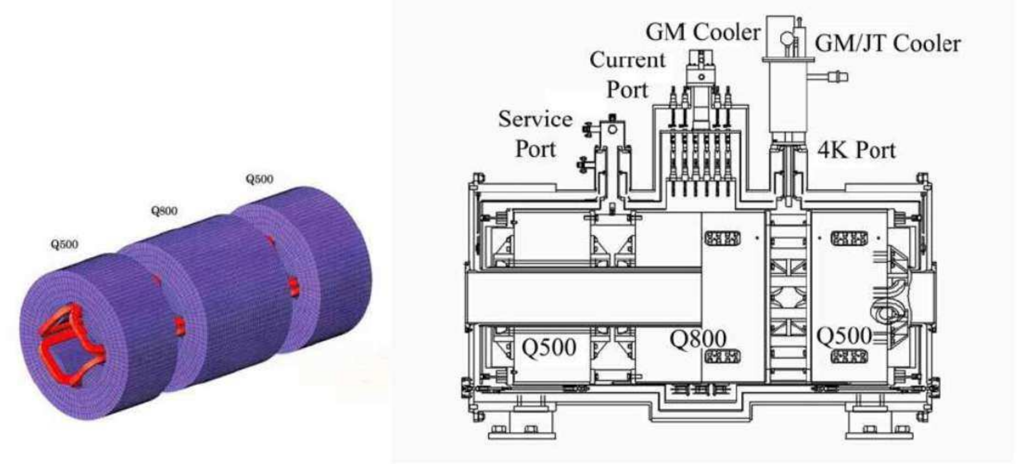


Figure 22: Schematic view of the RIKEN prototype quadrupole triplet (left side) and its installation into the cryostat (right side) [24].

- Supra-conducting coils (i very large, B close to saturation)

-Raperture very large =0.1m ; Bpole-max# 2 Teslas

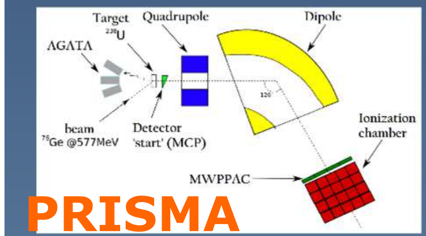
- GradientMax=2T/0.1m=20.T/m

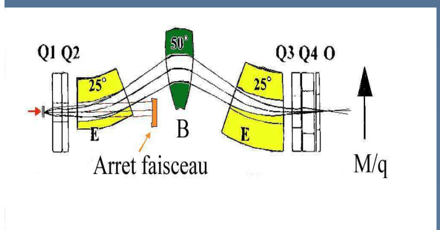
« Recoil » spectrometer : nuclear physics at low energy (1-10MeV/A)

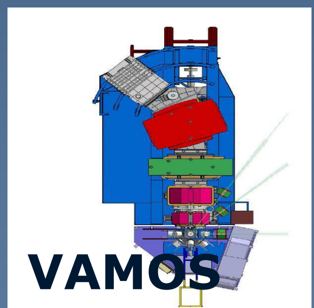
Many experimental problems => A large variety of devices
Reactions : fusion-evaporation, transfer,..

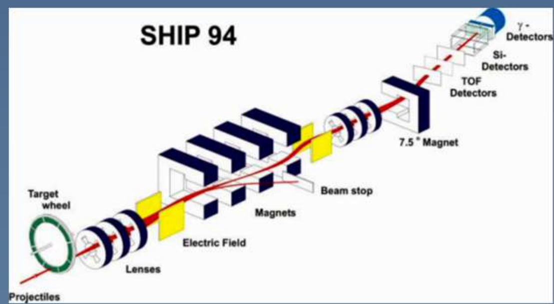
Goals :

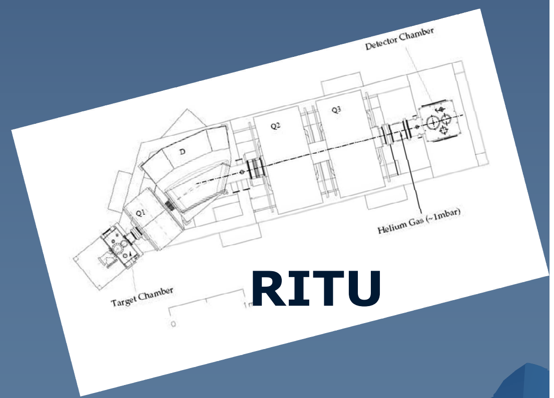
1) Very efficient primary beam suppression
2) Help identification











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>...

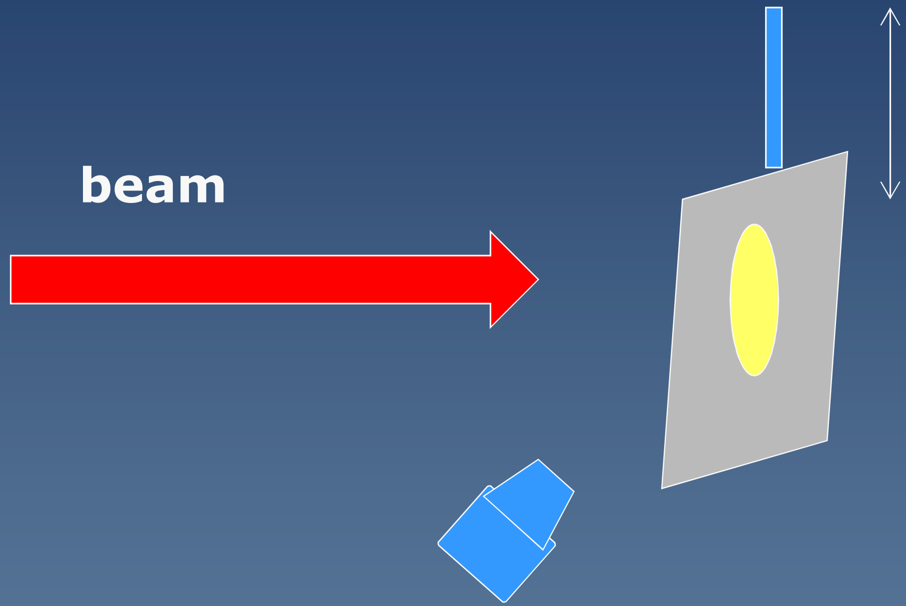
1rst step : check the primary beam

- **profil measurement (alignement, focus)**
- **intensity check**

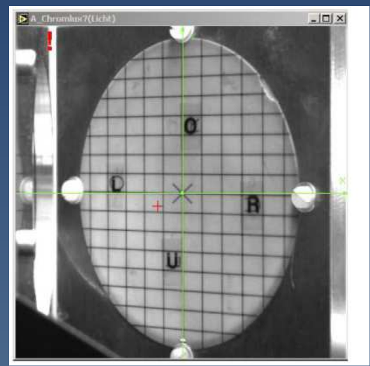
SPECTROMETER TUNING

Beam diagnostics : scintillator screen

beam

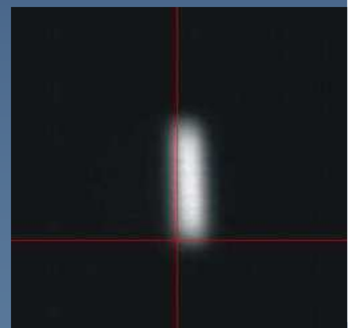


movement



beam spot

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



CCD Camera

Relatively low cost , but

- only 1 profil measurement
- not very precise

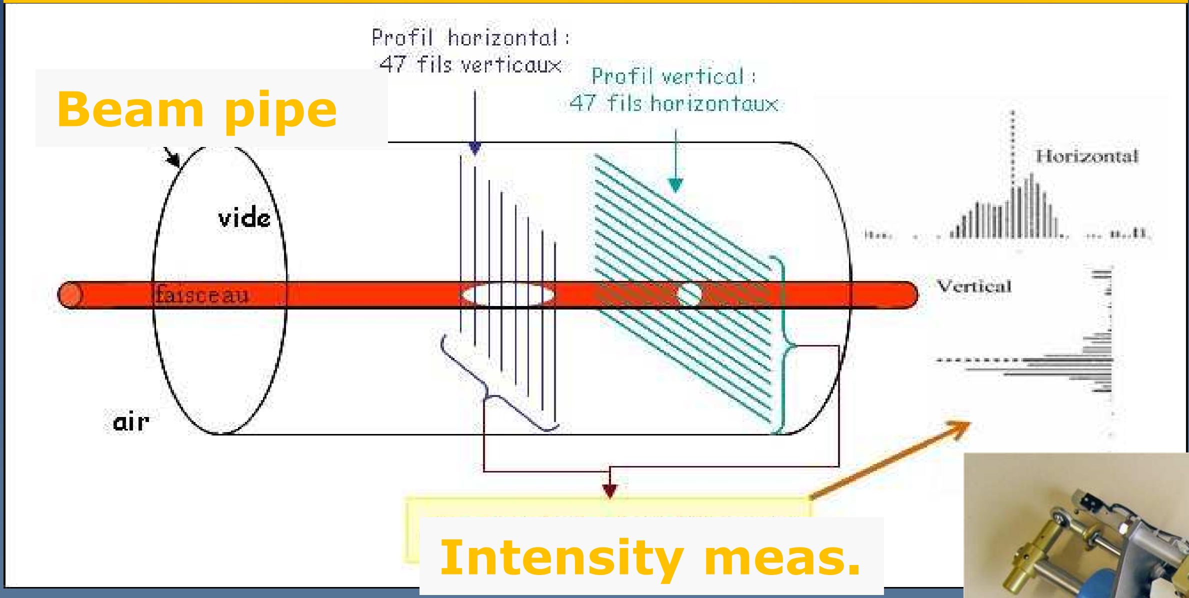
B.Jacquot// Ganil

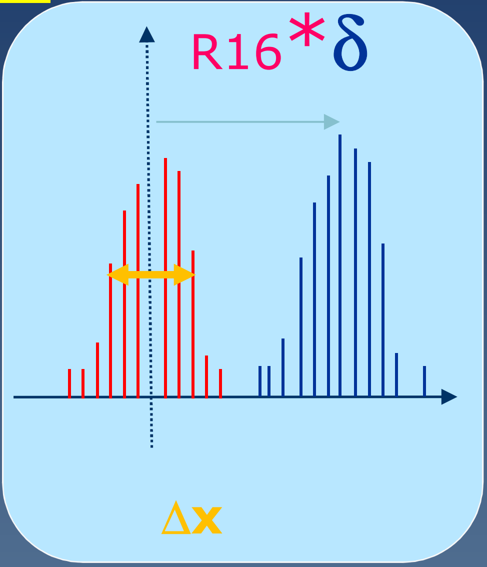
SPECTROMETER TUNING

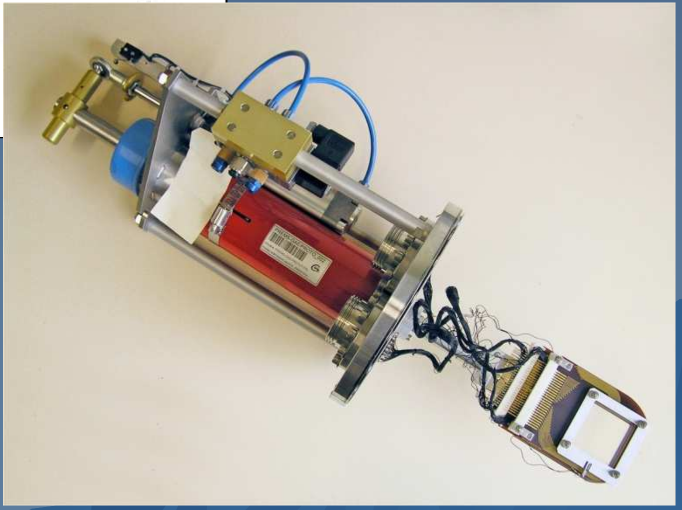
Beam diagnostics : **profil monitors**

Reconstruct the beam intensity in X and Y

Profil monitor : HORIZ. and VERT. wire

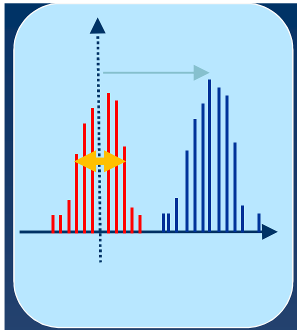






Usefull for beam alignement
focusing check
R*16* measurement

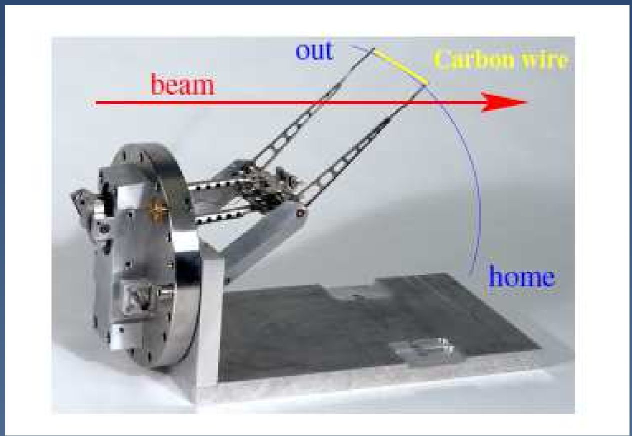
B.Jacquot// Ganil



SPECTROMETER TUNING

Many Profil monitors

for different beam intensities



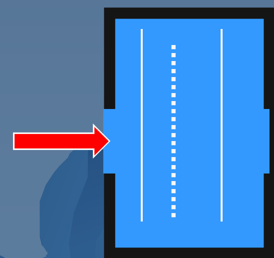
Rotating wire
ibeam# $10^{12\text{-}14}$pps
(Cern)

Wires
i# $10^{9\text{-}11}$pps

(Ganil)

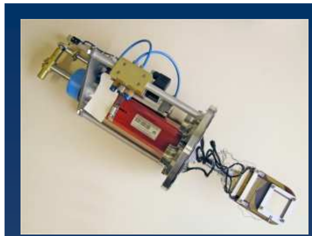
« Gas Profil »
i# $10^{3\text{-}7}$ pps

Gas $ArCO_2$ +HV



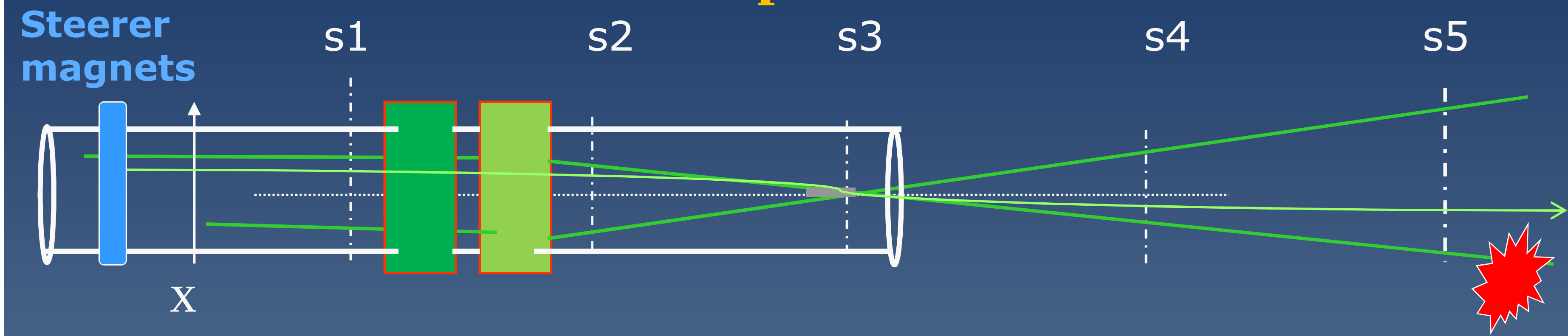
Proportional counter

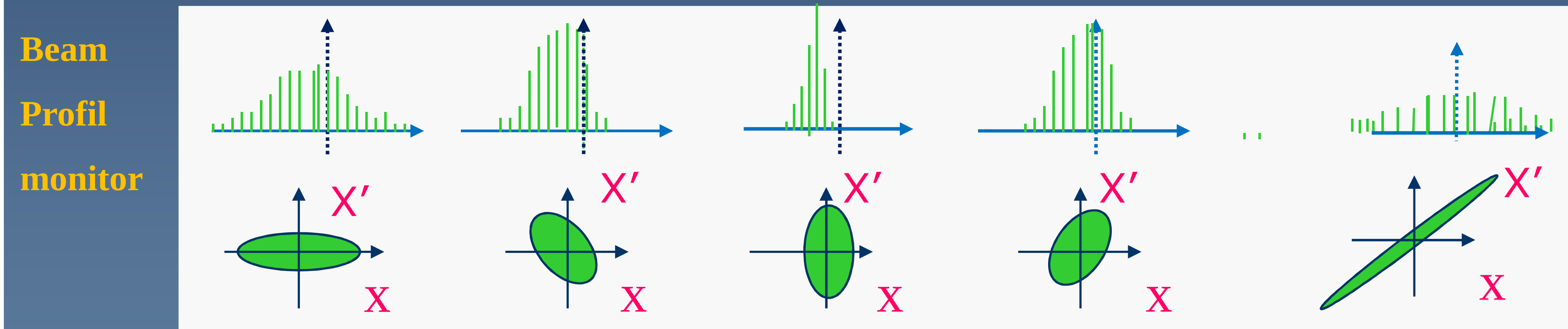
Specific technologies adapted for ≠(intensities, Energies)



TUNING

Checking size and alignement with profil monitors





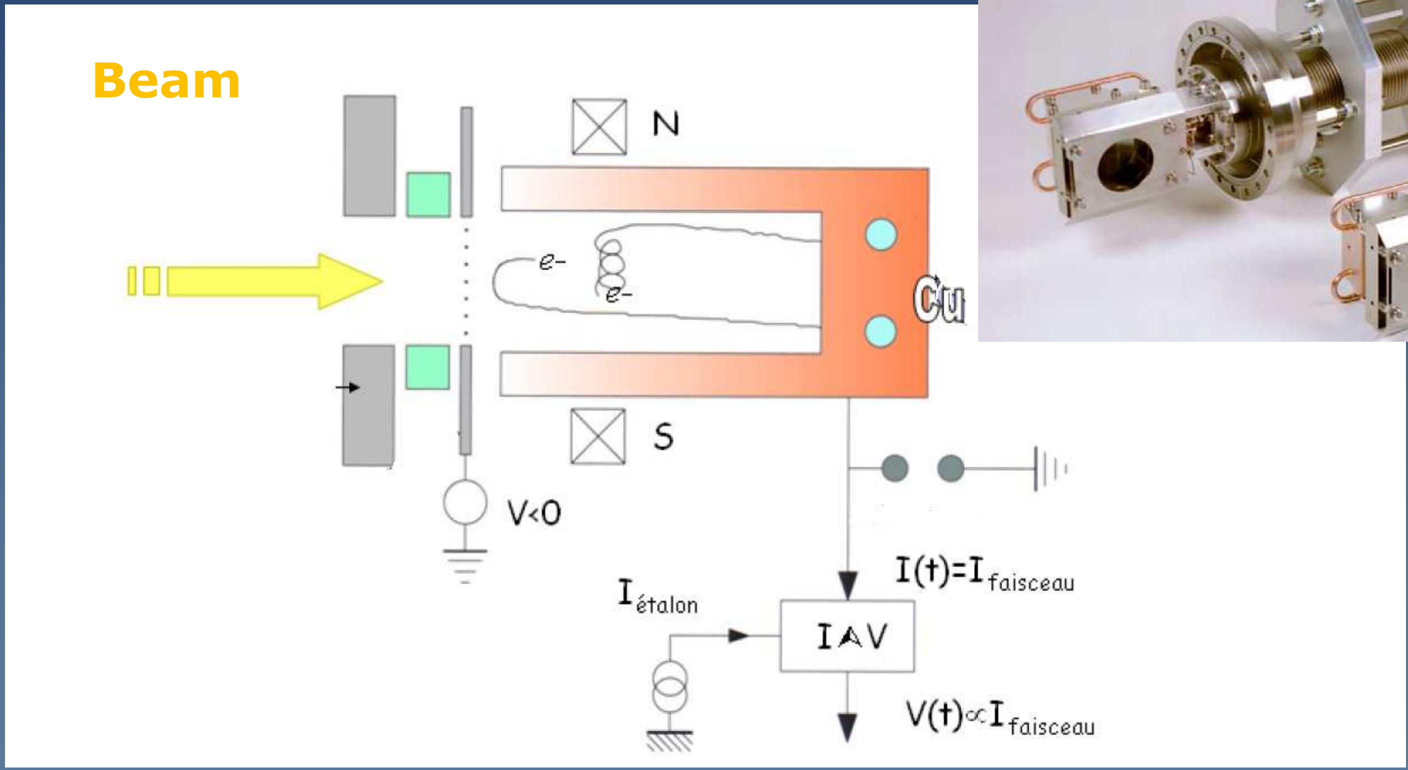
ellipsoid area = $\pi \, \Delta x \, . \, \Delta x'$ = Emittance

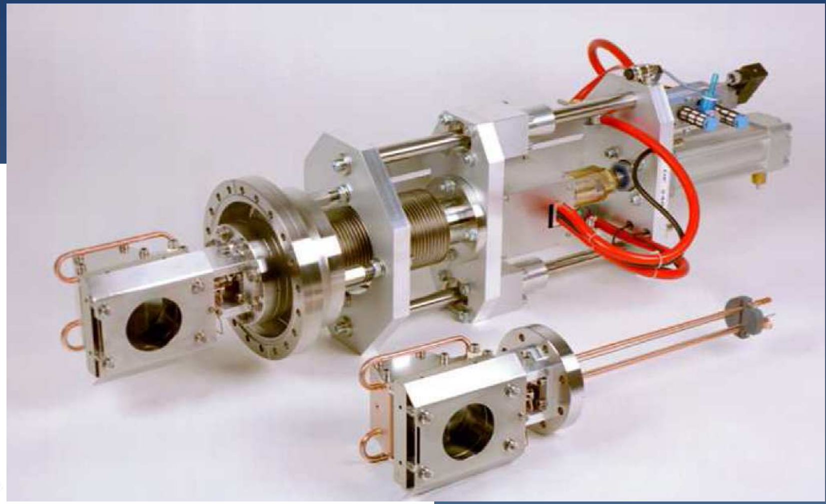
Emittance = constant if Energy=constant

SPECTROMETER TUNING : check the intensity

Beam diagnostics : **Faraday cup**

Intensity measurement





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

= IµA 10⁶/[Q 1.6 10⁻¹⁹]

Summary

- I) History and evolution of the spectrometer

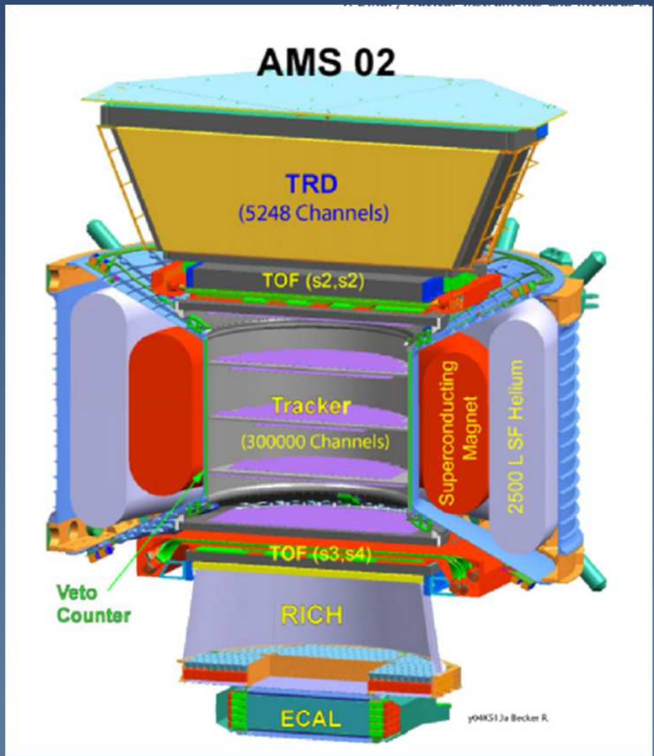
- II) Magnetics spectro/separators with accelerator's beams

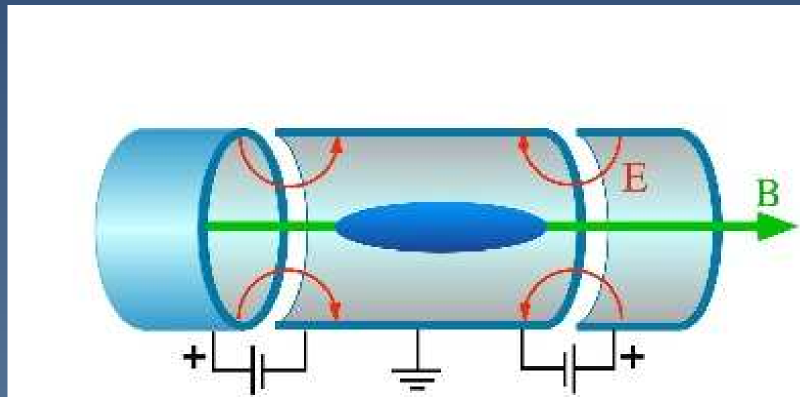
  technical device : quad, dipole

  Beam optics concept

- III) Spectrometers without accelerator
- 1 exemple for Astroparticle
- Penning Traps

III) Spectrometer experiments without accelerators





Penning Traps

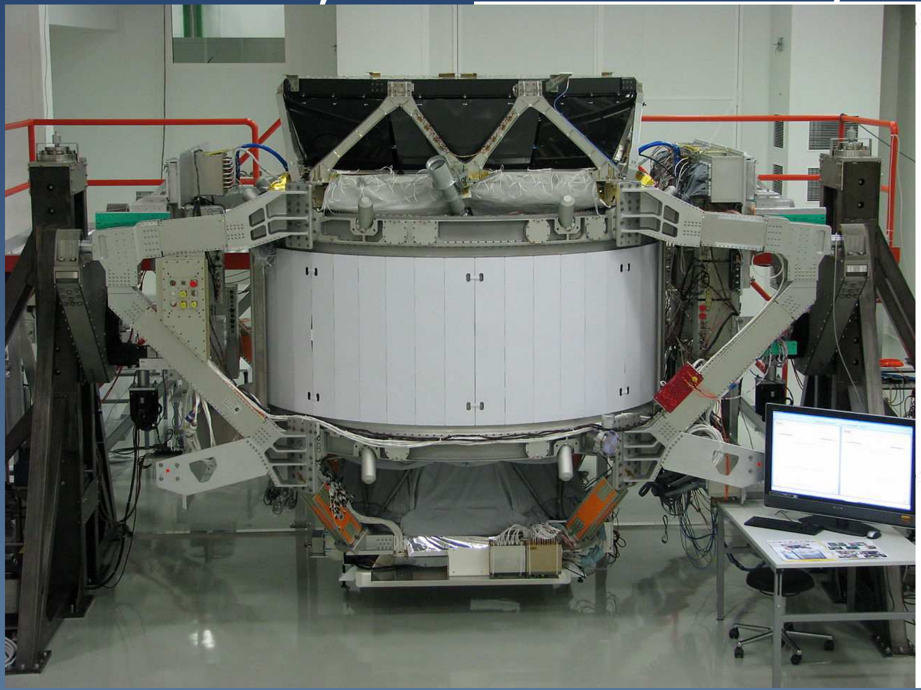
1eV ions

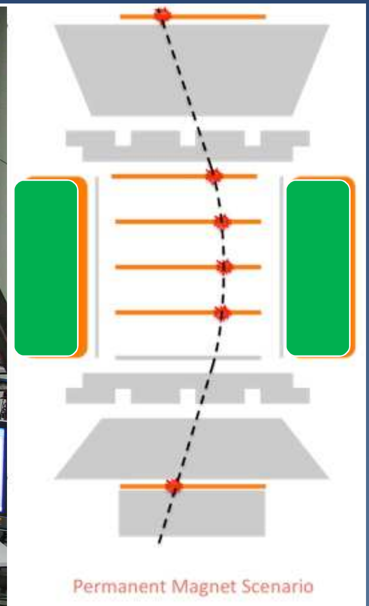
AMS at ISS (10-300GeV e-)

AMS :a Spectrometer in space

7 tons : 1 dipole magnet + trackers+ 1Calorimeter

P=2,3 kW S_{active}=0,8 m2



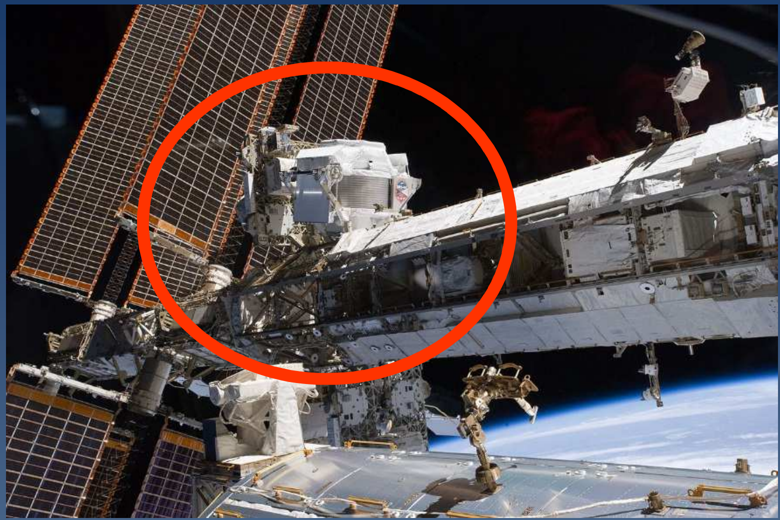


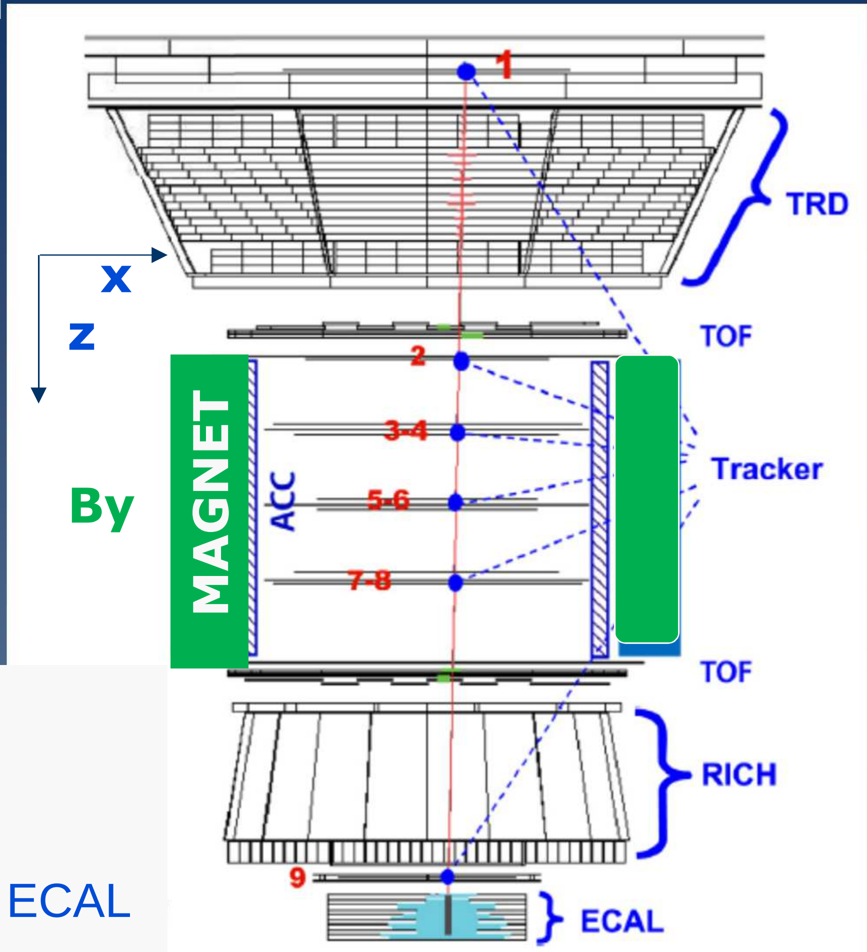
$$\frac{\Delta R}{R} \propto \frac{1}{B_{pm} l L}$$

Cosmic Ray Measurement + quantification of Matter/antimatter

e- //e+ ; p // pbar ; heavy ions He; Li;....

AMS2 at Int .Space Station





The reconstruction of a 300 GeV electron measured by AMS2,

with the signals in TOF, tracker, RICH and ECAL

- Spectrometer+detector that measures antimatter in cosmic rays : e-// e+ [10-300 GeV]
  p // pbar

AMS2 with « a dipolar field » B=Bx

higher field=higher dispersion= better Resolution

Electromagnet excluded : too heavy//high power

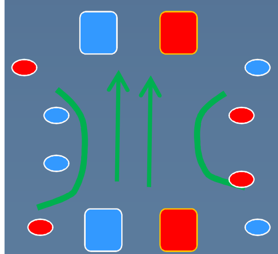
So 2 magnet options : sufficient field ? & uniformity ?

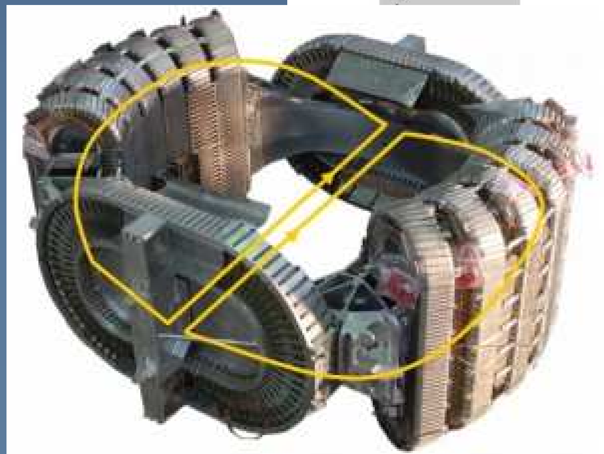
Superconducting coils

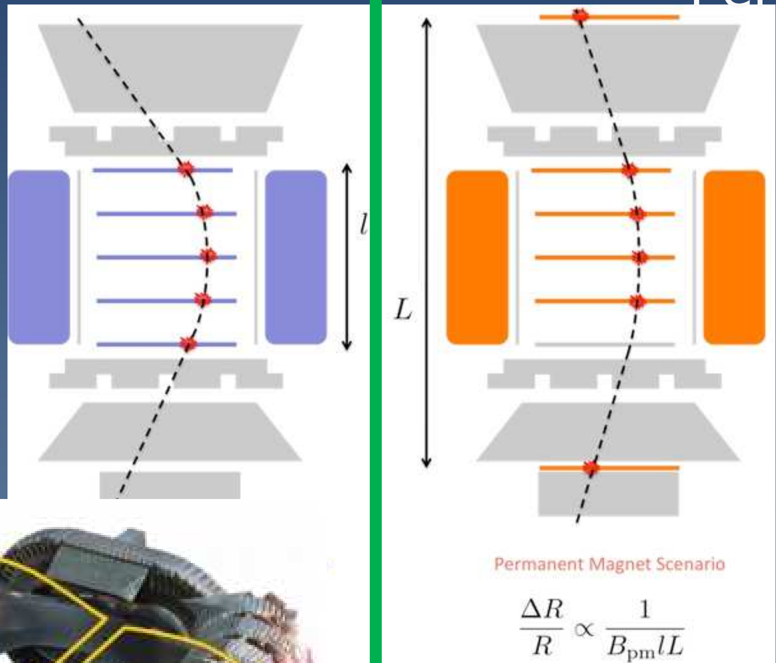
Bz~0,8 T

Bx Produces
by courant distribution

I(θ) #Io cos(θ)

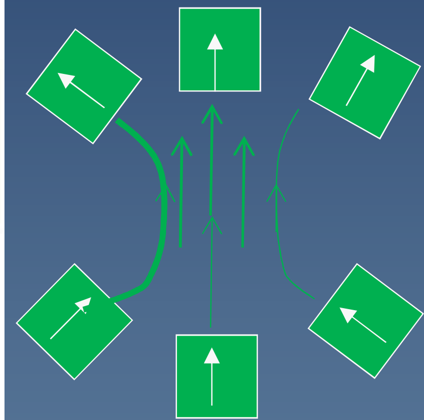






Permanent magnets

Bz~0,15 T



Bx Produces by magnetizatio
distibution

M(θ) =Mo cos(θ)

Rmatrix for a magnet (ϕ , R)
very convenient for the tracking in a spectro

$$X_{final} = -R_{11}\, x_0 + R_{12}\, X_0' + R_{16}\, (B\rho_0 - B\rho_0)/B\rho_0$$

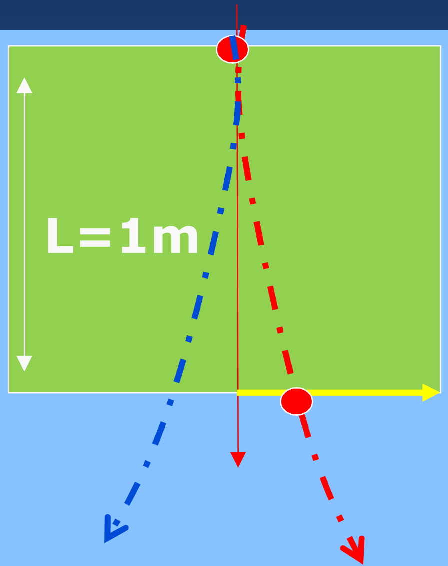
$$= -\cos(\phi)\, x_0 + R_0 \sin(\phi)\, X_0' + R_0(1-\cos(\phi))\, \delta$$

Rdipole=

$$\begin{pmatrix} \cos\varphi & R\sin\varphi & 0 & 0 & 0 & R(1-\cos\varphi) \\ -1/R\cdot\sin\varphi & \cos\varphi & 0 & 0 & 0 & \sin\varphi \\ 0 & 0 & 1 & R\varphi & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -\sin\varphi & -R(1-\cos\varphi) & 0 & 0 & 1 & R\varphi/\gamma^2 - R(\varphi-\sin\varphi) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Transport matrix For a dipole with angle ϕ

AMS2 :Traking in a dipole magnet
1rst order



Reference particules =e- 50GeV

e- (50GeV) = $B\rho_0$=167 Tm

$\theta = s/ R_0$ R_0 = 167T.m/0,8T=200m

By=0,8T

Position of 50geV e- : $X_{f0} = R_0 (1-\cos(\theta)) = L^2/2 R_0$ = 2,5 mm

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

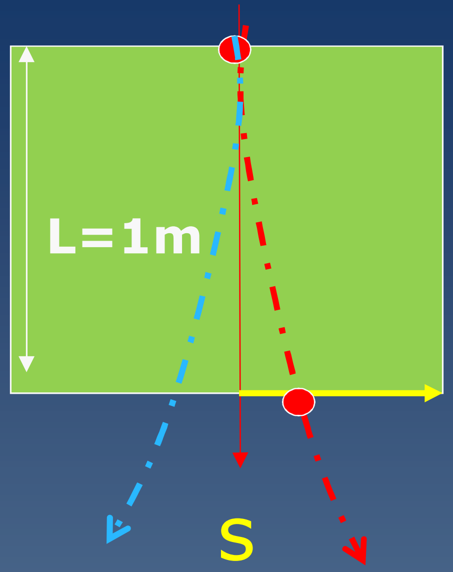
$X_{final} = -\cos(\theta)\, x_0 + R_0 \sin(\theta)\, X_0' + R_0(1-\cos(\theta))\ \delta$

(= see transport matrix of a dipole matrix)

So $X_{(S=L)}$= ?

$L^2/2 R_0 + X_0 + R_0\sin(\theta)\ x'_0 + R_0\ [1-\cos(\theta)]\ \delta$

AMS2 3 unknown (m, Z, E)



Traking e- in dipole magnet 1rst order

Reference particules =e- 50GeV

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

$X(s) = x_0 + s^2/2\,R_0 + S\,x'_0 + R_0\,[\,1-\cos(\theta)]\,\delta$

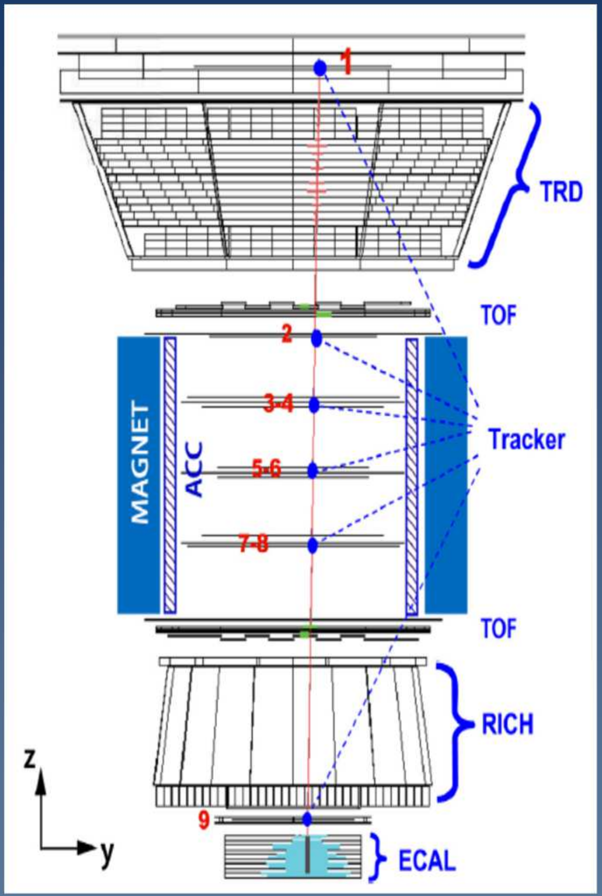
Tracker :Fit X(s) : find $\delta = (B\rho - B\rho_0) / B\rho_0$

Calorimeter = gives E & RiCh gives β

$B\rho = P/Q$ + $E = (\gamma - 1)\,mc^2$ + β = (m, Z, E)

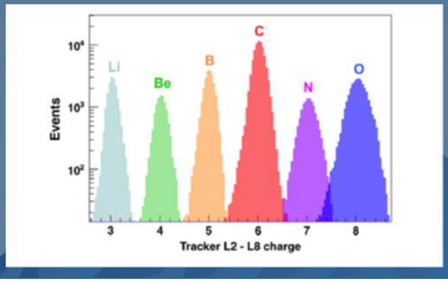
AMS detectors and results

-TRD :A transition Radiation detector (gas)
Allows the separation of e//p
-Ring Cerenkov detector :Δβ/β~ 0,1/Z %
zmeasurement
-TOF detectors : are a fast trigger
-Trackers : 10micron for e/p
e: R=2,5% in Brho up to 100GeV



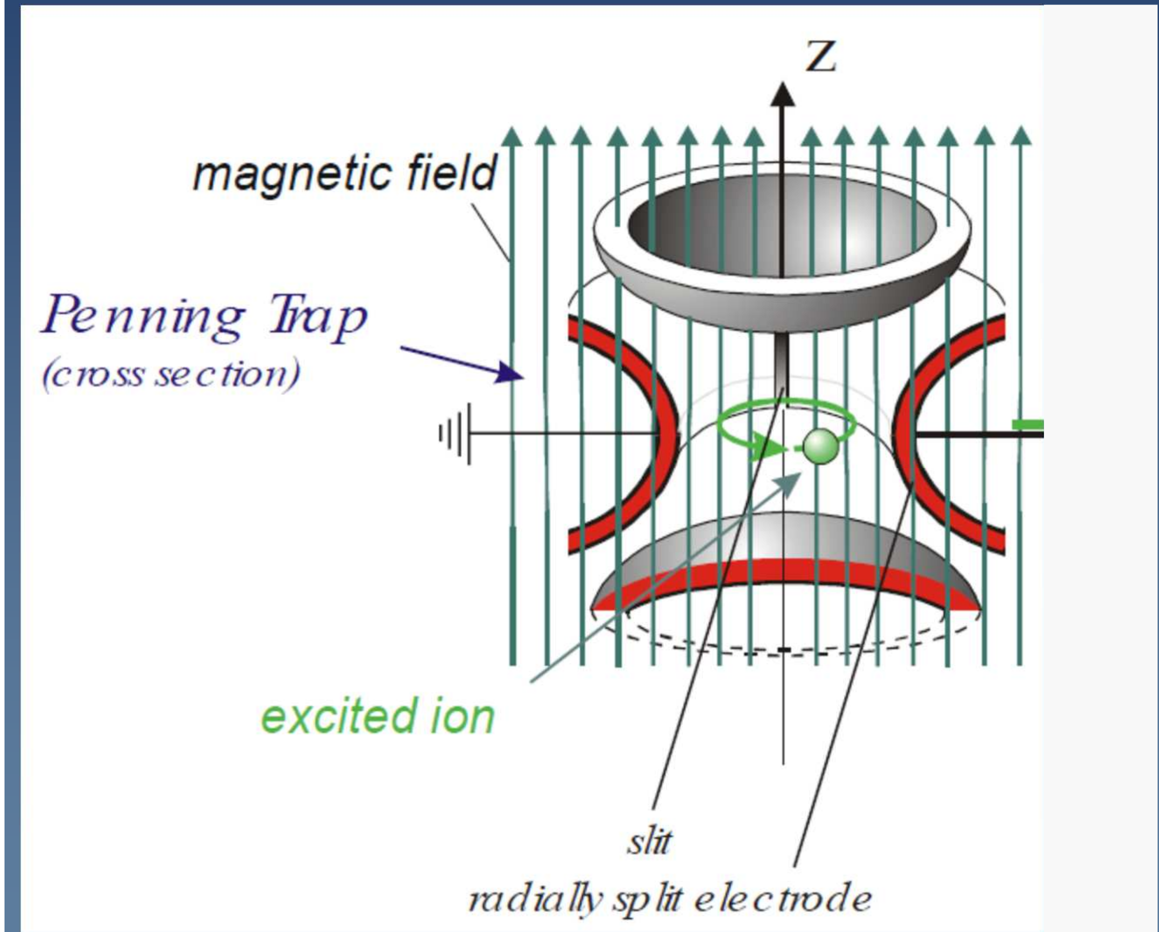
[2011-2015]
Some e+ has been detected @100GeV
source of antimatter in the universe ?!

Data has been collection for radioprotection issues (long fligth toward mars ?)
P, He, Li



Penning Traps : high resolution mass spectroscopy

Used in reseach but applications expending
The ultimate mass resolution device

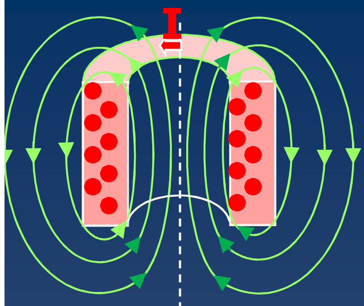


3 tricks

1) Confinement (Bz+Ez) static EMfieds

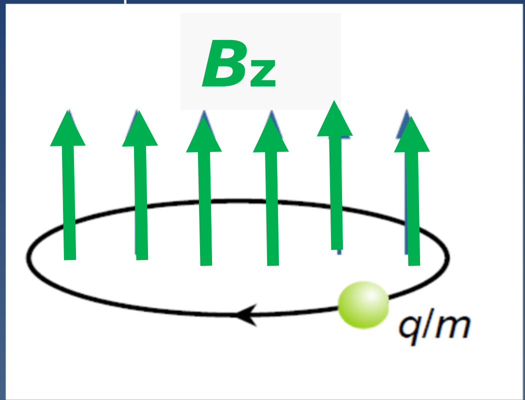
2) Excitation (RF field)

3) Extraction (Tof measurement)



Penning Traps (1) : confinement

Solenoid coil : field (Bz) is axial

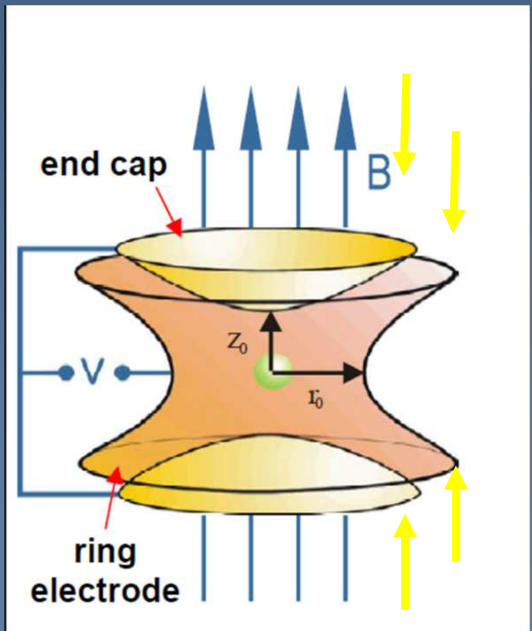


3 D trapping technics (Radial+longitudinal)

1a) Radial (x,y) confinenment with Bz

-natural cyclotron frequency

$$\omega_c = f_{revolution}/2\pi = qB/m$$

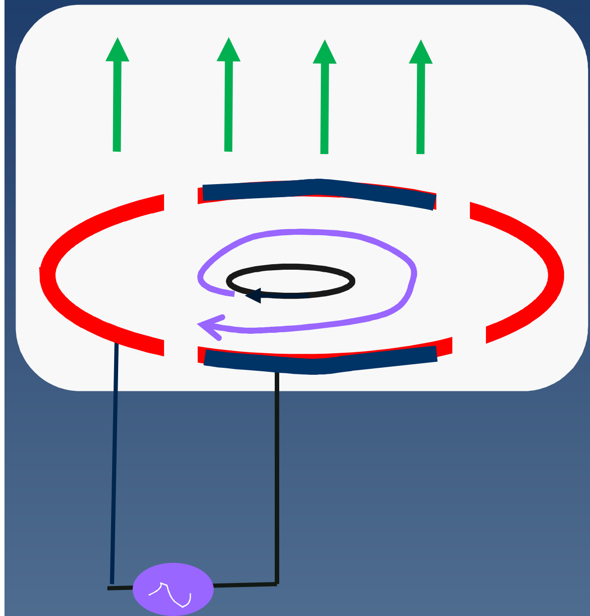


1b) Longitinal (z) confinement with Electric field

$$V = U_0\,(2z^2 - x^2 - y^2) \qquad F_z = -4\,z\,U_0$$

hyperbolic field : End caps + Ring electrode

Penning Traps (2) :excitation at resonance



excitation RF : 4electrodes

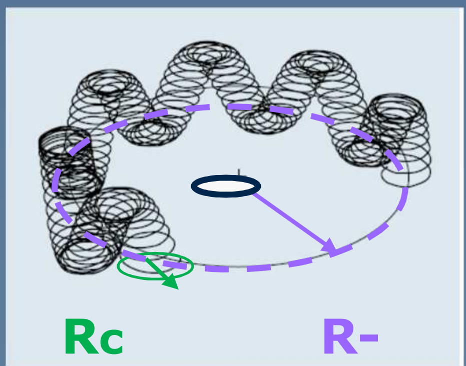
- natural cyclotron frequency

ωc =f revolution/2π =qB/m

-Excitation with RF electic field

$$V(t) = U \cos(\omega_{rf}\, t)$$

if $\omega_{rf} = \omega c$ Radial motion increases



in reality, the motion is complex (coupling)
radial (Bz) and axial motion (Fz

$\omega c = \omega^{+} + \omega-$ $\omega z^{2} = 2\, \omega^{+} . \omega-$

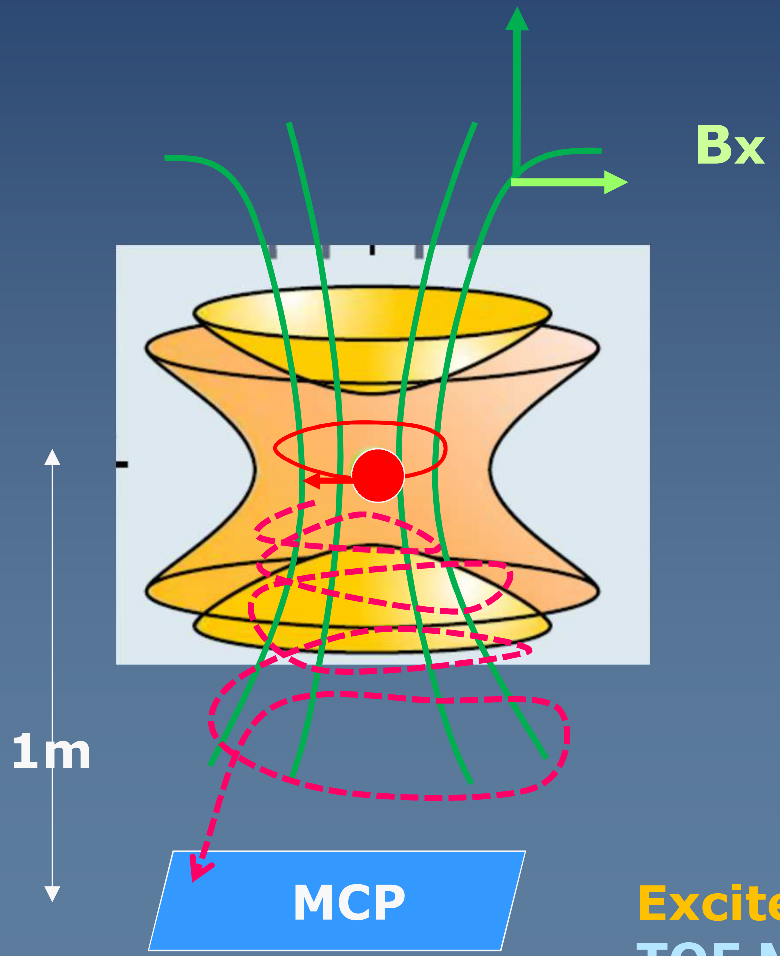
$\omega c^{2} = \omega^{+2} + \omega-^{2} + \omega z^{2}$

Penning Traps (3) : extraction

Extraction with a time of fligth measurement

Bz main Force(radial) = q $v \times Bz$:confinement

B = Bz+ By+ Bx



Extraction in solenoid's end fields

Force (z) = q [v_x By - v_y Bx]

B_{radial} act on

The Excited ions with large V_{radial}

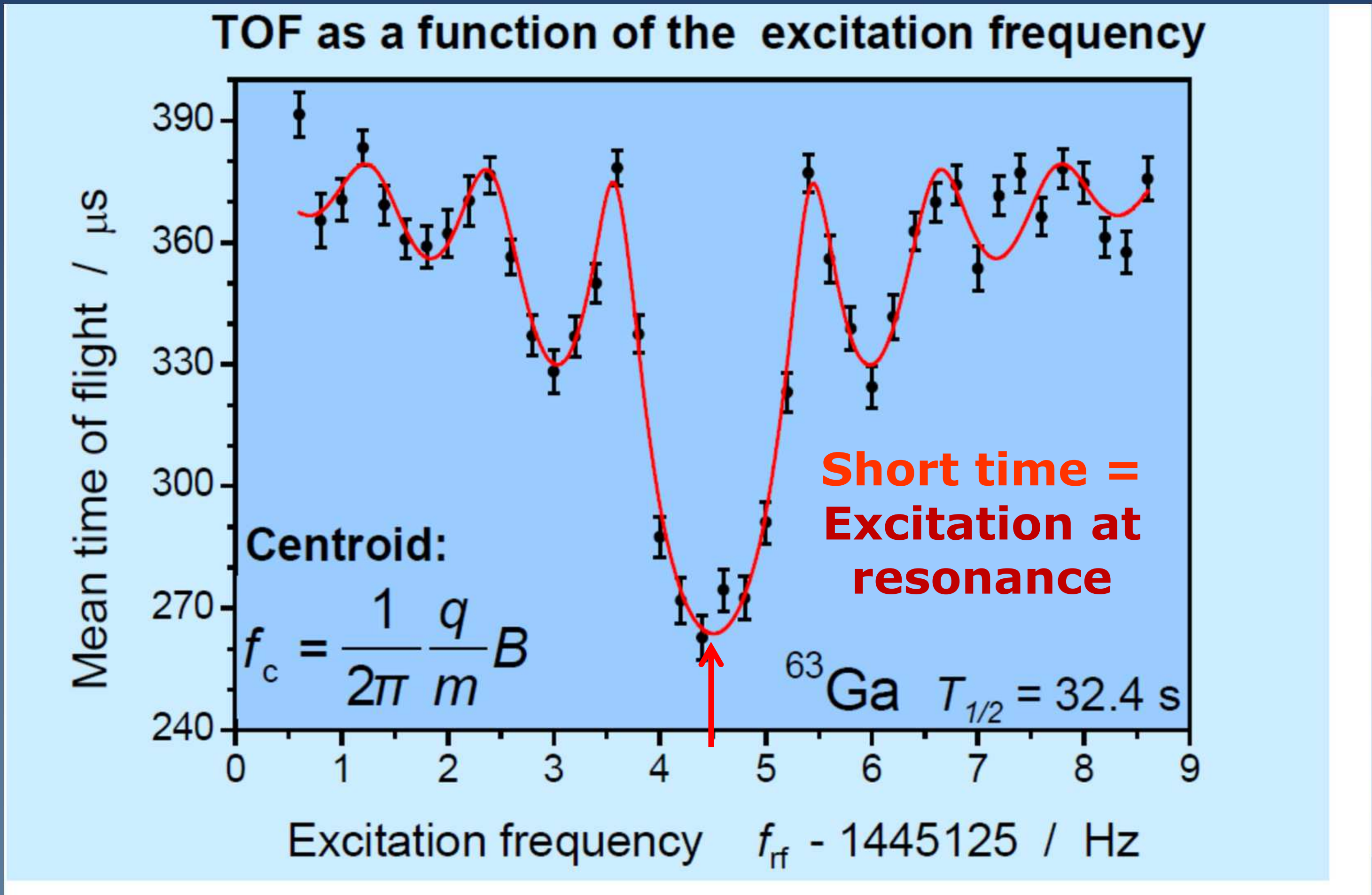
Excited ions reach the detector (MCP)

TOF Measurement

B.Jacquot// Ganil

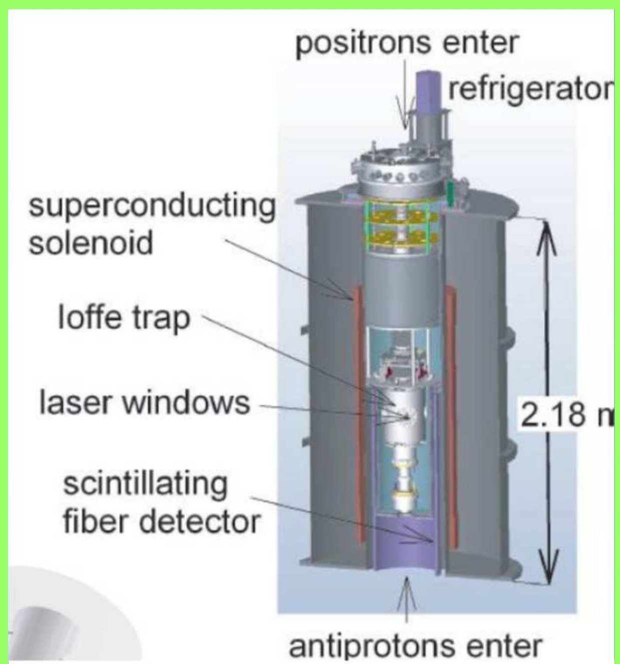
Penning Trap : mass measurement

R=δm/m #[10^{-5}-10^{-8}] ~ Texcitation Frf

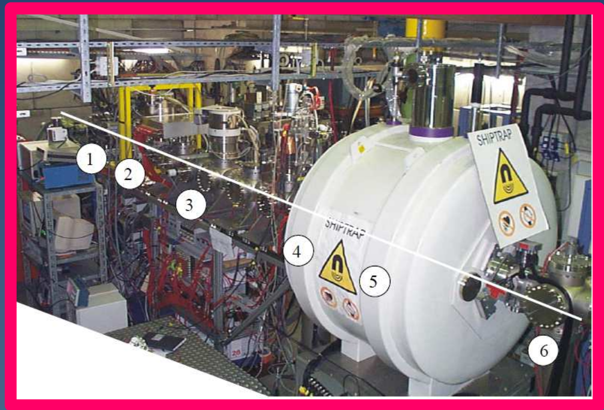


Penning Traps : Many experiments operated in the world

Magnet = superconducting solenoid (Bz#3-6 Tesla)



$$\overline{p} + e^+ + e^+ \rightarrow \overline{H} + e^+$$



Particle Physics at Cern
M/q of P and Pbar (R=10^{-10})

-ATrap - ATrap2 Athena …

-Anti Hydrogen Production cooling..
-Decay measurement
-Atomic spectroscopy

Nuclear Physics

-Ship Trap (GSI)
Z>92 mass measurement

-Isolde Trap (Cern)

- JYFL Trap (finland)

- …

End

- I) History and evolution of the spectrometers

- II) Magnetics spectro/separators with accelerator’s beams

technical devices : quad, dipole

Beam optics concept

- III) Spectrometers without accelerator
- 1 exemple for Astroparticle
- Penning Traps

Back-up slides

Usefull relations : Bρ, E, W

Resolution & dispersion

More on Optical matrix : the matrix for a drift

Beam ellipsoid

Exemple 1: Big Rips in Tokyo (Riken)
Exemple 2: VaMOS in Caen (Ganil)

- Non linear effect in optical systems

Useful relations :

$$E_0 = mc^2 \;;\; E = E_0\gamma = mc^2\gamma \;;\; p = mc\beta\gamma \;;\; cp = mc^2\beta\gamma = E_0\beta\gamma \;;\; E^2 = E_0^2 + p^2c^2$$

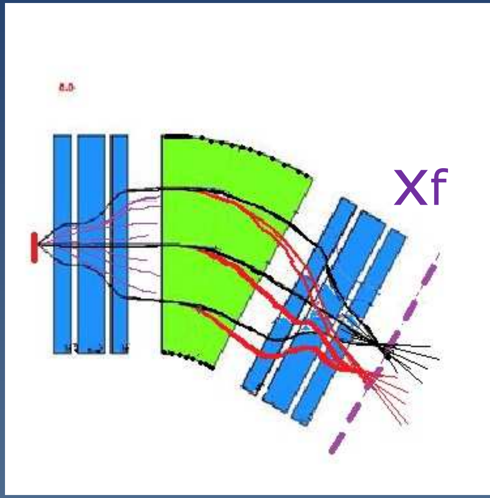
$$\beta\gamma = \frac{cp}{E_0} \;;\; \gamma = (1-\beta^2)^{-\frac{1}{2}} \;;\; \beta^2\gamma^2 = \gamma^2 - 1 \;;\; W = E - E_0 \;;\; \frac{mc\beta\gamma}{q} = B\rho \;.$$

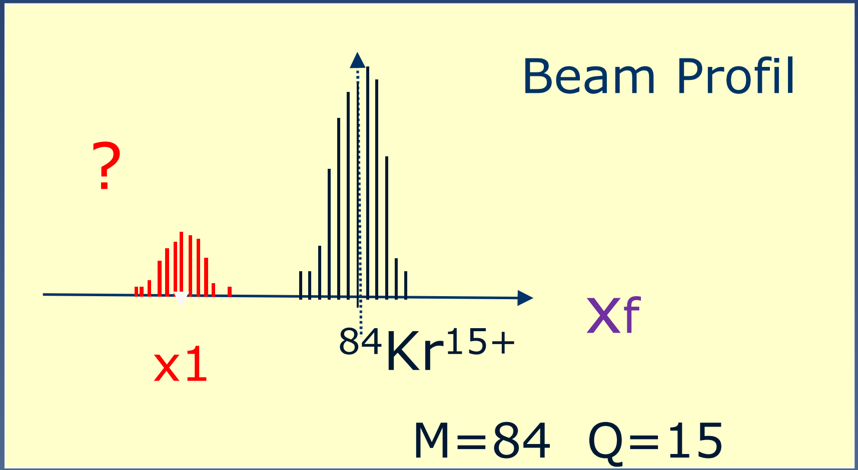
	β	γ	W	cp
β	β	$\frac{\sqrt{\gamma^2-1}}{\gamma}$	$\frac{\sqrt{(1+W/E_0)^2-1}}{1+W/E_0}$	$\frac{cp/(mc^2)}{\sqrt{1+[cp/(mc^2)]^2}}$
γ	$\frac{1}{\sqrt{1-\beta^2}}$	γ	$1+W/E_0$	$\sqrt{1+\left(\frac{cp}{mc^2}\right)^2}$
W	$\left(\frac{1}{\sqrt{1-\beta^2}}-1\right)E_0$	$E_0(\gamma - 1)$	W	$mc^2\left[\sqrt{1+\left(\frac{cp}{mc^2}\right)^2}-1\right]$
cp	$mc^2\frac{\beta}{\sqrt{1-\beta^2}}$	$E_0(\gamma^2 - 1)^{1/2}$	$[W(2E_0+W)]^{1/2}$	cp

Magnetic Spectrometer :

A tool for identification

Suppose 2 ions beams





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

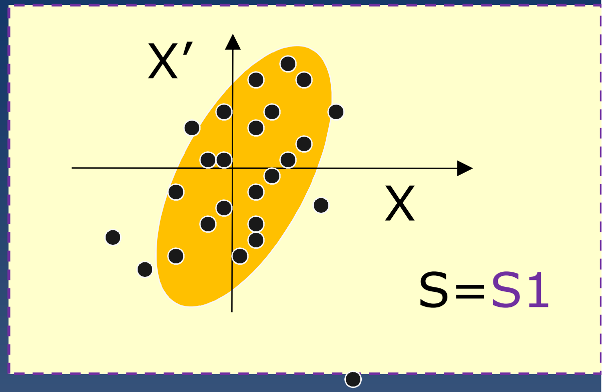
-Position measurement (Xf =X1)

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

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

B.Jacquot// Ganil

The beam : N particles in a 6D ellipsoid



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

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

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 σ(s)
b) -of one trajectory Z(s)

Beam emittance : (# optical quality)

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

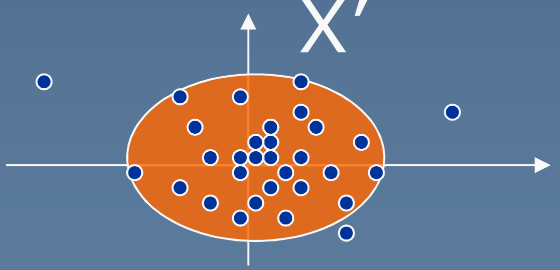
6 Dimensions

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)



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

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

Liouville theoreme : emittance is conserved in a beam line..

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) ???????

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

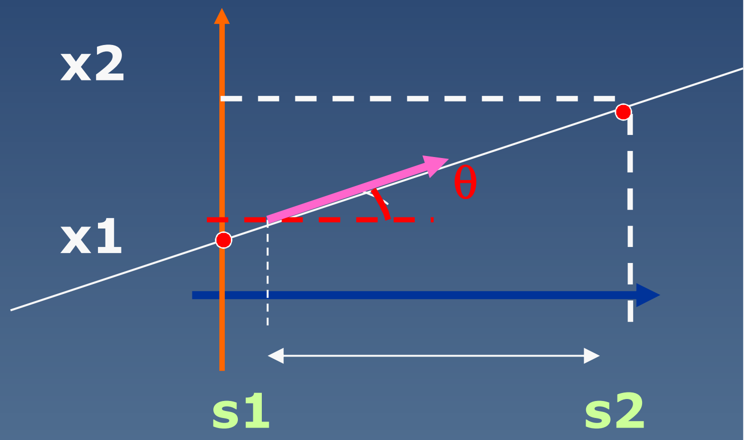
$\theta 1 = \theta 2$

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

$\varphi 1 = \varphi 2$

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

and $(s2-s1) = L$



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

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

Exemple n°1: fragments separator @Riken(Japan)

E#300-500 MeV/A   L=77m

6 dipoles magnets, 42 quadrupole magnet

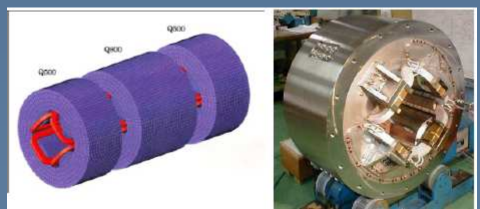
Suppression of the primary beam

(many dipoles, degrador selection)

Help the selection of very rare nuclei

Selection of 4-5 nuclei

Identification (DE-TOF)



Superferric quads

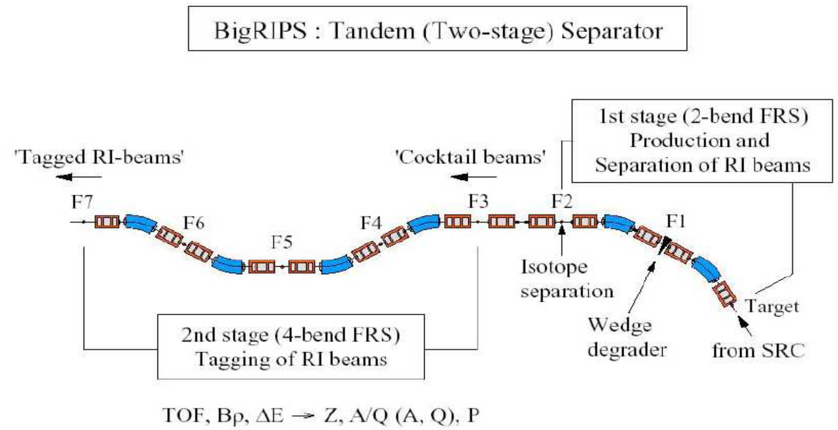


Fig. 2. A schematic diagram of the RI-beam tagging in the BigRIPS separator.

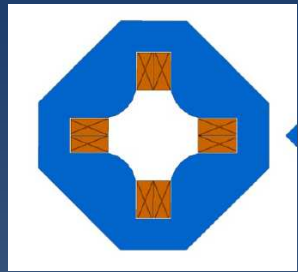
B.Jacquot// Ganil

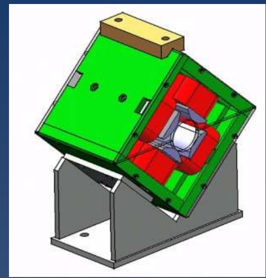
Quadrupole technology

1 :Normal conducting quad

hyperbolic pole (Fe)
coils (Cu)

G~ 10 Tesla/m





Larger Aperture

or/and

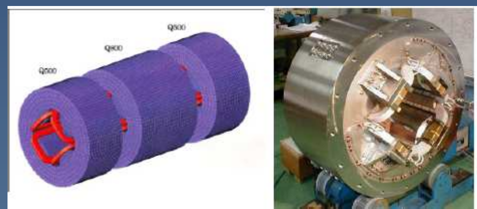
Higher strength

2 : Superferric quad

hyperbolic pole (Fe)
coils (NbTi)

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

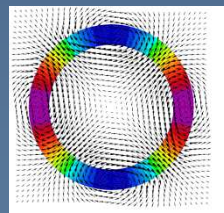
G~ 20-30 Tesla/m

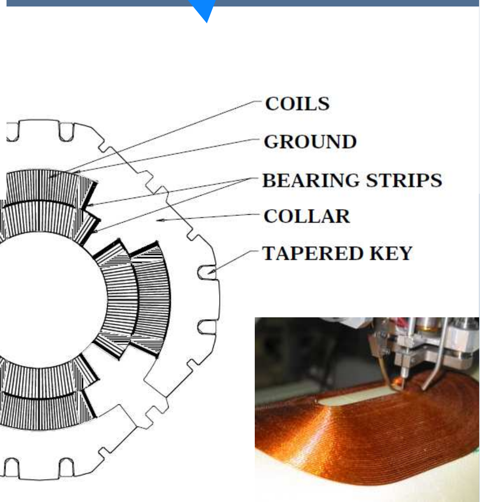


3 : Superconducting quad

No pole !!!!!!
cos(2θ) coils (NbTi)

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

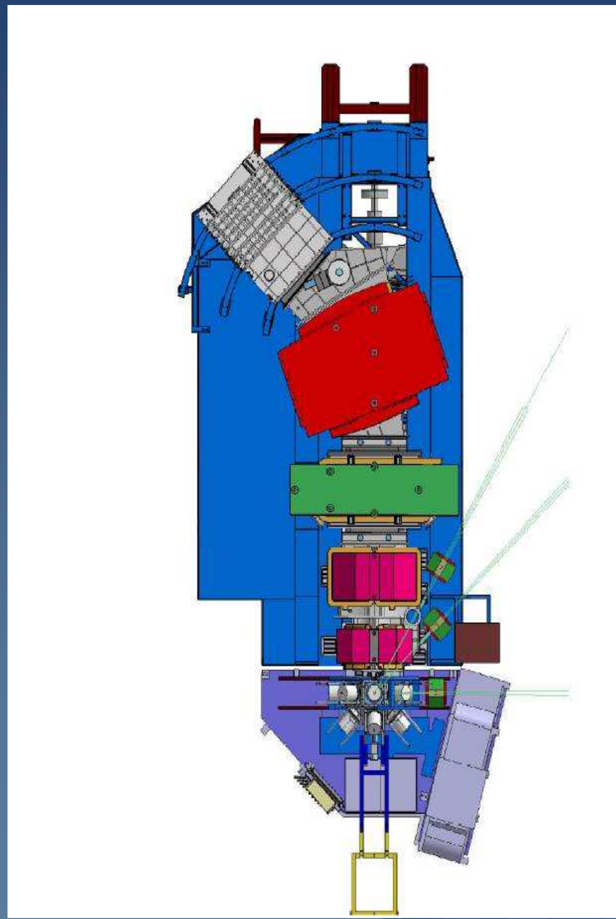




Exemple n°2: VAMOS Spectrometer

L=8 meters, 1 dipole, rotative platform

Large angular Acceptance spectrometer : 70mstrd



B.Jacquot// Ganil

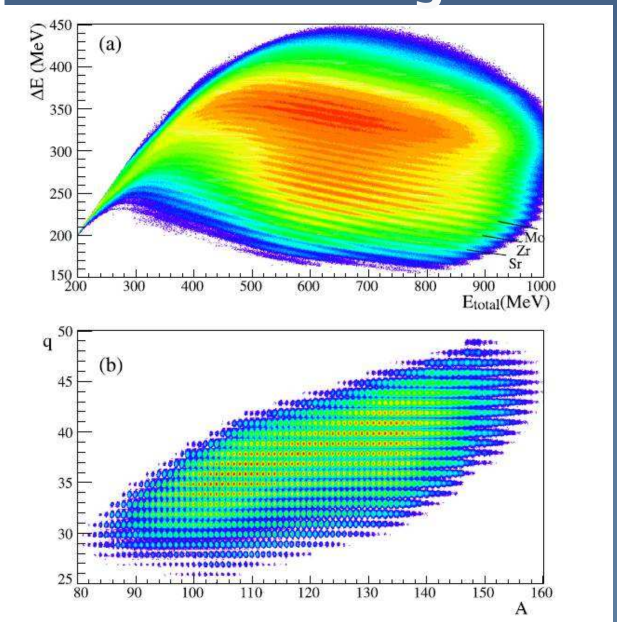
Exemple n°2: VAMOS Spectrometer (Ganil)

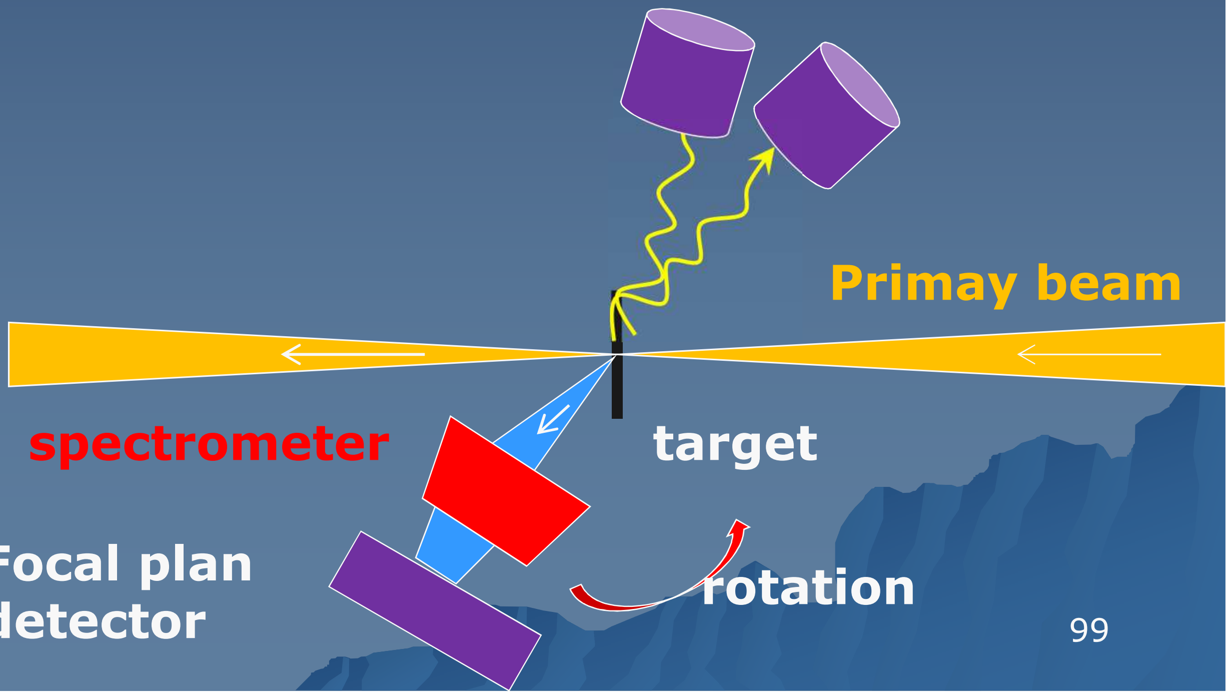
Suppression of the primary beam (by rotation)

Selection of 20-300 nuclei

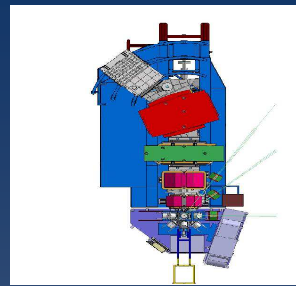
Help Identification (ΔE-TOF, position and angle measurements)

300 fission fragments id.



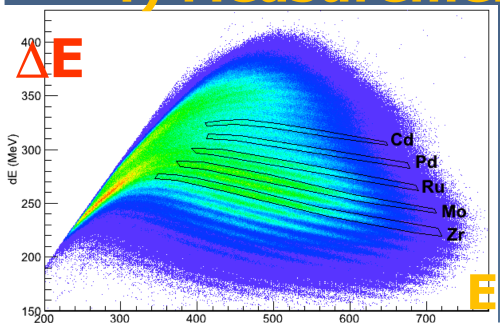


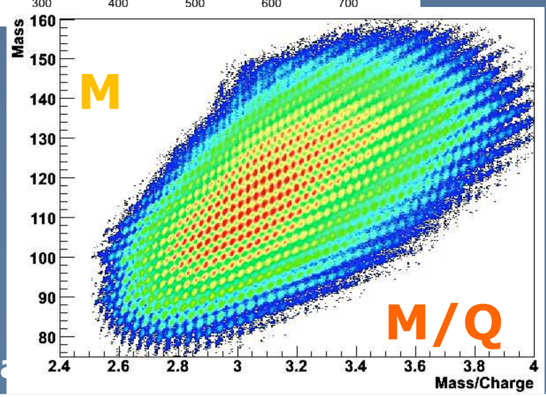
Example n°2: VAMOS Spectrometer



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 $\quad$ $v = T$ fligth $/ L_0$

M/q $\quad$ $M/q = B\rho / \gamma v$

Z $\quad$ Z# k ΔE .....

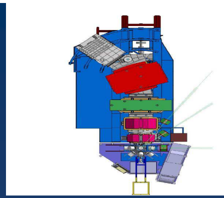
M_1 $\quad$ $M_1 = (Er + \Delta E) / [c^2 (\gamma - 1)]$

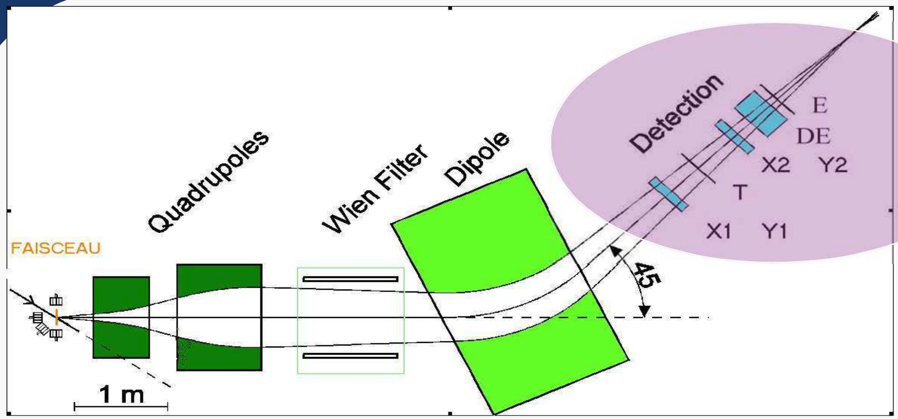
finally $\quad$ $Q = M_1 / [M/q]$

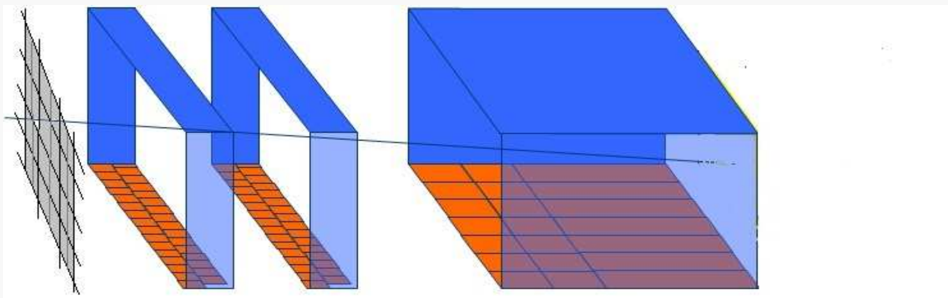
$M = [M/q] . Q$

Z # k(E) ΔE

Example n°2: VAMOS Identification







MWPPAC (Tof)

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

Ionis. Ch. (ΔE,E)

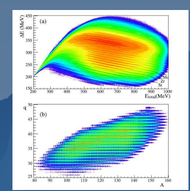
In the focal plane, 7 quantities are measured :
T, x1, y1, x2, y2, ΔE, E

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

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

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

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

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

1rst order 2nd order

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

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

B.Jacquot// Ganil

Non linear effects in optical system

Beam optics is linear when x < 5cm

x'<30mrad

δ<2%

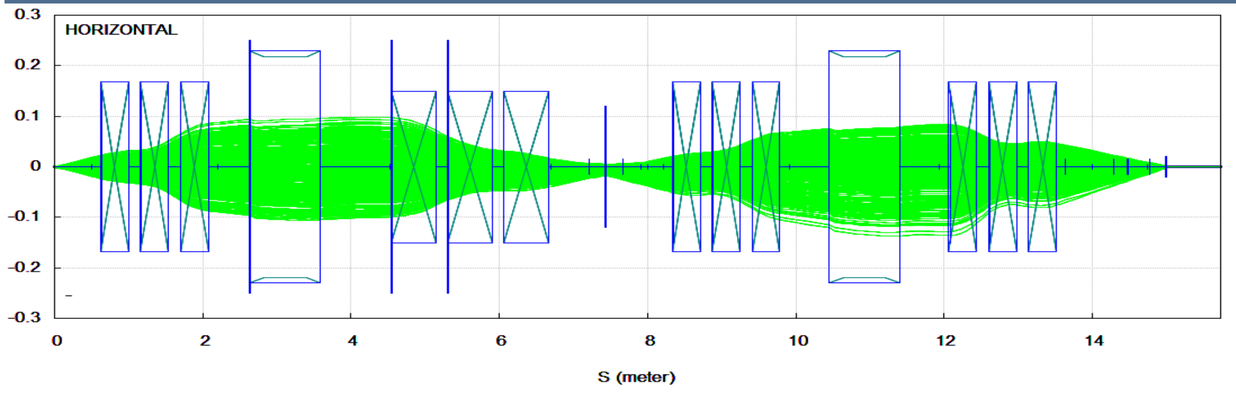
Beam is a nice ellipse in phase space, R matrix is sufficient

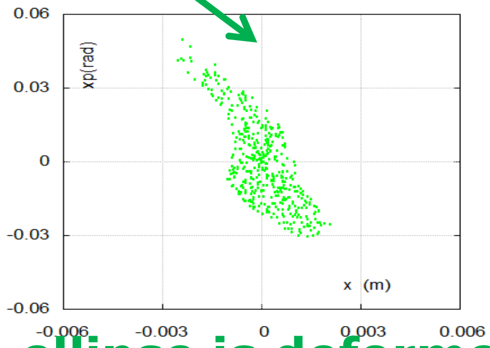
If |X'| > 30mrad or |δ| > 2%

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

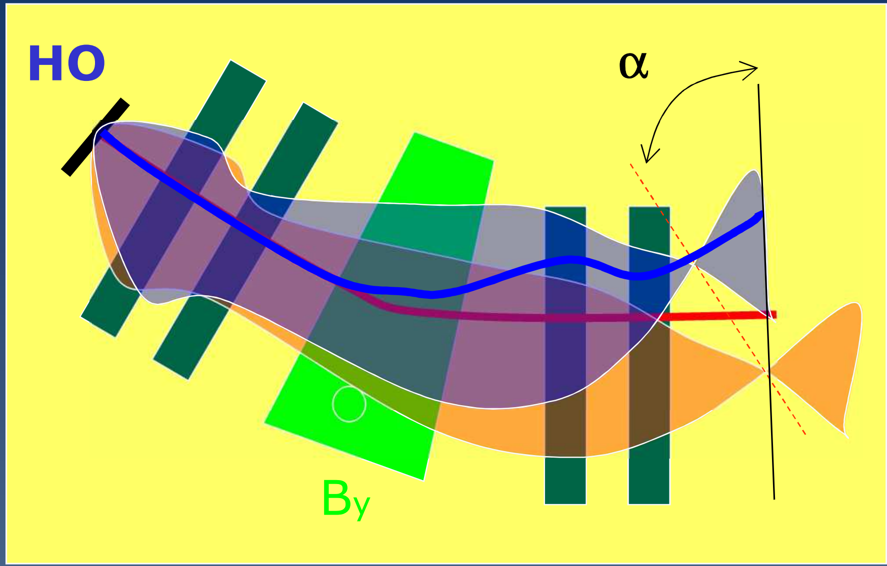
Non linear effects in optical system

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