Mass separation on radionucleides

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Timetable

$\sim 30\ min$	**1. Mass separators – overwiew [1]** • **First notions** • **Components of a spectrometer** • **Beam optics and resolution** • **Design of a mass separator**	General lecture
$\sim 15\ min$	2. High resolution separators (HRS) • Scope • Optical aberrations and correction	Zoom on a specific type of instrument
$\sim 15\ min$	3. Characterisation and operation	Personal feedback/examples

[1] *Courtesy of :* Bertrand Jacquot, Introduction aux spectromètres et séparateurs en physique nucléaire
https://heberge.lp2ib.in2p3.fr/heberge/EcoleJoliotCurie/coursannee/cours/coursBertrandJacquot.pdf

A brief introduction

The role of a spectrometer/separator is to ensure selection and/or identification of the reaction products with the best possible efficiency, while rejecting the flow of the unwanted ions.

The spectrometer boosts **the selectivity** of any experiment: that is to say the ability to select rare events with a huge amount of unwanted events

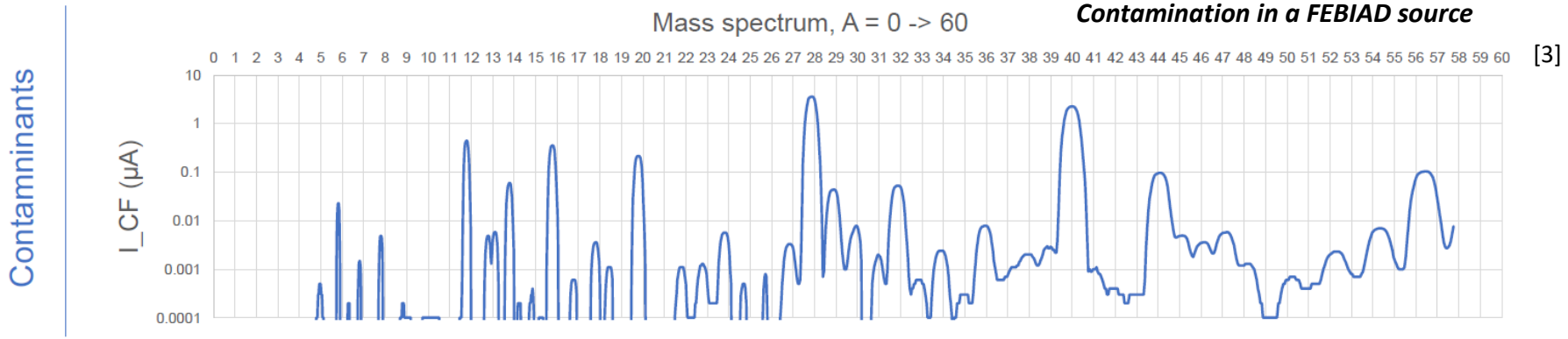
Difference between a separator and a spectrometer : sames devices but different functions

- The **spectrometers** function is the measurement of some properties of the beam (rigidity, energy, velocity…)
- The **separators** function is the elimination of a part of unwanted events (contaminants), and/or selection of desired events

Example : ion production rate of $10^{12} - 10^{14}$ *at target, but detectors limited to* $10^{3} - 10^{5}$ *Hz*

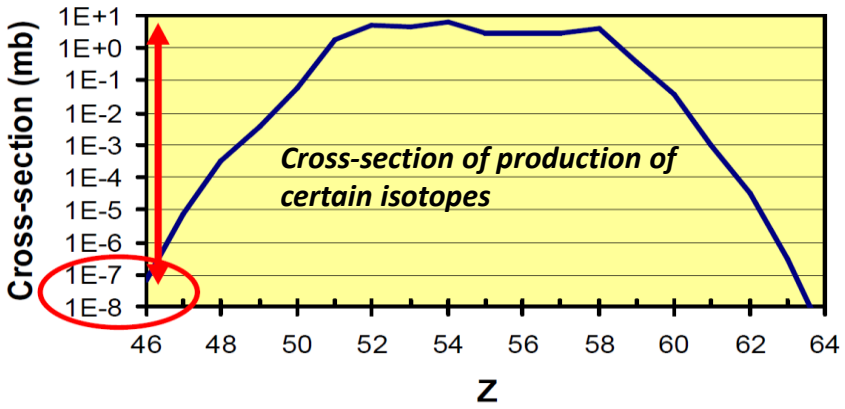
In this lecture, mostly the **separator** function will be treated

Interest of magnetic mass separators

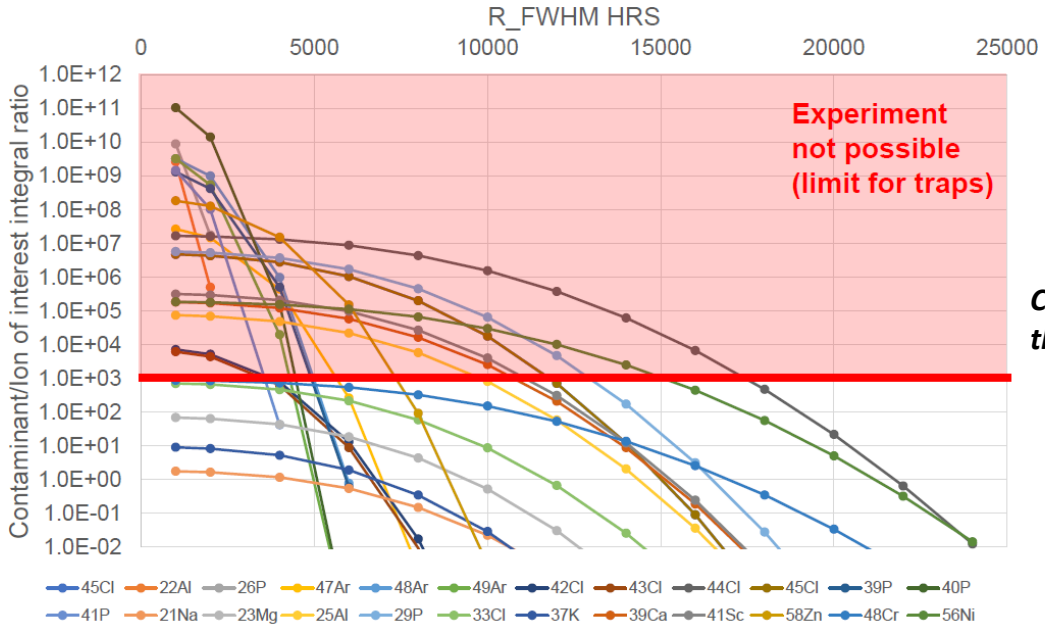


Contamination in a FEBIAD source [3]

The challenge of the extremes! [2]



1. low cross-sections ⇒ optimize efficiency
2. enormous production of isobars ⇒ optimize selectivity
3. short half-lives ⇒ optimize rapidity



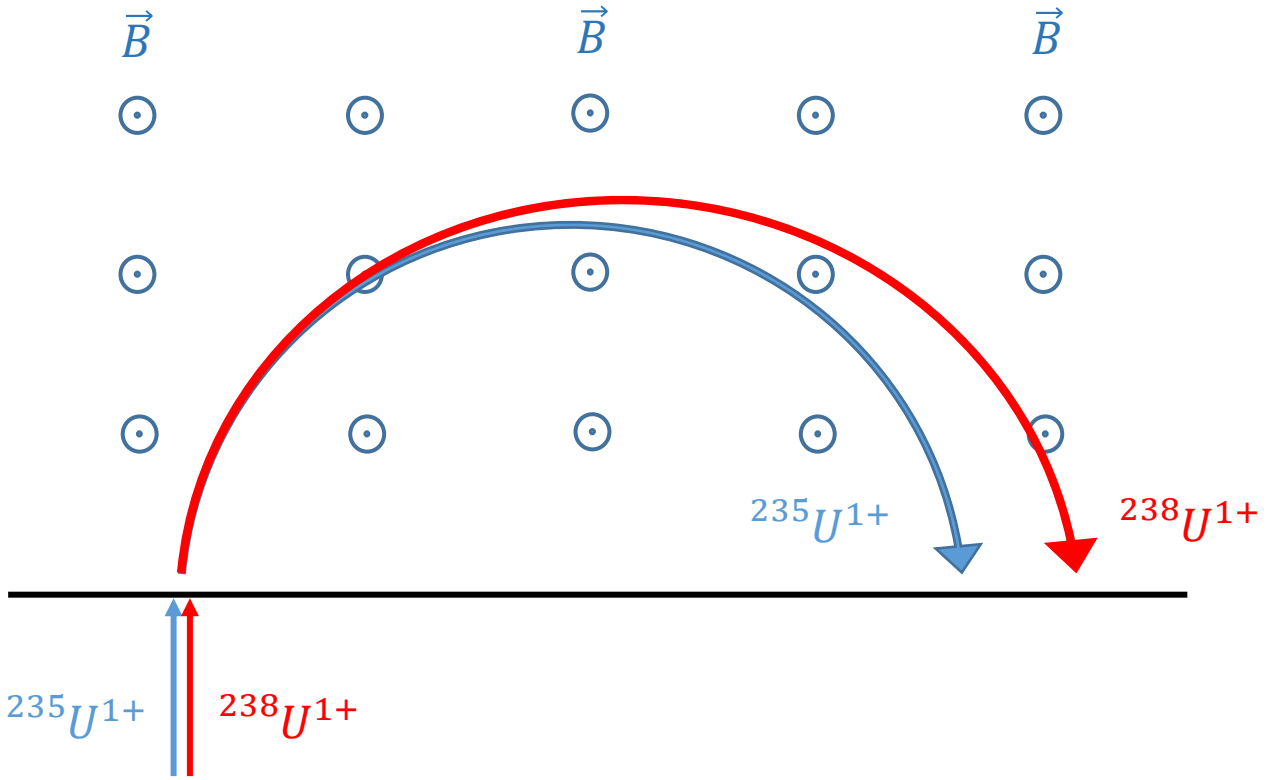
[3]

Contamination expected with the separator resolution

[2] Ulli Köster, Electromagnetic separators, Institut Laue Langevin, Grenoble, France

[3] P. Chauveau, SPIRAL1 beams for DESIR status and development, DESIR Workshop, 2024

The basic principle of a magnetic separator



$$\vec{F} = q \cdot (\vec{v} \times \vec{B})$$

The magnetic rigidity: The "Bρ" (Tesla.m)

Demonstration [1] :

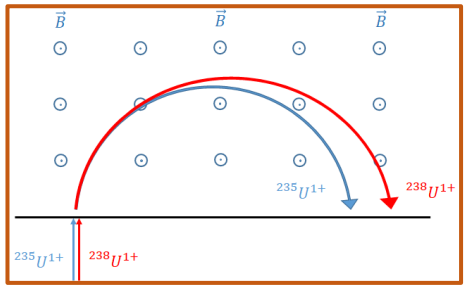
A charged particle (M, q, v) moving in a field B (magnetic induction) uniform and transverse (**v**⊥**B**), follows a circular path. The radius of curvature of an ion is determined by the equilibrium of the centrifugal force and the Lorentz force:

$$\frac{d\mathrm{p}}{dt} = \mathrm{F} = q\,(\mathrm{v} \times \mathrm{B}) \qquad \text{With} \quad \mathbf{p} = \gamma\,\mathrm{M}\,\mathbf{v}$$

Where $(\mathbf{v} \perp \mathbf{F})$, **hence** the modulus |v|=Constant and γ=constant

The motion is circular and uniform: $\frac{d\mathbf{v}}{dt} = \frac{|\mathrm{v}|^2}{R} e_r$ and so $\gamma\, m\, \mathrm{v}^2 / R = q\,|\mathrm{v}|\,|\mathrm{B}|$

The curvature radius of the trajectory is then $R = \frac{\gamma\, m\, \mathrm{v}}{q\, B}$



The most important formula of this lecture :

Magnetic rigidity :

$$B\rho = \frac{\gamma m v}{q} = \frac{p}{q}$$

- $B\rho$ is called the magnetic rigidity, expressed in T.m
- The knowledge of the $B\rho$ is the only information required to guide an ion in a magnetic spectrometer
- Extensively used in most facilities where dipoles are needed

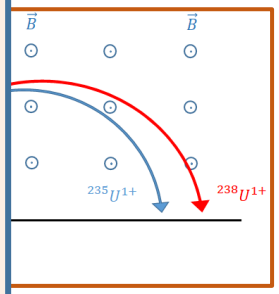
The magnetic rigidity: The "Bρ" (Tesla.m)

A charged particle (M, q, v) moving in a field B (magnetic induction) uniform and transverse

Demo

Numerical example :

A carbon ion beam $^{12}C^{6+}$ having a kinetic energy of 47.05 MeV/A (E=564.65 MeV), has a magnetic rigidity of (……). A magnetic dipole with a bending angle ϕ=45° and a reference curvature radius R_{dipole}=3.0m, has to be tuned at B=(……..) With such a field the ion deflection will really be 45°.



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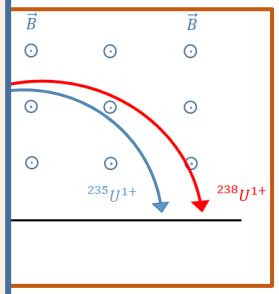
The magnetic rigidity: The "Bρ" (Tesla.m)

A charged particle (M, q, v) moving in a field B (magnetic induction) uniform and transverse

Demo

Numerical example :

A carbon ion beam $^{12}C^{6+}$ having a kinetic energy of 47.05 MeV/A (E=564.65 MeV), has a magnetic rigidity of **2.0 T.m**. A magnetic dipole with a bending angle ϕ=45° and a reference curvature radius R_{dipole}=3.0m, has to be tuned at **B=0.6666 Tesla**. With such a field the ion deflection will really be 45°.



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An important point…

(Non-relativistic approx.)

$$B\rho = \frac{mv}{q} = \frac{p}{q}$$

$$E_k = \frac{1}{2}mv^2 \Rightarrow v^2 = 2\frac{E_k}{m}$$

$$B\rho = \frac{\sqrt{2\,\boldsymbol{m}\,\boldsymbol{E}}}{q}$$

Dipoles work the same for mass or energy shift (momentum separation) at first order

A magnetic separator can separate either masses or energies. But this has a cost : it is doing both at once

➔ Importance of having a low as possible energy spread for maximizing mass resolution

The electric rigidity: The “ Eρ” (in Volt or MVolt)

Similarly to $B\rho$, we can define the electric rigidity :

$$E\rho = \frac{\gamma m v^2}{q}$$

Useful in spectrometers with electrostatic elements

BUT (low energy approximation) $E_k = \frac{1}{2} m v^2 \Rightarrow v^2 = 2\frac{E_k}{m}$

$$E\rho = \frac{2E_k}{q}$$

NO mass separation with electric fields

*Possibility of using a combination of **E** and **B** fields for a mass-only separation*

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   - Scope
   - Optical aberrations and correction
3. Characterisation and operation

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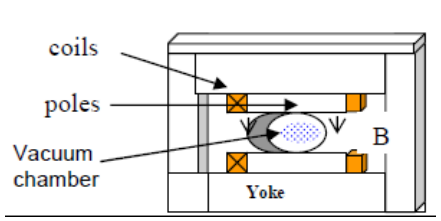
The components of a spectrometer 1/2

Optical elements :

The magnetic dipole

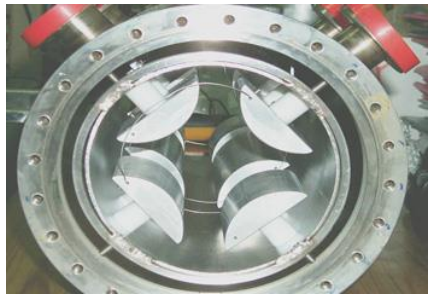


- Main element of separator
- Responsible of mass separation
- Magnetic (Copper)
- Need high currents
- B limited to 1,6T for hot dipoles (saturation of iron poles)
- Outside vacuum chamber

Electrostatic « dipoles » (steerers)

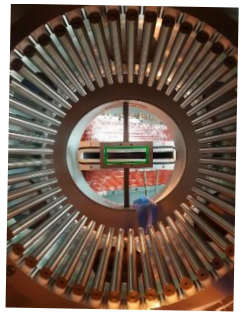
- Orbit correction (0th order)
- Metallic plates
- Electrostatic
- Voltage
- From V to kV
- Inside vacuum chamber

Electrostatic quadrupoles



- Focalisation (1st order)
- Metallic poles
- Electrostatic
- Voltage
- From V to kV
- Inside vacuum chamber

Multipoles



- Higher-order corrections
- Metallic poles
- Electrostatic
- Voltage
- From V to kV
- Sextupoles, octupoles or general multipoles
- Inside vacuum chamber

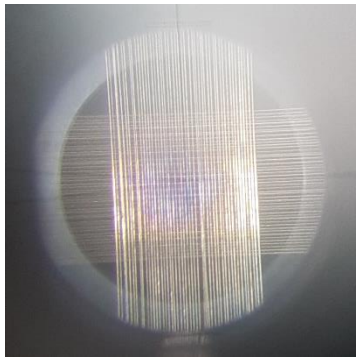
Magnetic

Electrostatic (no mass dependance)

The components of a spectrometer 2/2

Instruments and diagnostics (not exhaustive)

Beam profile monitors (BPM)

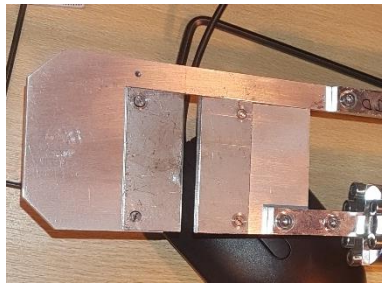


- Beam center (μ) and size (σ)
- Conductive wires or gaz
- For pA to mA range

Current measurement

- Faraday cups
- > pA currents

Beam manipulation and selection (slits)

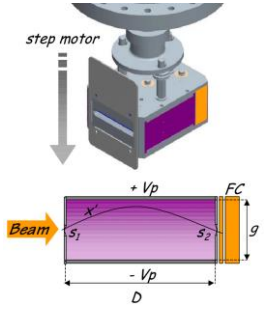


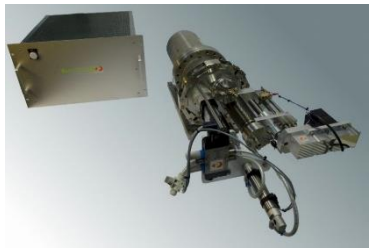
- Vertical & horizontal
- Beam/mass selection
- Position measurement

Particle detectors

- Micro-chanel plates (MCP)
- Silicon detectors
- Low currents (<pA)

+ more specific diagnostics : emittance-meters (see later)





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Particle dynamics is calculated using the « Newton-Lorentz » equation :

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

It is usually sufficient to describe beam dynamics at 1st order.

➔ Development of equations along reference path at 1st order, as a function of the 3D phase space.

This can be expressed under the form of matrix transport :

General transport matrix :

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

Matrix of a quadrupole (x focusing)	Matrix of a drift length L:	Matrix of a dipole magnet with length
. where L is its length and k=G /Bρ$_{ref}$ with $G = dB_y / dx$	γ is the relativistic factor for the reference trajectory	L & deviation ϕ L=ϕ R and R$_{16}$ =1-cos(kL) , with k_x=1/ R
$R=\begin{bmatrix} \cos\sqrt{k}L & \frac{\sin\sqrt{k}L}{\sqrt{k}} & 0 & 0 & 0 & 0 \\ -\sqrt{k}\sin\sqrt{k}L & \cos\sqrt{k}L & 0 & 0 & 0 & 0 \\ 0 & 0 & \cosh\sqrt{k}L & \frac{\sinh\sqrt{k}L}{\sqrt{k}} & 0 & 0 \\ 0 & 0 & \sqrt{k}\sinh\sqrt{k}L & \cosh\sqrt{k}L & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \frac{L}{\gamma_0^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$ *horizontal focusing part* *Vertical defocusing part*	$R=\begin{bmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & L/\gamma^2 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$	$R=\begin{bmatrix} \cos k_x L & \frac{\sin k_x L}{k_x} & 0 & 0 & 0 & R_{16} \\ -k_x \sin k_x L & \cos k_x L & 0 & 0 & 0 & R_{26} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -R_{16} & -R_{26} & 0 & 0 & 1 & R_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$ dispersive part

se space.

General t

$$\begin{bmatrix} z \\ \delta \end{bmatrix}_{final} \quad \begin{bmatrix} R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66} \end{bmatrix} \quad \begin{bmatrix} z \\ \delta \end{bmatrix}_{init}$$

Particle dynamics is calculated using the « Newton-Lorentz » equation :

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

It is usually sufficient to describe beam dynamics at 1st order.

➔ Development of equations along reference path at 1st order, as a function of the 3D phase space.

This can be expressed under the form of matrix transport :

For spectrometers :

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

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Dispersion (sometimes expressed in cm/%)

Point-to-point focusing

Magnification (minimize if possible)

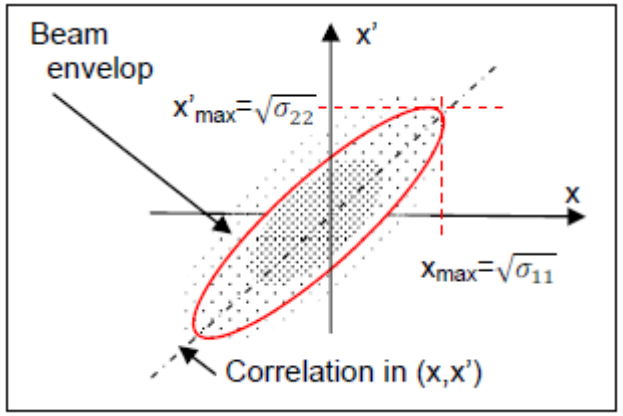
Time of fligth (bunched beams)

No energy change

$$\Rightarrow x_1 = R_{11} \cdot x_0 + R_{16} \cdot \delta_0$$

The final position of a particle depends on the magnification and the dispersion

Beam representation



The ellipse equation is

$$\varepsilon_x^{\,2} = \sigma_{22}(s)\, x^2 + 2.\sigma_{12}(s)\, x\, x' + \sigma_{11}(s)\, x'^2$$

The ellipse area, called the (RMS) beam emittance, is a quantity which is conserved along the beam trajectory:

$$\textit{Ellipse Area} = \textit{Emittance} = \pi\, \varepsilon_x = \pi\sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}\sigma_{21}}$$

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_{11} & \sigma_{12} & 0 & 0 & 0 & \sigma_{11} \\ \sigma_{12} & \sigma_{22} & 0 & 0 & 0 & \sigma_{16} \\ 0 & 0 & \sigma_{33} & \sigma_{34} & 0 & 0 \\ 0 & 0 & \sigma_{43} & \sigma_{44} & 0 & 0 \\ \sigma_{51} & \sigma_{52} & 0 & 0 & \sigma_{55} & \sigma_{56} \\ 0 & 0 & 0 & 0 & \sigma_{65} & \sigma_{66} \end{pmatrix}$$

With $\sigma_{ij} = \frac{1}{N}\sum_{\alpha}(Z_\alpha^i - \overline{Z^i}).(Z_\alpha^j - \overline{Z^j})$

$$\sigma_{11} = < x.x > = \frac{1}{N}\sum_{\alpha} x_\alpha . x_\alpha$$

$$\sigma_{22} = < x'.x' > ;\ \sigma_{33} = < y.y >$$

No correlation for the beam between (y,y') and (x,x') because of the forces induces by the quadrupoles field (F_x=G x ,F_y=G y): the forces in the horizontal plane, experienced by the particles are only correlated to the horizontal position in a quad….

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The central parameter : separator resolution

Resolution : separation needed to distinguish 2 beams with a size σ_x at the focal plane

$$R_{FWHM} = 2{,}35\sigma_x/R_{16}$$ where R_{16} is the separator dispersion

Be careful : there is plenty of definitions

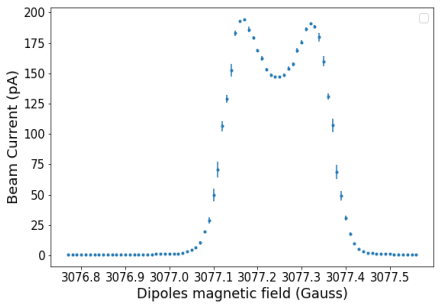
$R_{1\sigma} = \sigma_x/R_{16}$ → Most of the time insufficient

$R_{FWHM} = 2{,}35\sigma_x/R_{16}$ → Most commonly used, but insufficient separation sometimes

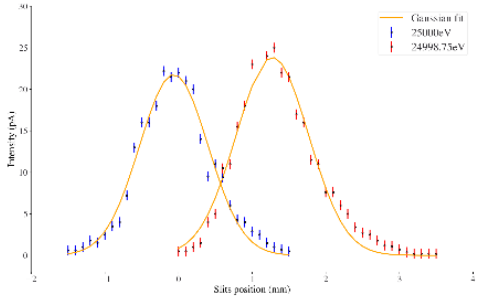
$R_{4\sigma} = 4\sigma_x/R_{16}$

$R_{10\%valley}$: $10\%\ valley\ sep.$

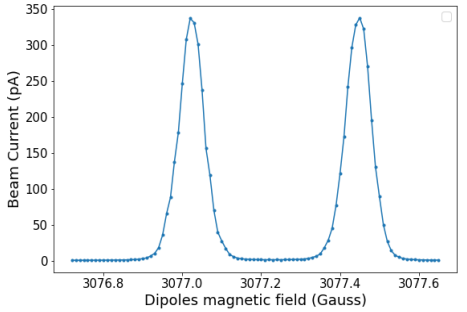
→ More acceptable separation



Poorly separated



Well separated



Totally separated

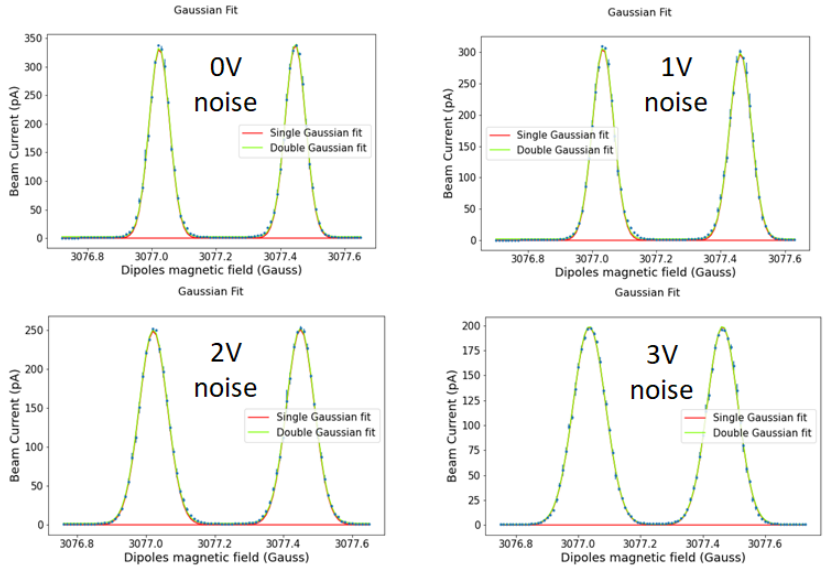
Spectrometer resolution

Warning : resolution itself does not mean « clean » separation

Spectrometer resolution

Warning : resolution itself does not mean « clean » separation

- **Intrinsic resolution (power of separation) ≠ effective resolution (capacity to resolve beams)**
  - Power of separation : linked to separator parameters (dispersion, magnification, object size)
  - Effective resolution depends on beam parameters (emittance, energy spread)



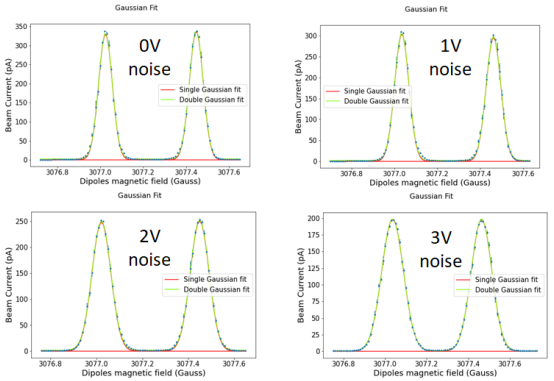
➔ Resolution decrease with increasing energy spread and emittance

Separation of two beams with different energy spreads (⇔ noise on acceleration voltage)

Spectrometer resolution

Warning : resolution itself does not mean « clean » separation

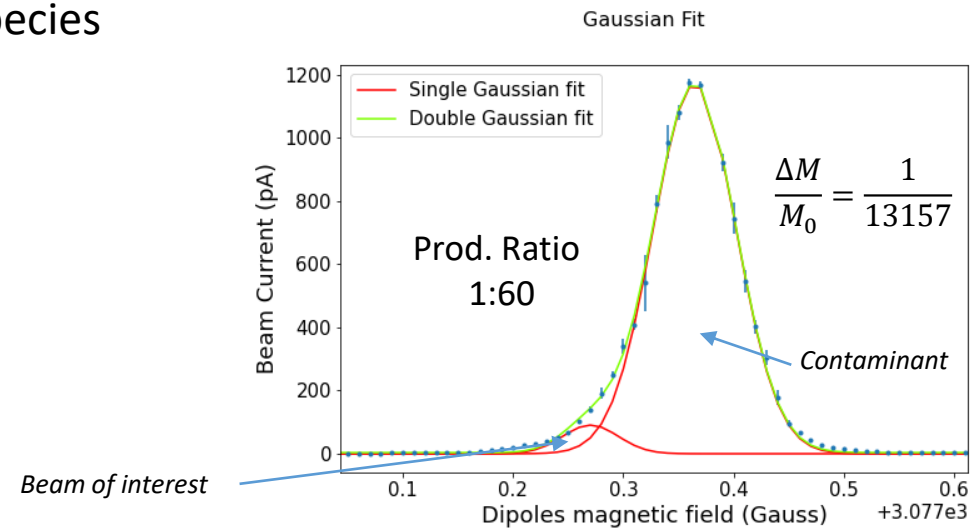
- **Intrinsic resolution (power of separation) ≠ effective resolution**
  - Power of separation : linked to separator parameters (dispersion, magnification)
  - Effective resolution depends on beam parameters (emittance, energy spread)



Separation of two beams with different energy spreads (noise on acceleration voltage)

- **Production ratio of contaminants**
  - Tails of contaminants can override peaks of interest species

Example : separation of ^{100}Sn and ^{100}In with a resolution of R ~24000

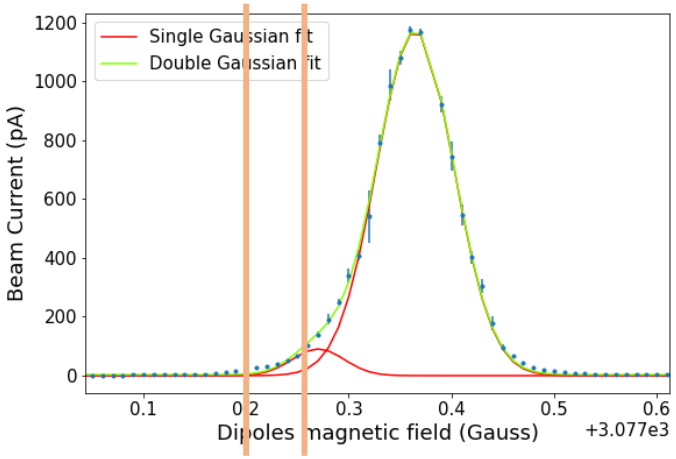


Designing a new spectrometer

The design of a separator consists mainly in optimizing two quantities :

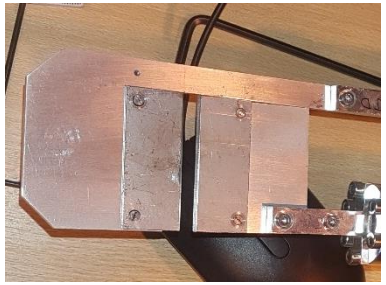
- The cleaning power through **resolution** : the ability to separate two beams of different masses or energy. The **higher** the better.
- The **transmission** : the fraction of the beam which passes through the separator. Must tends towards **1** (**100%**).

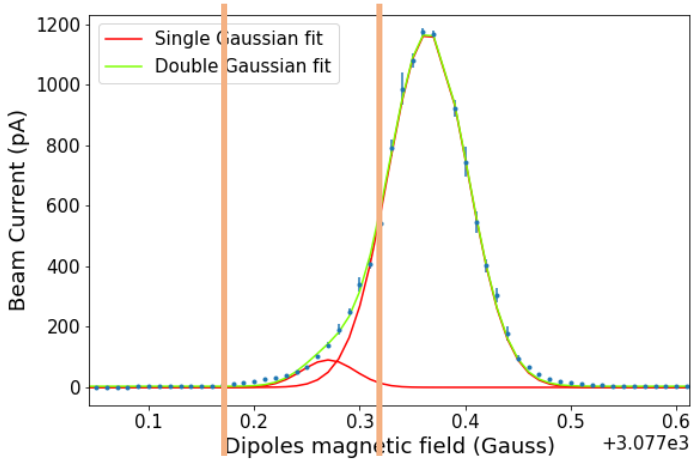
Sometimes both objectives are mutually exclusive and cannot be fullfilled together : compromise needed (use of slits).



Cleaning quality maximized :
pure beam/low statistics

use of slits





Transmission maximized :
high statistics/unpure

The steps of the design of a separator

The design of a new separator starts with the first order study.

Step 1) Define the beam of interest after the target :

- Spot size on target
- Angular distribution
- Energy dispersion
- Maximum rigidity

The steps of the design of a separator

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Step 1) Define the beam of interest after the target :

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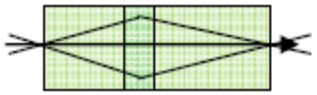
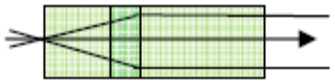
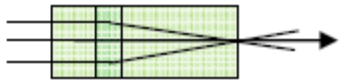
- Angular distribution
- Energy dispersion
- Maximum rigidity

Step 2) Adjust the quadrupole sequence to transport the beam with the desired optical properties :

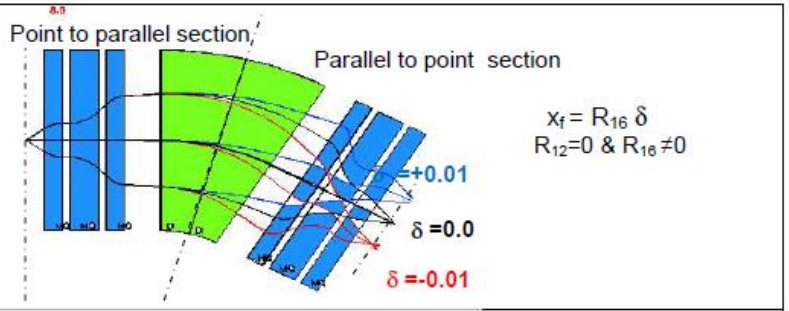
- Number
- Length
- Gradient

"Point to point" focus	"Point to parallel" focus	"Parallel to point" focus
		
R_{12}=0: The final position does not depend on initial angle.	R_{22}=0: The final angle does not depend on initial angle.	R_{11}=0: The final position does not depend on initial position.

The different focusing conditions and the corresponding matrix coefficient for an optical system.

The steps of the design of a separator

Step 3) Check the dispersion R_{16} and compute the resolution at the final focal point:



Trajectories with different angles x' and rigidities δ in a spectrometer having 1 dipole and 6 quadrupoles. Globally, the quadrupoles have been tuned to get a system which is "Point to point" focusing ($R_{12}=0$) and dispersive ($R_{16}\neq 0$).

The steps of the design of a separator

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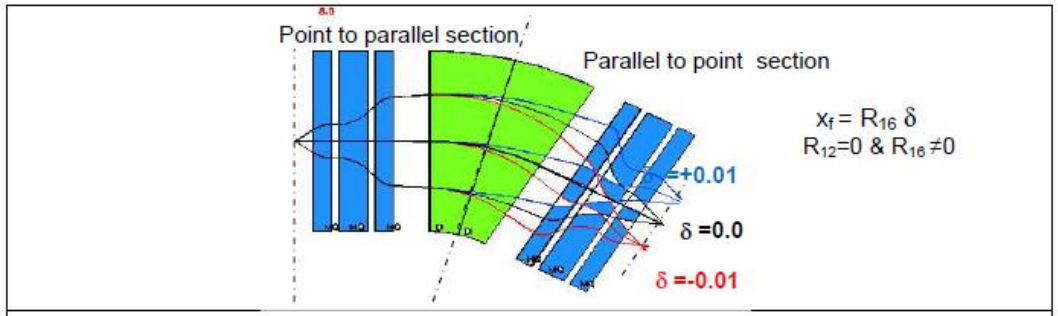

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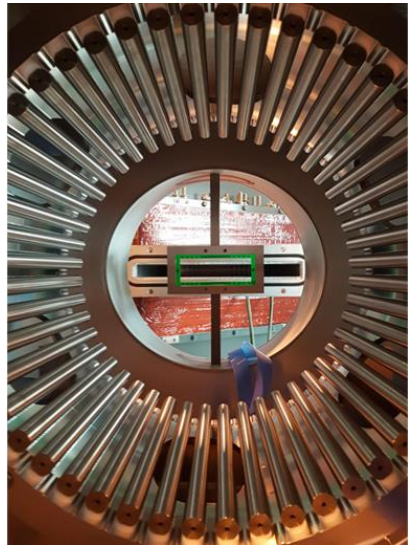
Step 4) *Optional* High order study:

- Use of realistic field maps
- Use of Taylor maps (equations of motion developed at order >1)
- Insertion of multipoles (sextupoles mainly, then octupoles…)

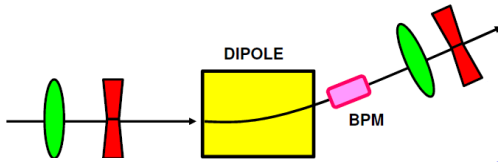


Timetable

1. Mass separators – overwiew
   - First notions
   - Components of a spectrometer
   - Beam optics and resolution
   - Design of a mass separator
2. **High resolution separators (HRS)**
   - **Scope**
   - **Optical aberrations and correction**
3. Characterisation and operation

Ranges of mass separators

« Standard » separator



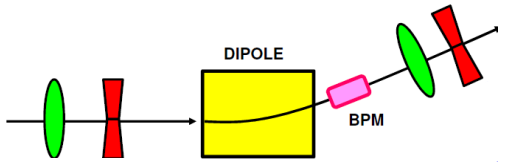
- Simple design (1 dipole)
- On-line separation (fast)
- High currents tolerated

$$Reso < 1000$$

Species to isotope separation

Ranges of mass separators

« Standard » separator



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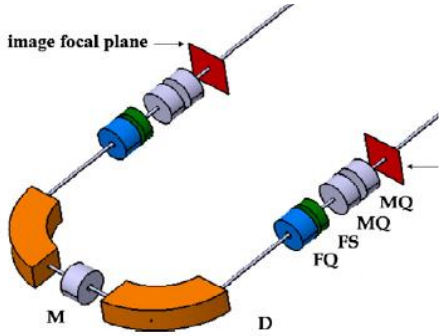
High Resolution Separators



- More complex optics (2 dipoles)
- Fast separation (~µs)
- Electrostatic elements (quads, steerers)
- Multipoles (sextupoles, octu…)
- High currents tolerated

$$3000 < Reso < 30000$$

$m_p = 938{,}272$ MeV/c2

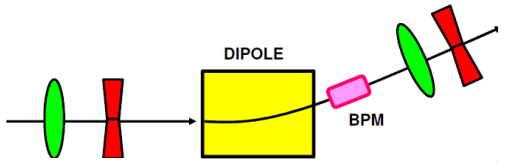
$m_n = 939{,}565$ MeV/c2

$$\frac{\Delta m}{m} = \frac{1}{725}$$

Isotopes to isobars separation

Ranges of mass separators

« Standard » separator



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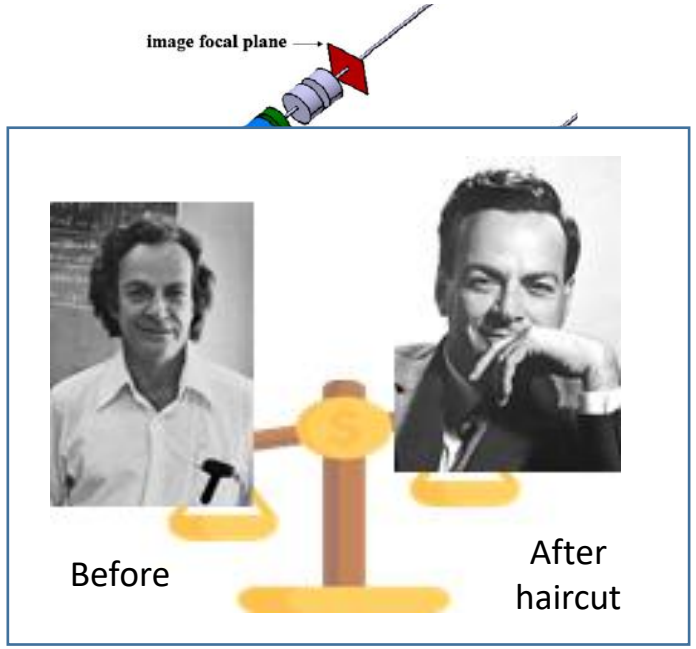

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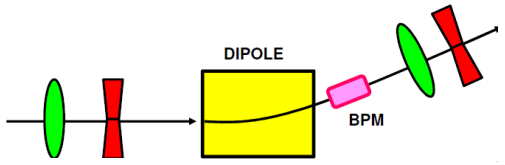

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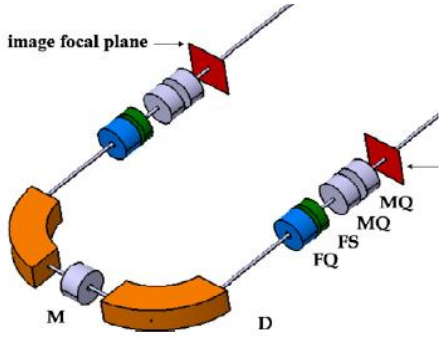

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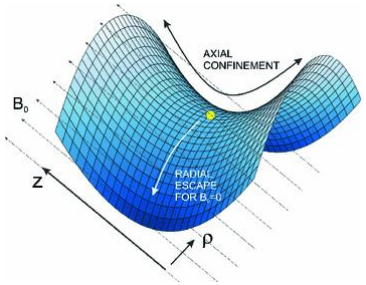
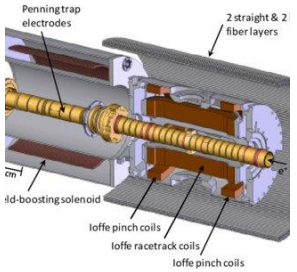
Isotopes to isobars separation

Traps : Paul traps, penning traps, MR-TOF-MS …





- Very complex
- (relatively) Slow separation (few ms)
- Limited in current

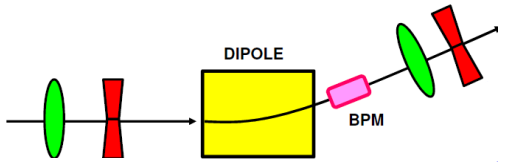
$$Reso > 100000$$

Mass measurements !

Up to isomers separation

Ranges of mass separators

« Standard » separator



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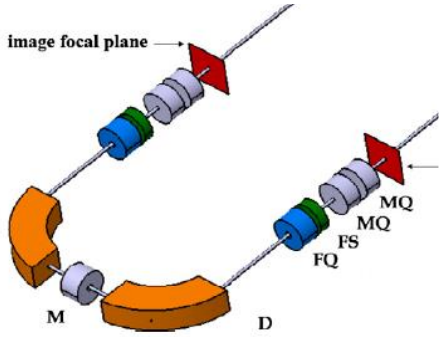
Species to isotope separation

High Resolution Separators



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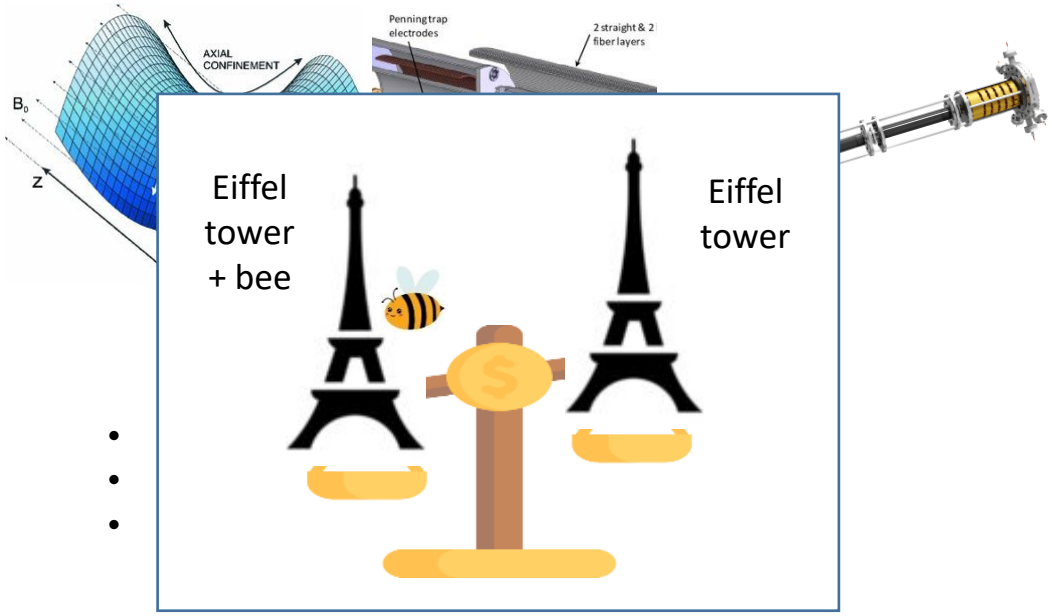


-
-
-

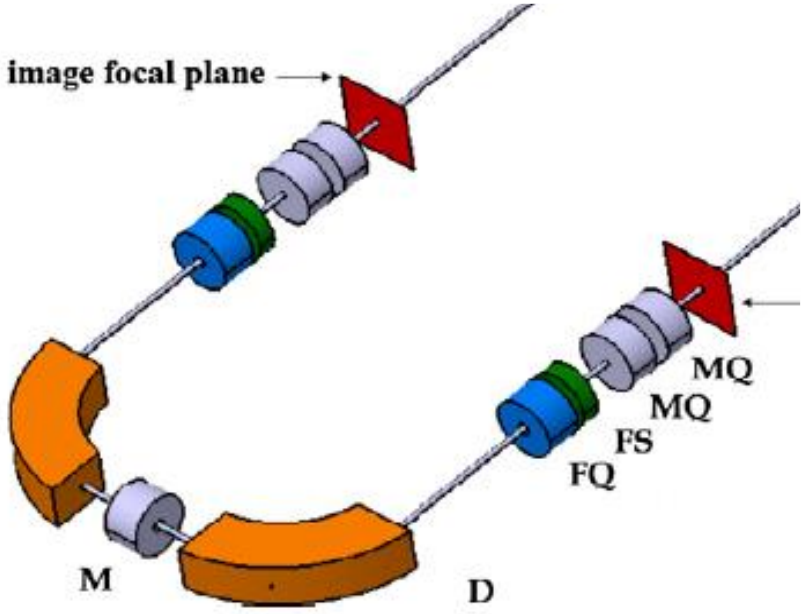
$$Reso > 100000$$

Mass measurements !

Up to isomers separation

High-resolution separators

Examples of HRS :



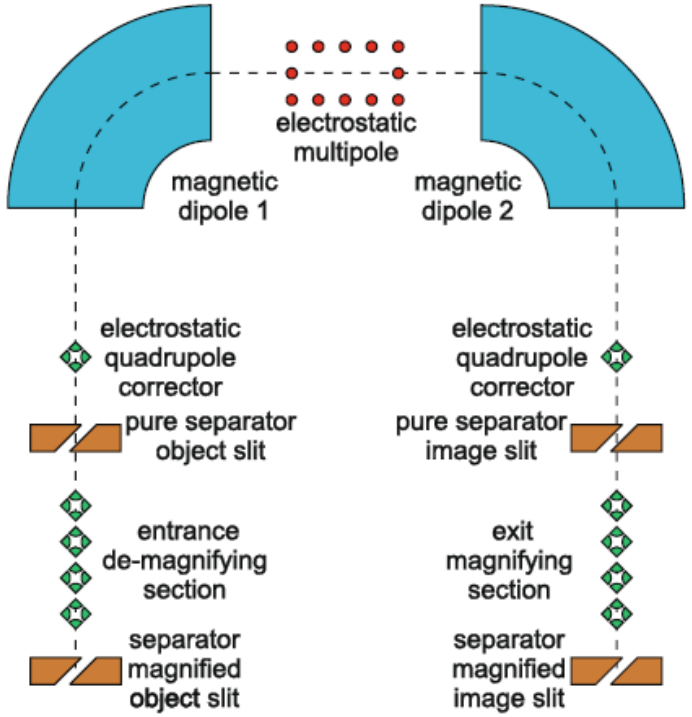
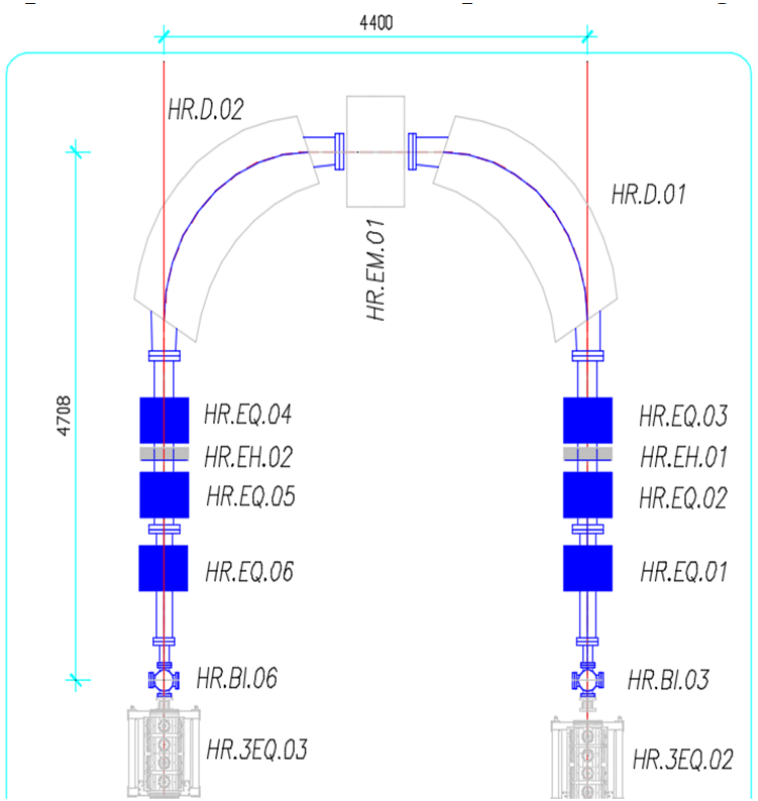


Fig. 2. Schematic of the ARIEL high-resolution separator.



DESIR HRS [4]

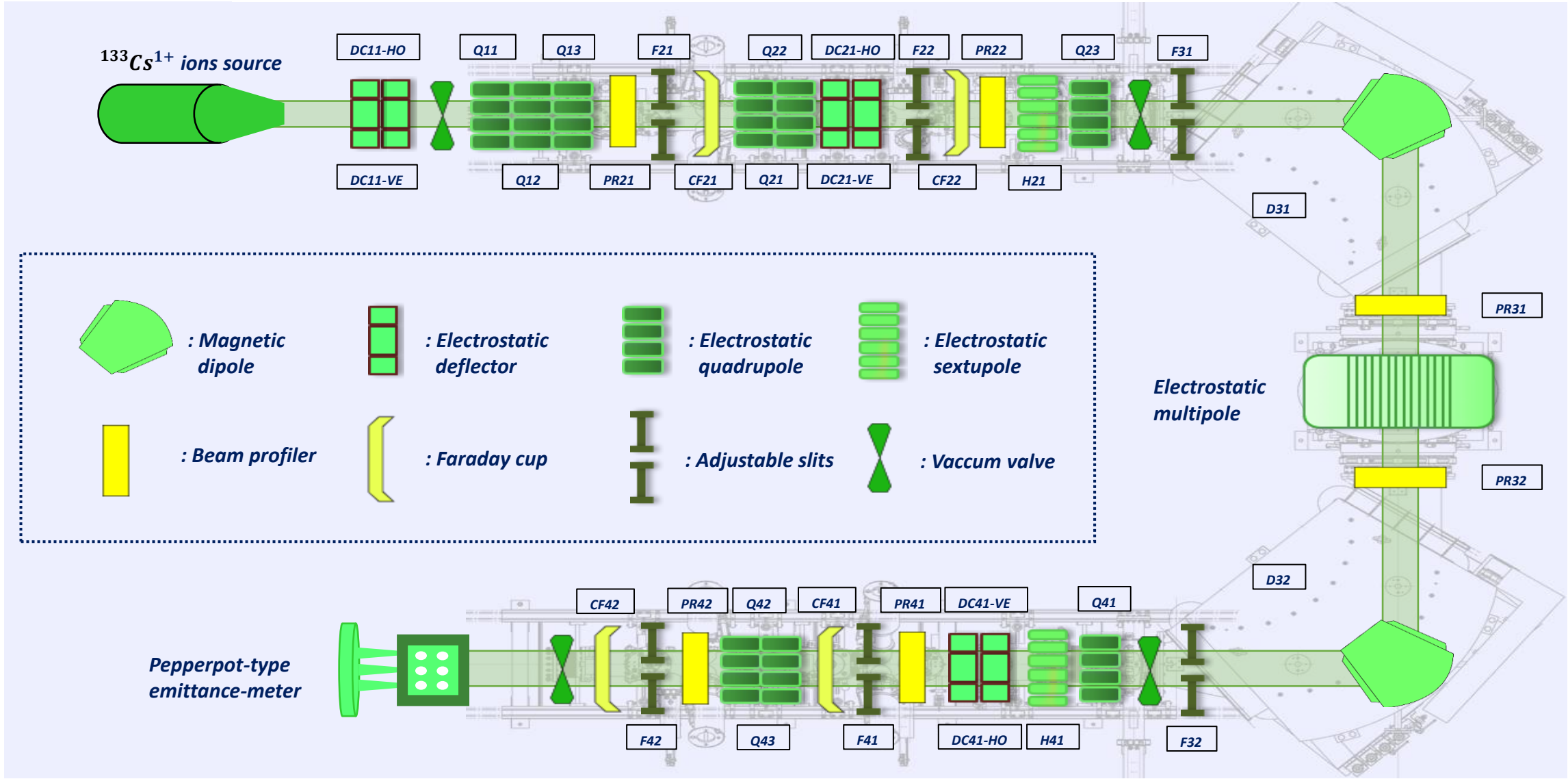
CANREB HRS [5]

SPES HRMS [6]

Design : mirror symmetric. 2 dipoles, matching quadrupoles, (de)focusing quadrupoles, sextupoles and multipole

[4] J. Michaud et al., Commissioning of the DESIR high-resolution mass separator, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, https://doi.org/10.1016/j.nimb.2023.05.013.
[5] M. Marchetto et al., Status of the CANREB high-resolution separator at TRIUMF, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, https://doi.org/10.1016/j.nimb.2019.05.032.
[6] C Baltador et al 2020 J. Phys.: Conf. Ser. 1401 012014 DOI 10.1088/1742-6596/1401/1/012014

Example of the DESIR HRS synoptics & CC



Higher-order fields

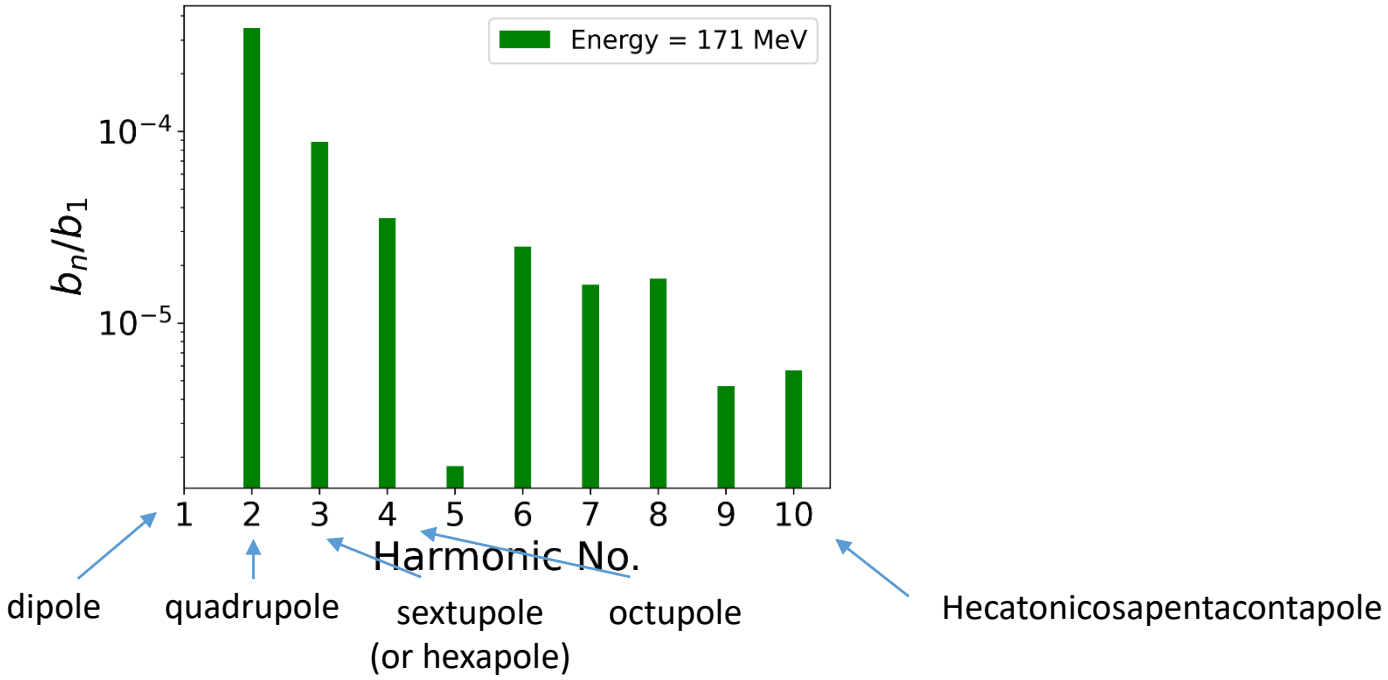
A magnetic dipole, is meant to apply a… dipolar field on the beam

Higher-order fields

A magnetic dipole, is meant to apply a… dipolar field on the beam

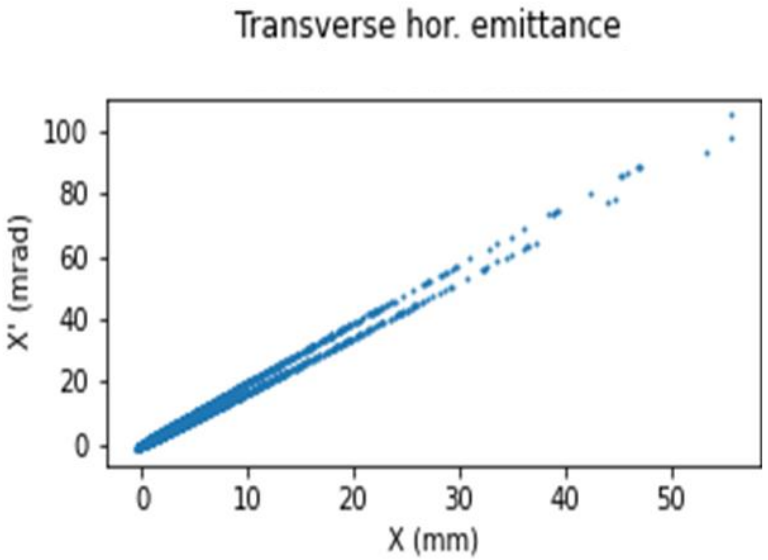
A perfect dipole would, but reality hits sometimes :

Harmonic content of a magnetic dipole (for illustration)



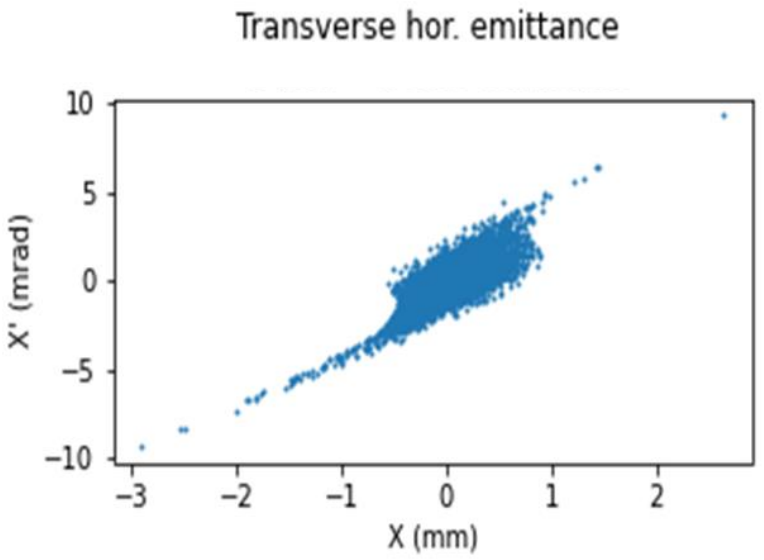
Higher-order fields will affect the shape of the beam : this is called optical aberrations

Different levels of aberrations (simulations)



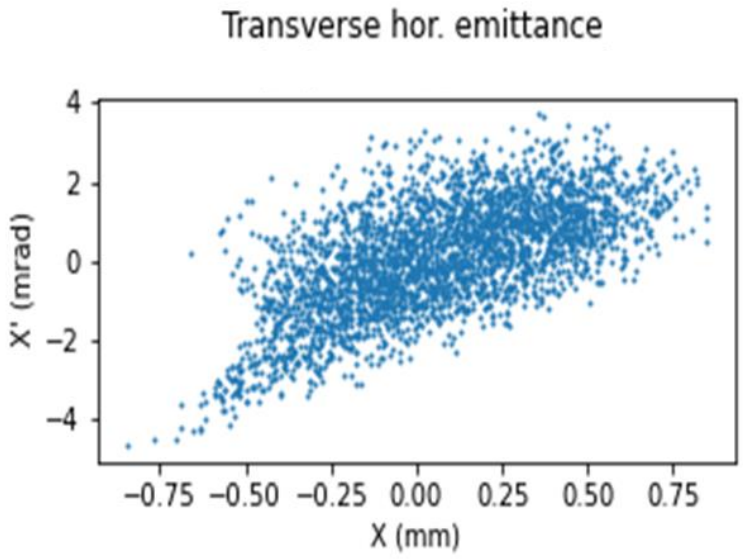
Hexapolar aberration (2^{nd} order) is dominant

Typically « C-shaped »



Octupolar aberration (3^{rd} order)
Hexapolar corrected

Typically « S-shaped »



Higher order aberration ($> 3^{rd}$ order)
Octupolar corrected

Optical aberrations tend to increase the beam size and need to be corrected

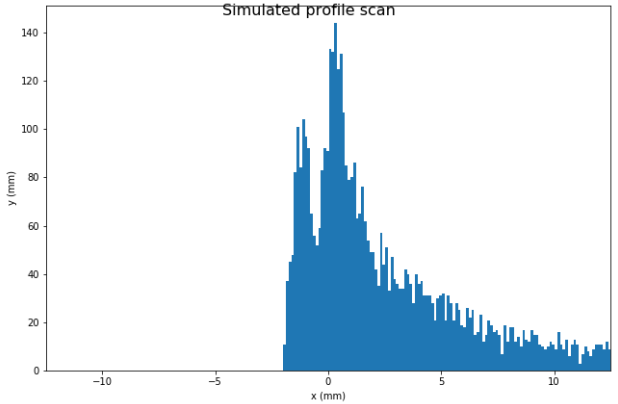
Effect of optical aberrations on beam separation (simulations)

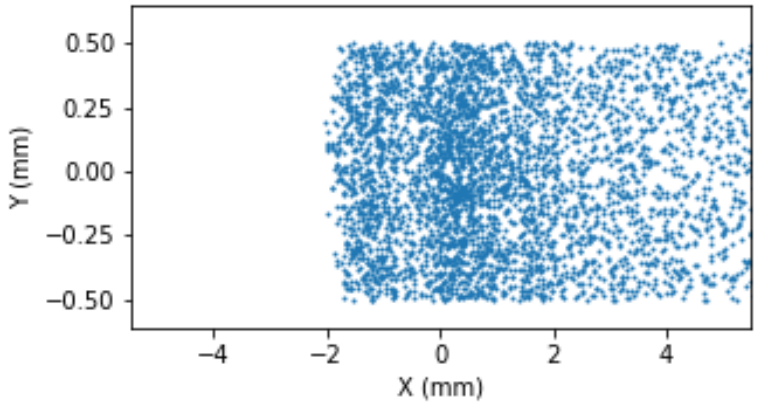
Beam position spectra

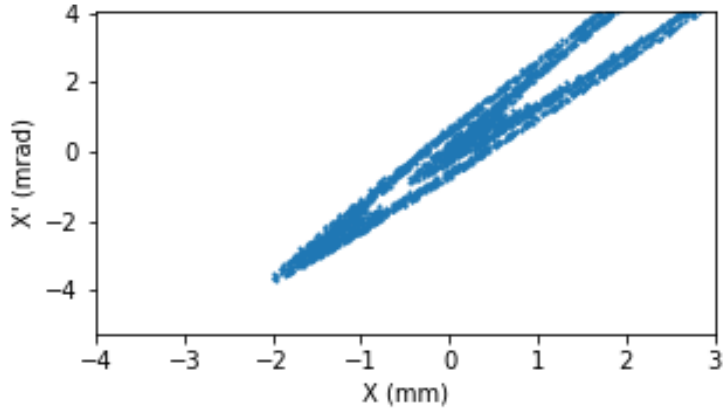
Front view of the beam

Emittance profile (XX')

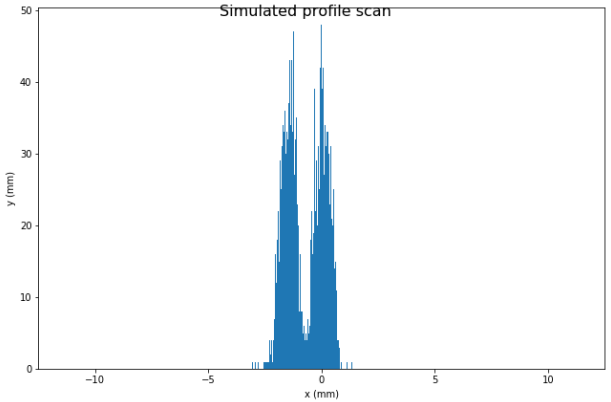
Hexapolar aberration dominant (HRS-like)

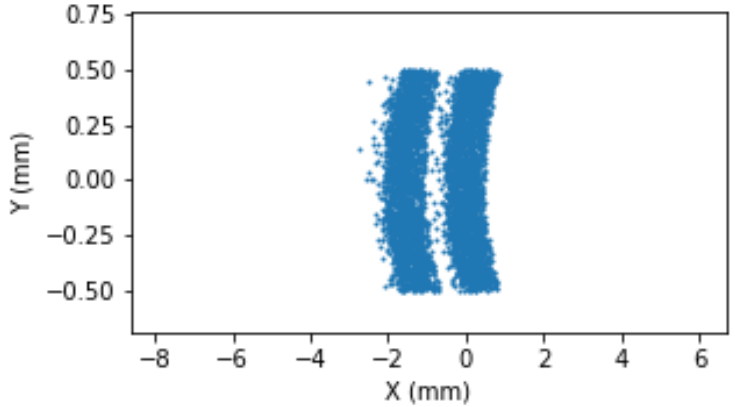


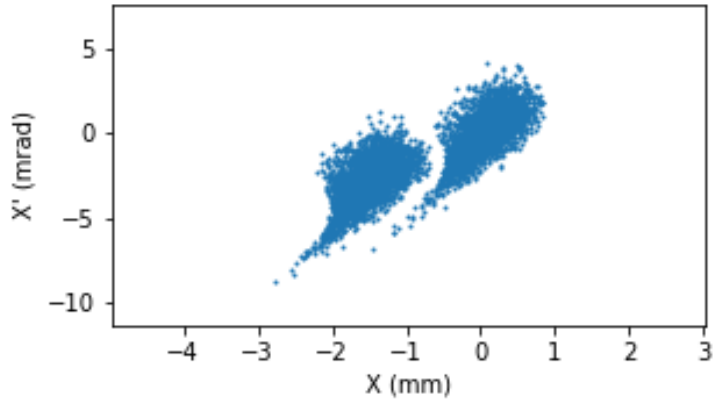




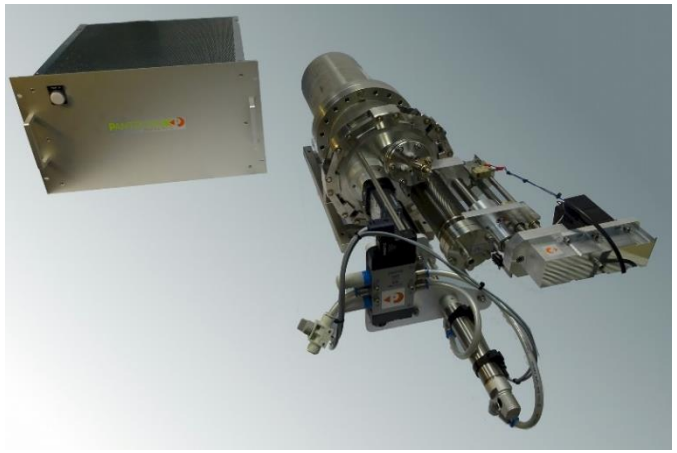
Corrected beam (few aberrations)

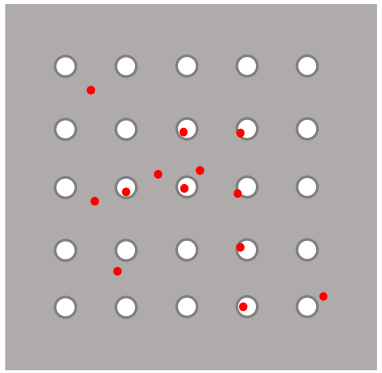




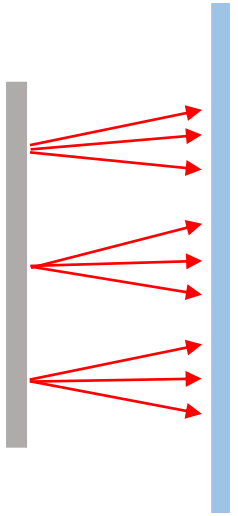


Measurement of aberrations : example of the pepperpot





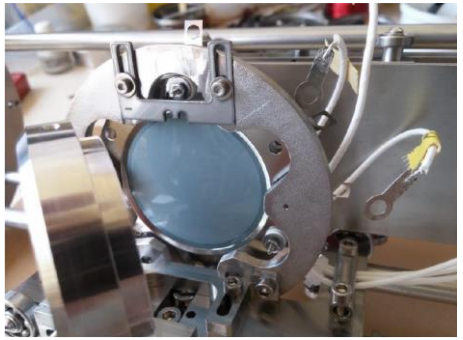
Front view:
tantal mask



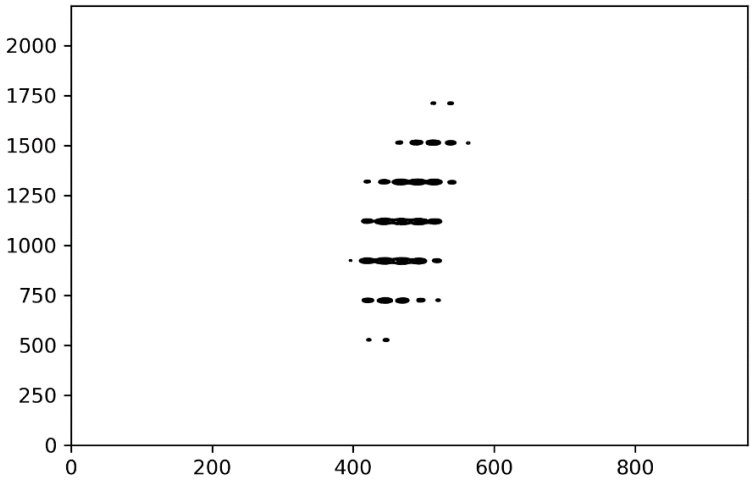
Side view:
MCP + Phosphore screen

Front view:
CCD camera

Pepperpot
Emittance-meter



Reconstruct the emittance



66	65	66	66	68	68	69	67	69	67	67	67	66	65	64	65	64	65
66	66	68	66	66	67	68	71	68	69	69	67	67	67	67	65	65	66
66	67	67	68	70	72	73	72	74	69	67	68	66	66	68	66	66	66
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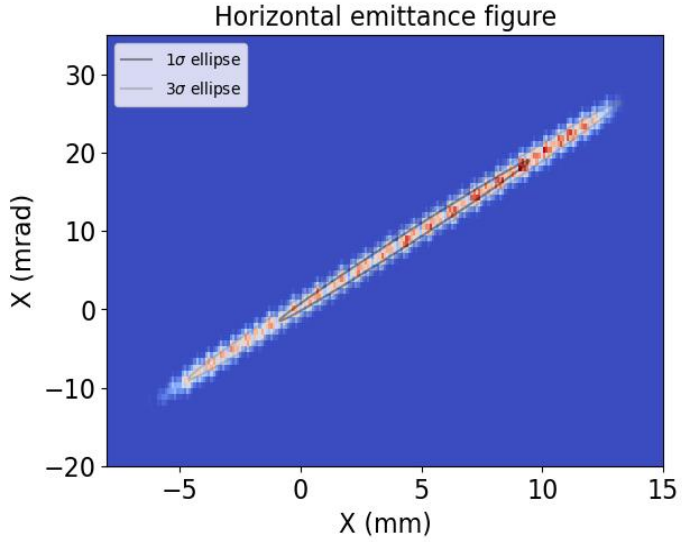
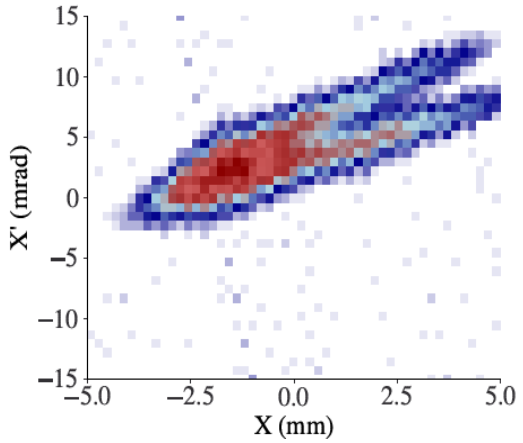
66	65	65	64	66	67	68	67	67	66	66	66	65	64	64	63	65	63
66	64	64	67	63	67	67	66	66	64	67	67	65	66	64	65	64	66

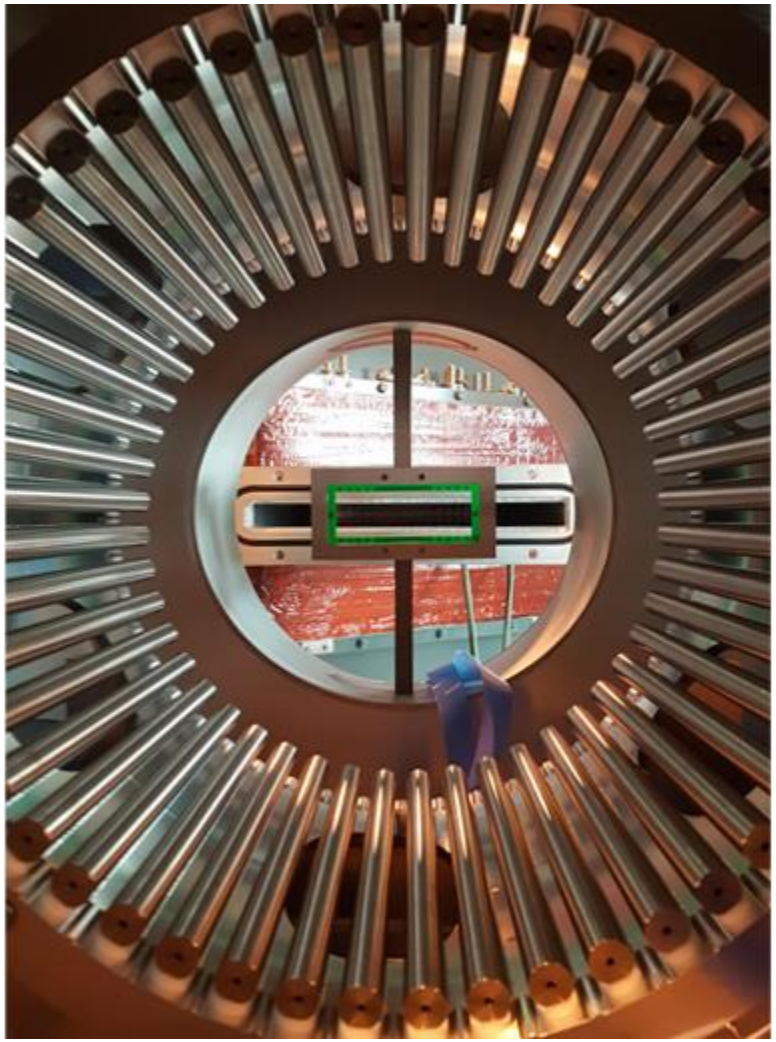


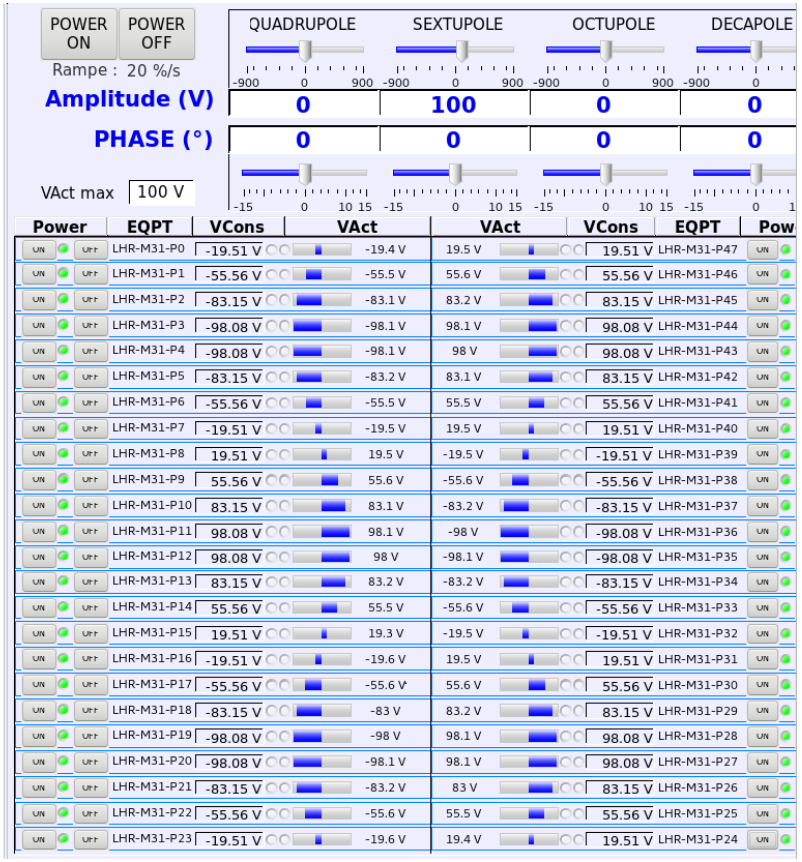
No aberrations



With 2nd order aberrations

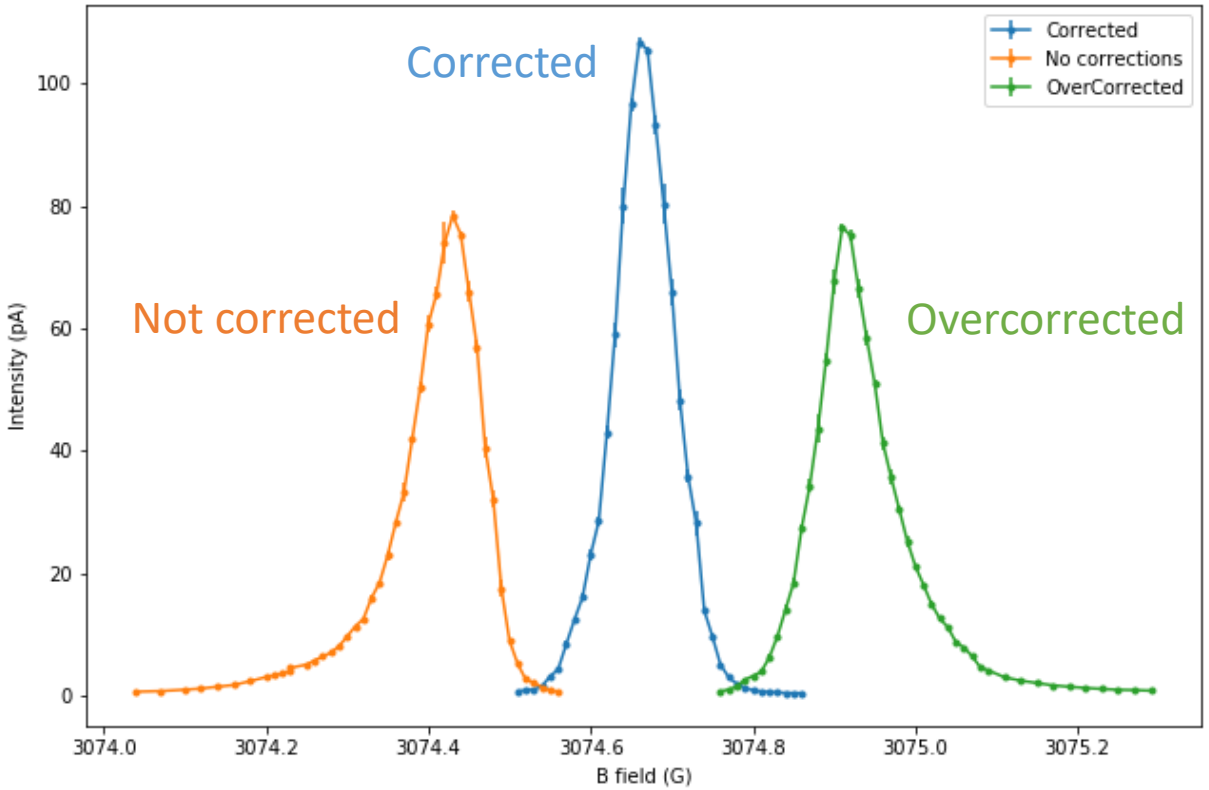
Then correct the aberration with the associated field





$$V(P) = \sum_{n=2}^{n} V_n . \sin\left(n * \frac{2\pi(P+0.5)}{48} + \phi_n \right)$$

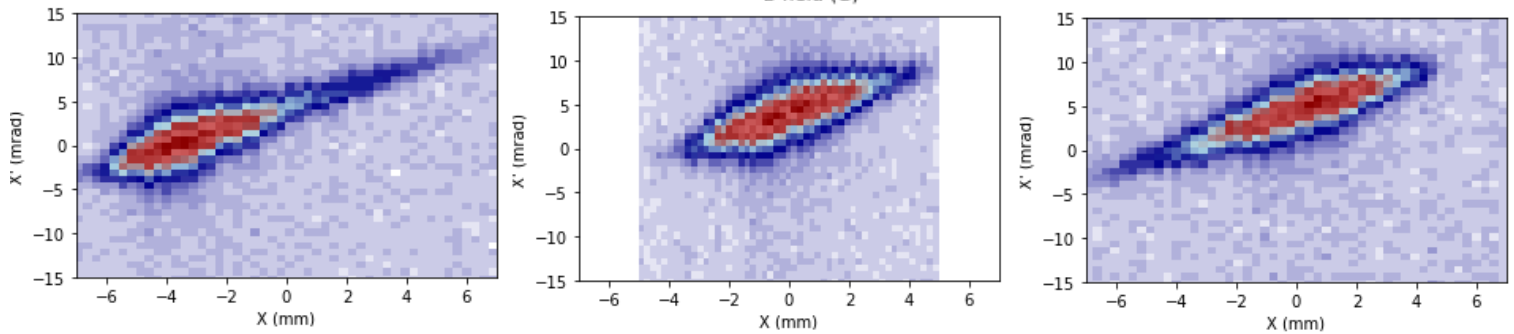
Hexapolar correction (2nd order)



-> Shifted left -0,2G
-> Shifted right +0,2G

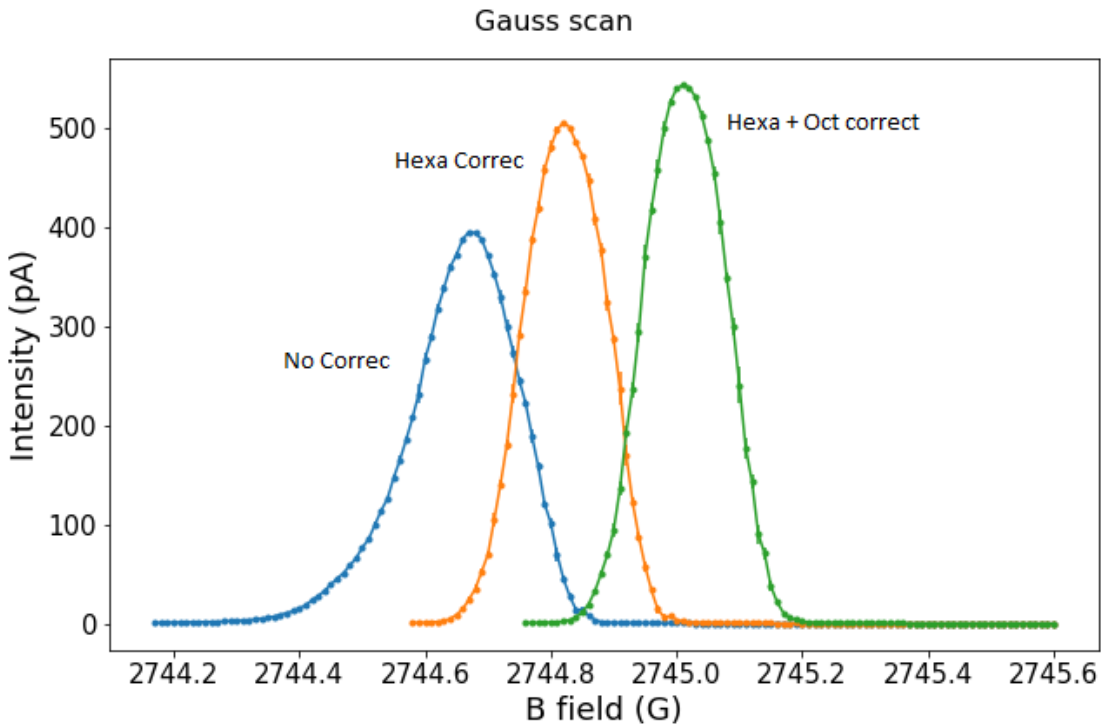
Beam profiles obtained by scanning the beam with the dipoles (more precise than wire profilers)

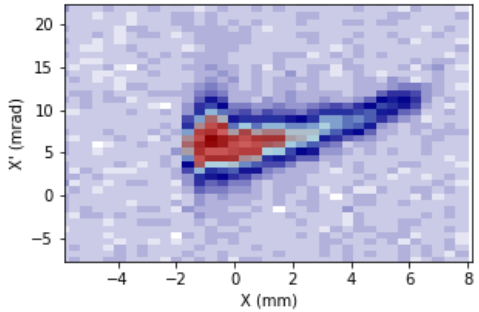
Emittance measurements

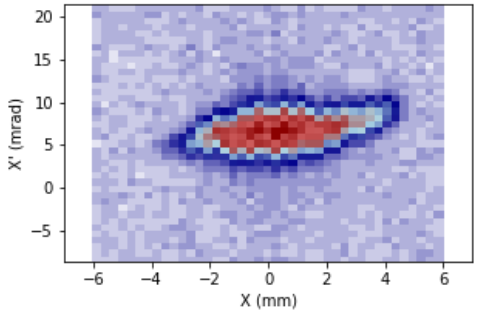


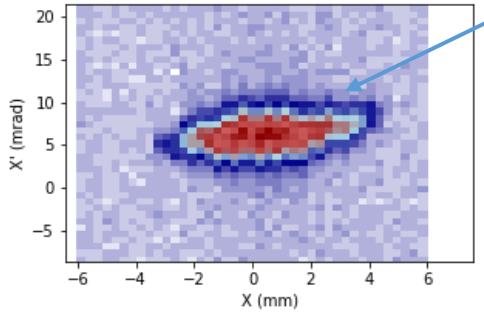
Projection on x axis gives beam profiles

Higher order correction (up to 3rd order)









Hard to see a change, but a computer should

1. Mass separators – overwiew
   - First notions
   - Components of a spectrometer
   - Beam optics and resolution
   - Design of a mass separator
2. High resolution separators (HRS)
   - Scope
   - Optical aberrations and correction
3. **Characterisation and operation**

Experimental methods of measuring the resolution

Method 1 : from beam size measurement

The resolution of a separator can be expressed as :

$$R = \frac{D}{x_0 M + \delta_{abb}}$$

where

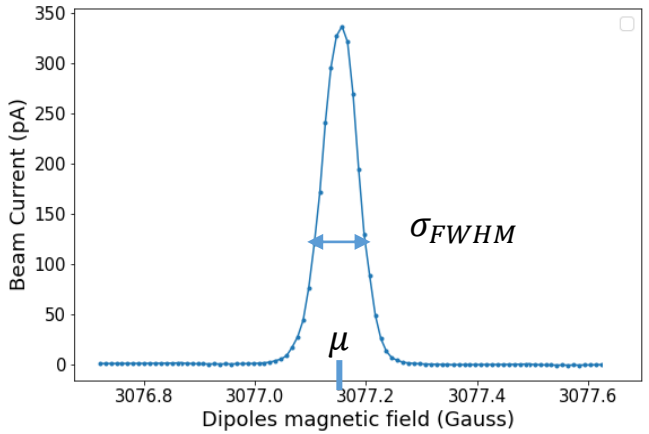
D : dispersion (R16)
x_0: Initial beam size
M: Magnification (R11)
δ_{abb}: Addition of aberrations

hence $\underbrace{(x_0 M + \delta_{abb})}$ is the final beam size

Measured with BPM

Method 2 : from magnetic field measurement

$$R = \frac{1}{2}\frac{\mu}{\sigma_B}$$



$$2\frac{dp}{p} = \frac{dm}{m} + \frac{dE}{E}$$

These are indirect methods as no real beam separation is done

Offline commissioning of a High Resolution mass Separator

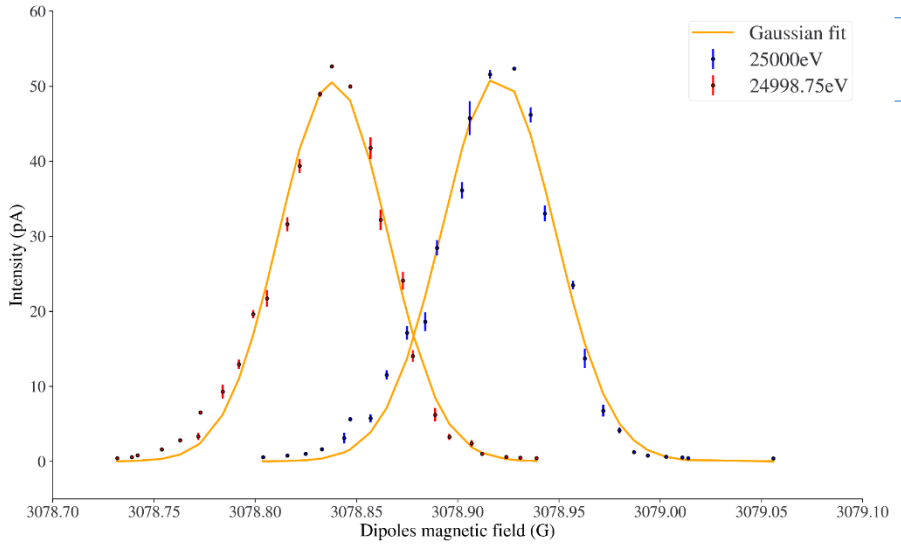
Method 3 : relative measurement with 2 beams

Offline sources are generally monoisotopic ion sources: no direct mass measurement/separation possible

But (remember): $$B\,\rho = \frac{p}{q} = \frac{\sqrt{2\,\boldsymbol{m}\,\boldsymbol{E}}}{q}$$

It can also be observed in the separator transfer matrices where: {x , $\frac{\Delta M}{M}$} = {x , $\frac{\Delta E}{E}$} = R16 cm/%

Resolution can be measured by measuring position/size of two beams with close energies



$$\frac{\Delta E}{E} = \frac{1}{20000}$$

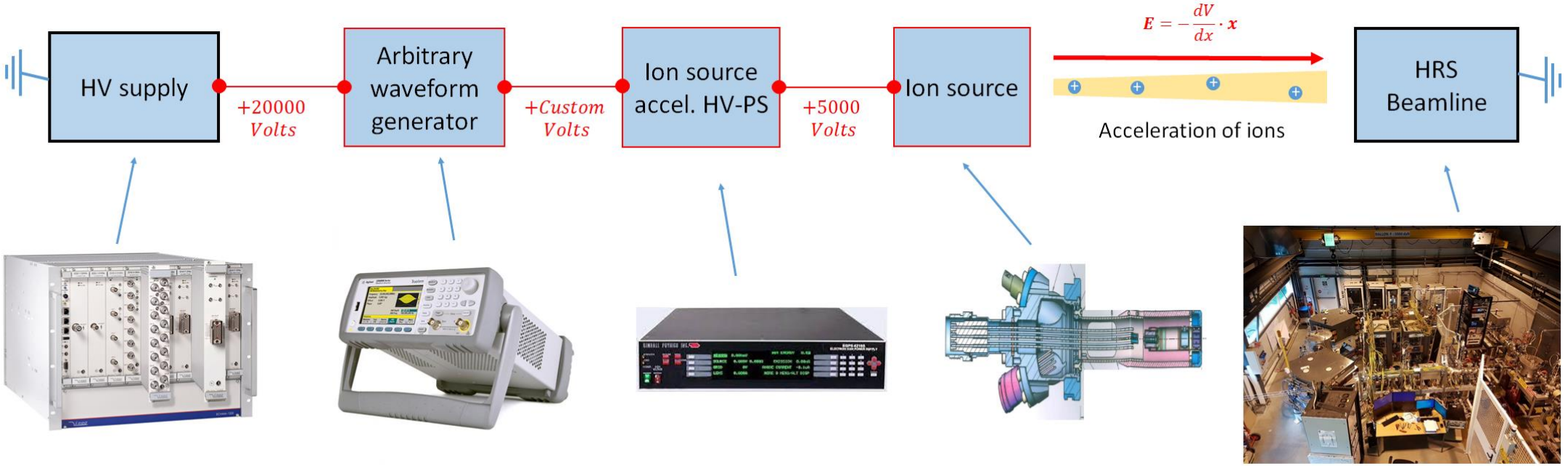
This HRS can separate two identical beams with $\frac{\Delta E}{E_0} = 1/23400$ *at their FWHM or* $\frac{\Delta E}{E_0} = 1/13500$ *at 10% valley*

(Hexapolar and octupolar corrections applied)

Not a direct measurement (needs two independant measurements)

Bonus : Populate multiple energies of a beam for tests

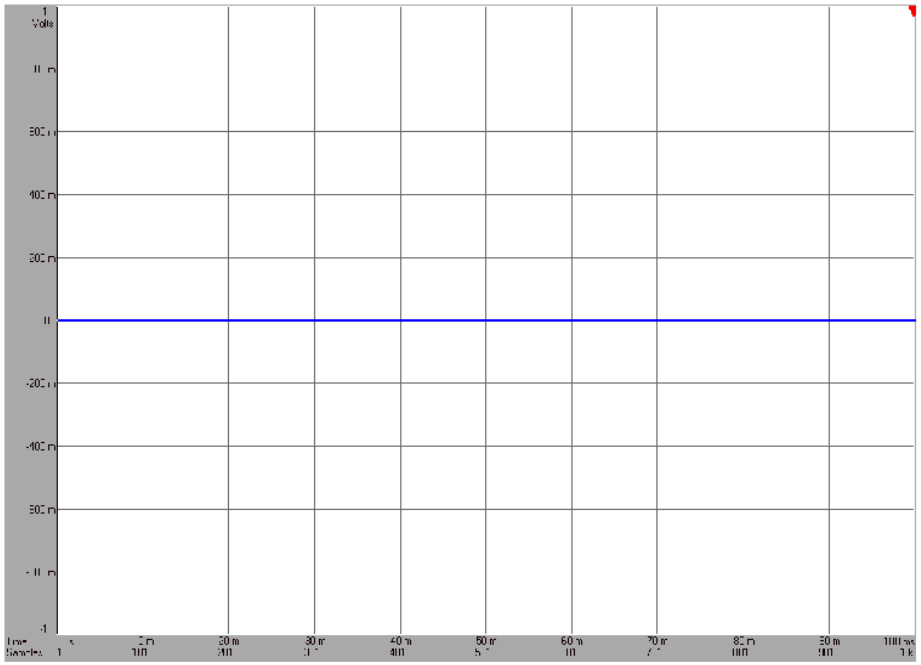
- Acceleration of ions depends on the potential between the source and the beamline
- High voltage supplies can't handle fast and small voltage variations (less than 1V on many kV)
- A pulse generator can supply such variations



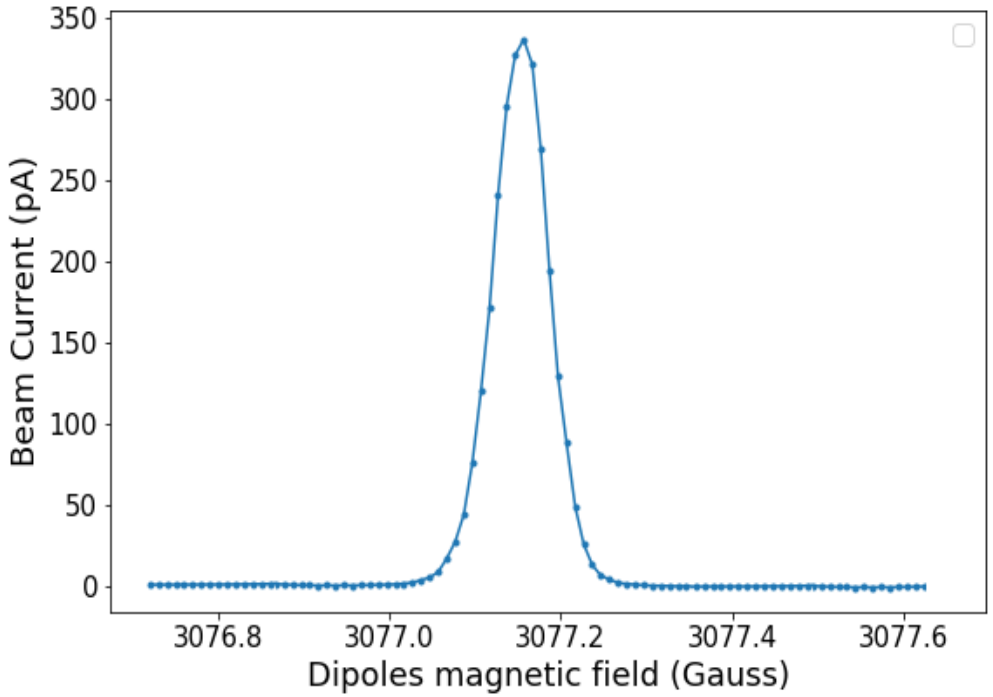
$$Energy_{total} = 25000eV + custom\ distribution\ (\pm 5eV)$$

Signal generator : baseline

No signal (DC 0V signal)



Beam is a gaussian

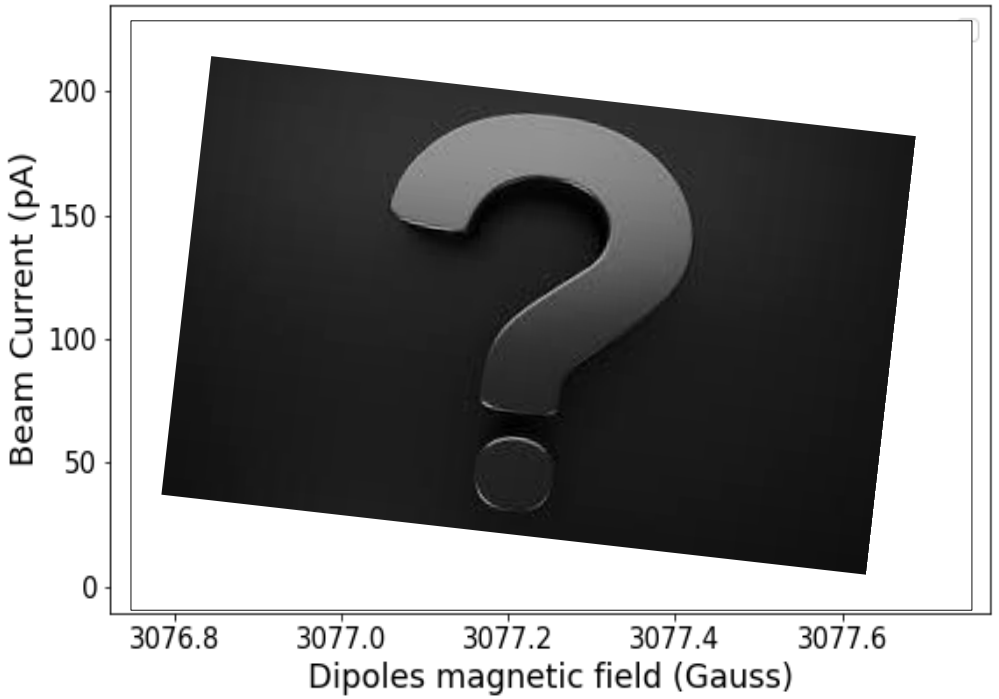


Beam already corrected from aberrations

Signal generator : Guess who (triangle signal)

No signal (DC 0V signal)

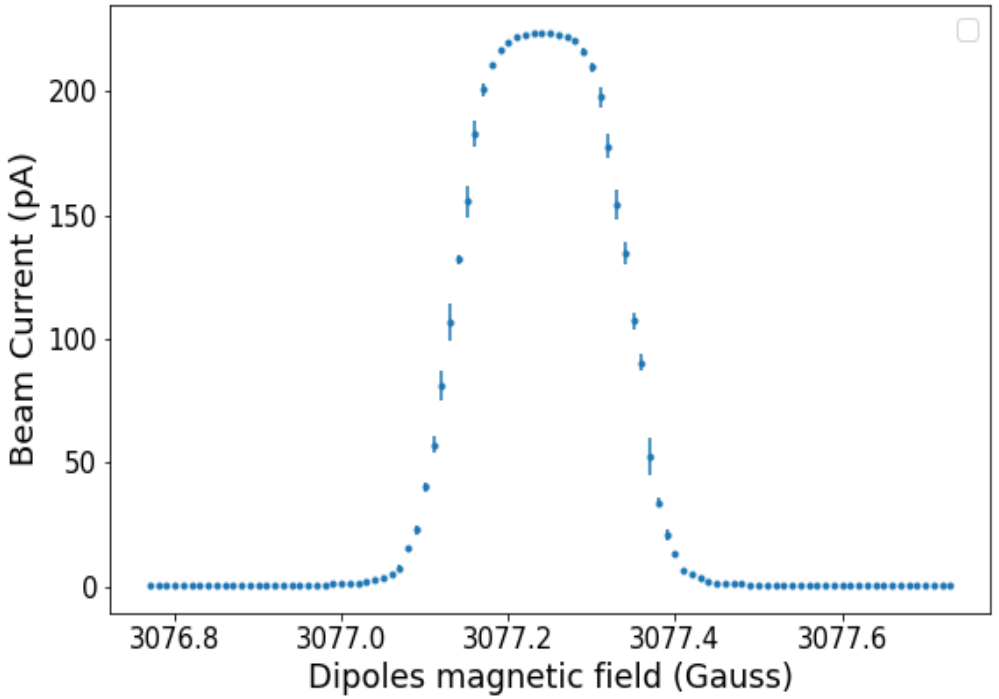
Beam is ??



Signal generator : Guess who (baseline)

No signal (DC 0V signal)

Gaussian beam with « plateau »



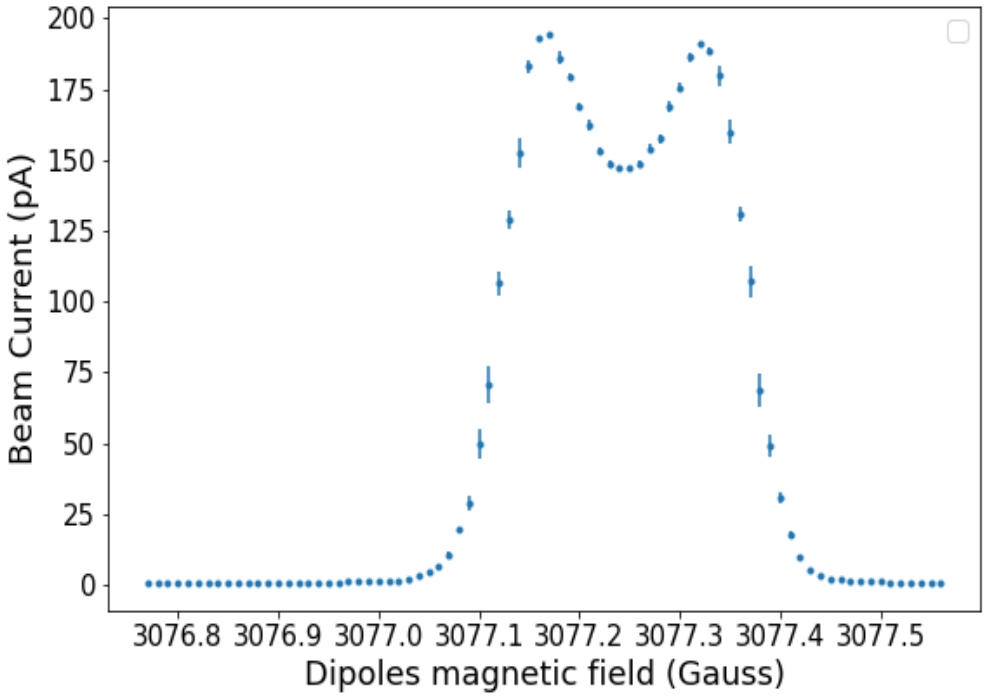
Can be used to create uniform plateau-beams of single species/radioisotopes

-> Uniform irradiation with extremely low energy spread (here 3eV/30keV = 1/10000)

Signal generator : Guess who reversed

??? signal

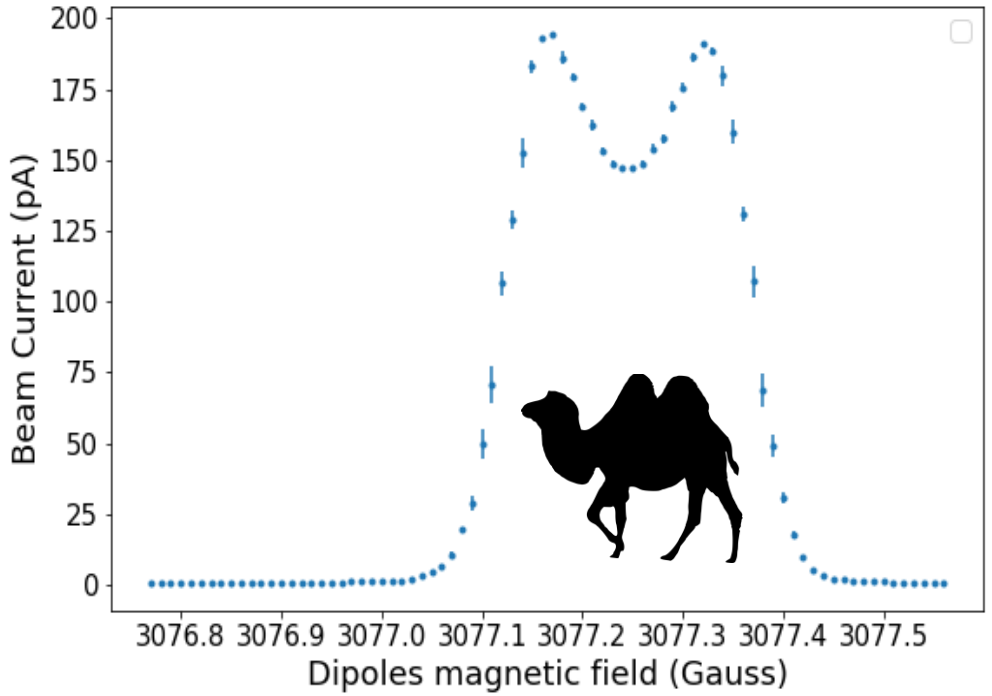
Double-peaked beam



Signal generator : Guess who reversed

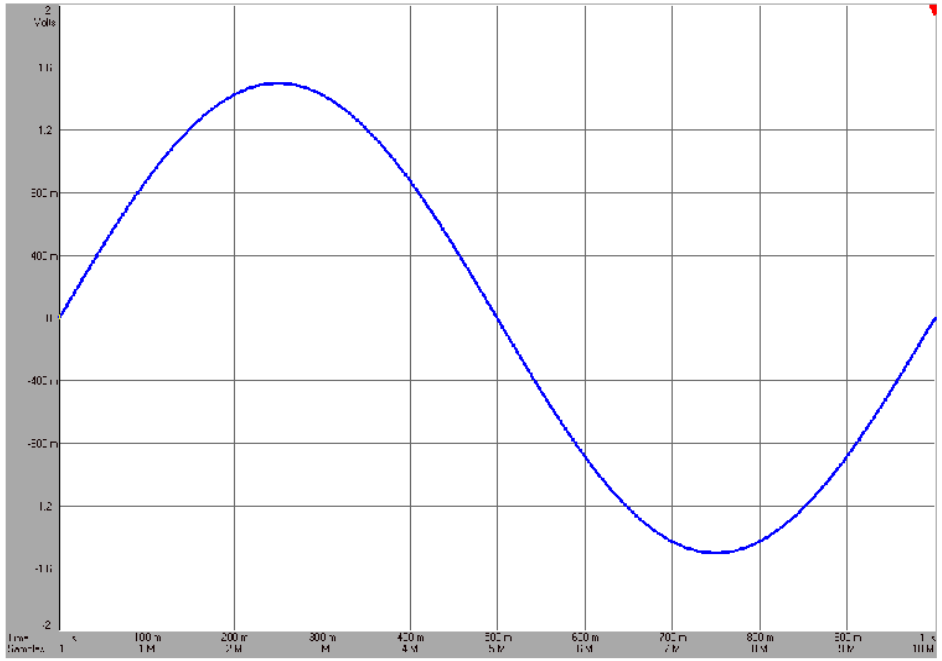
??? signal

Double-peaked beam

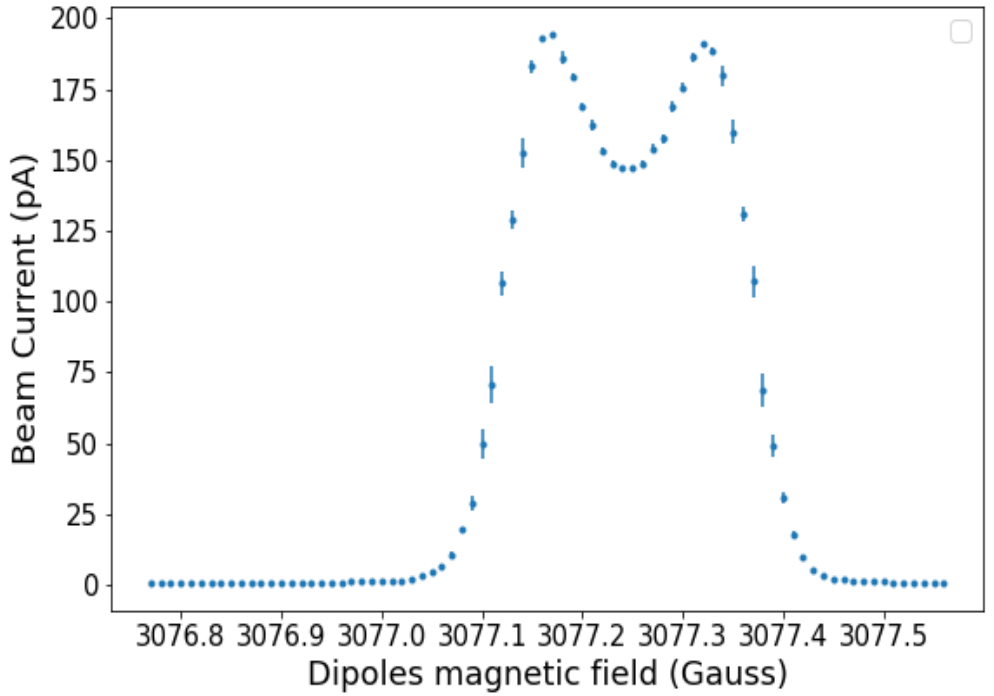


Signal generator : Guess who reversed

Sinusoïdal signal or noise



Double-peaked beam

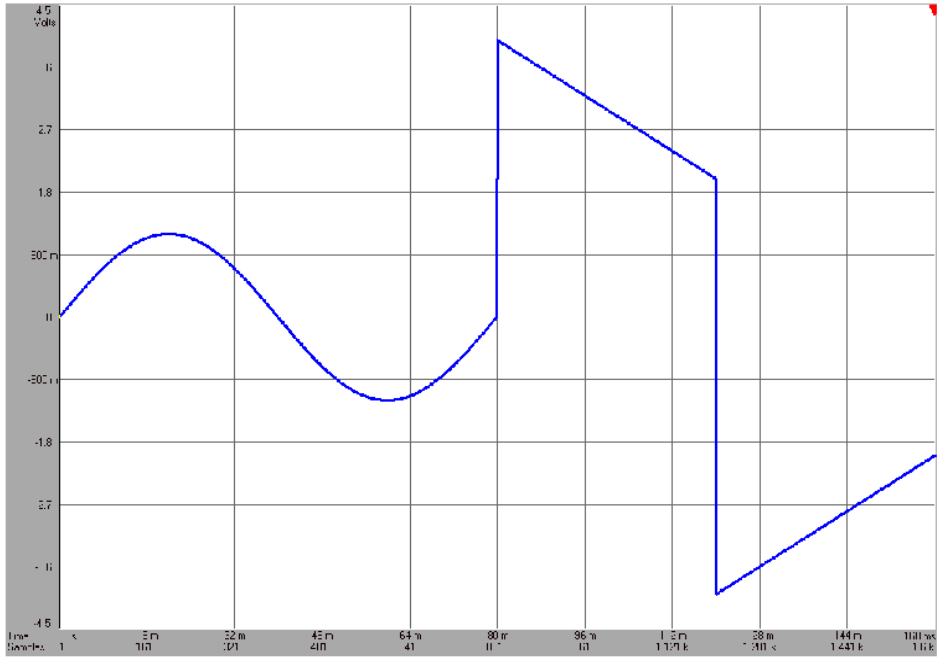


Can be a sign of jitter (noise) on HV acceleration platform or other system !

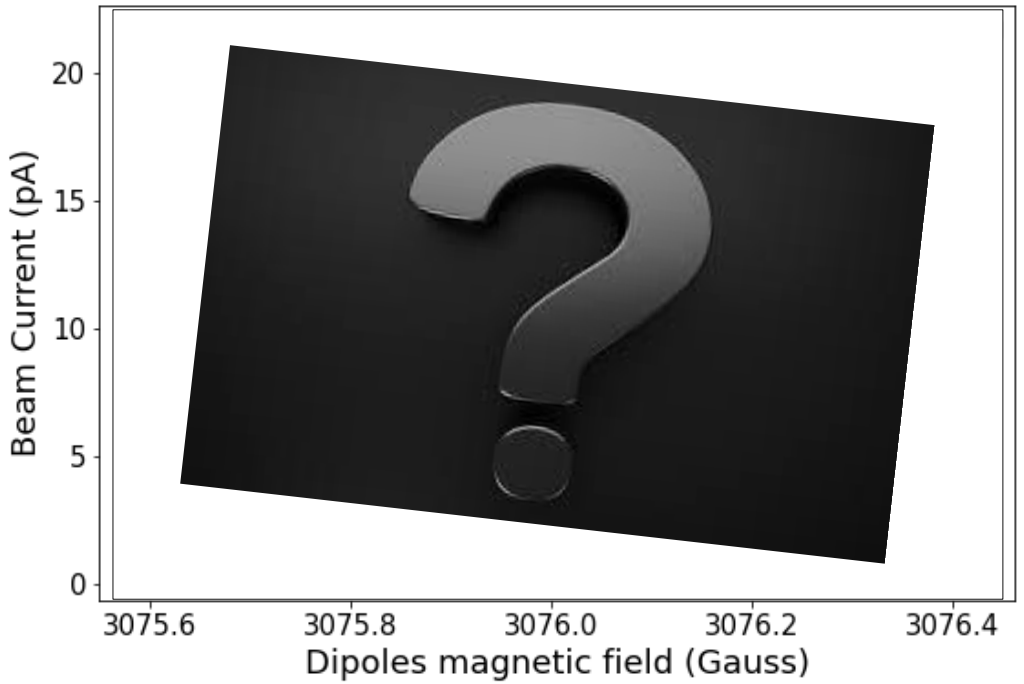
The spectrometer behaves as a really precise (and expensive) voltmeter !!

Signal generator : Guess who (unknown signal)

Mysterious signal

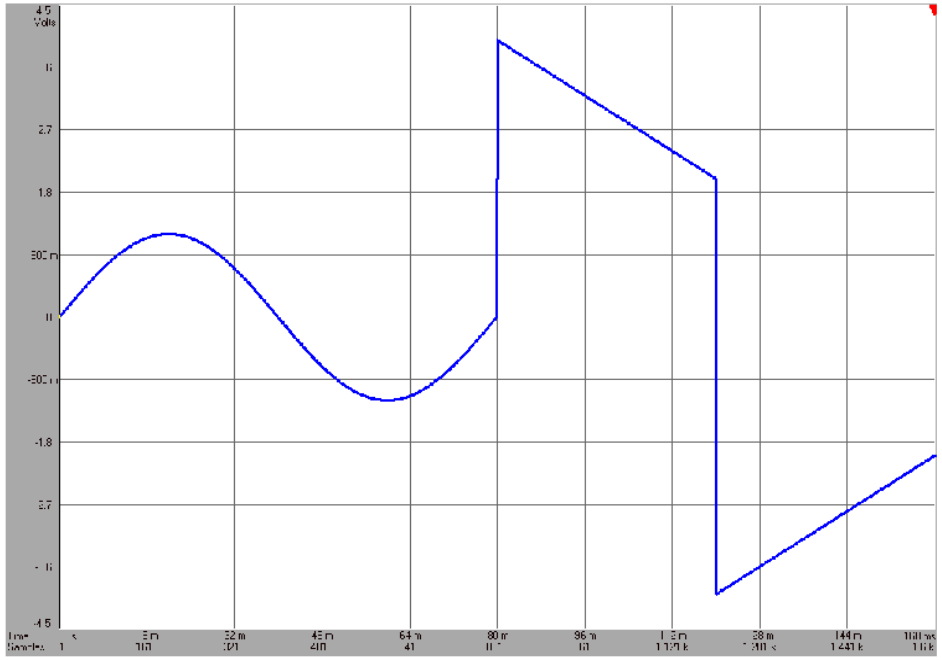


Unknown beam

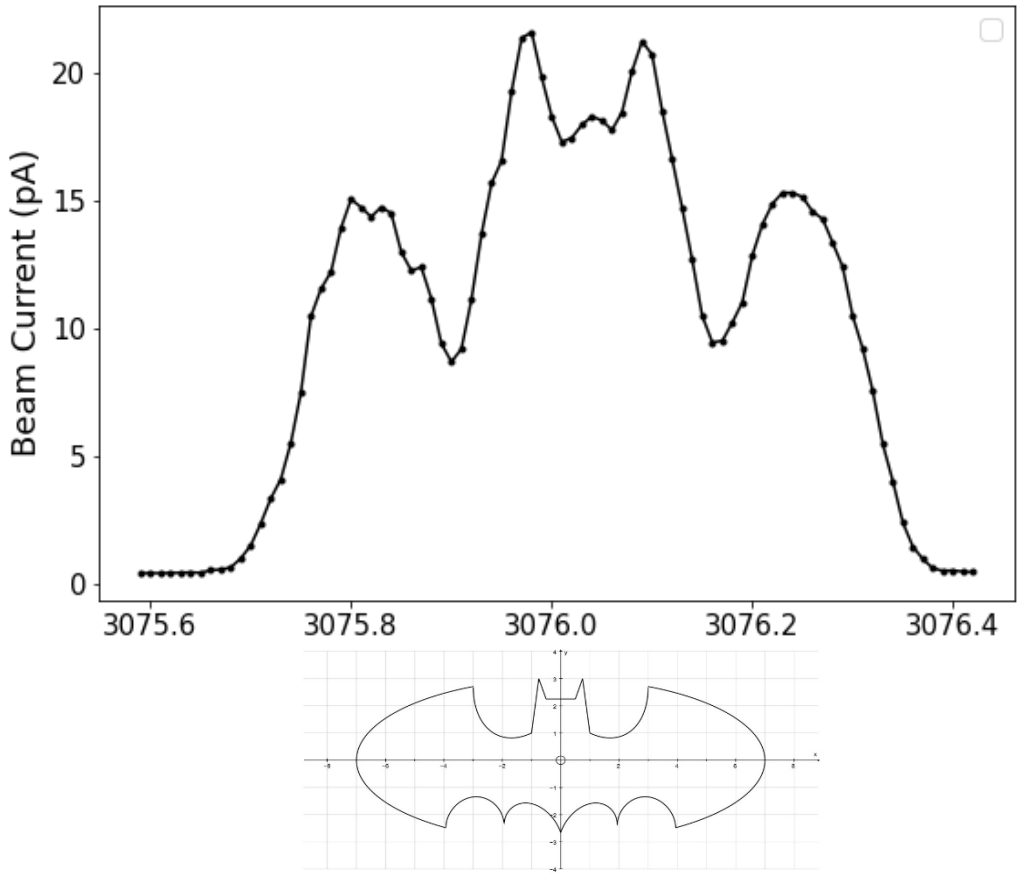


Signal generator : Guess who (unknown signal)

Mysterious signal



The bat-beam

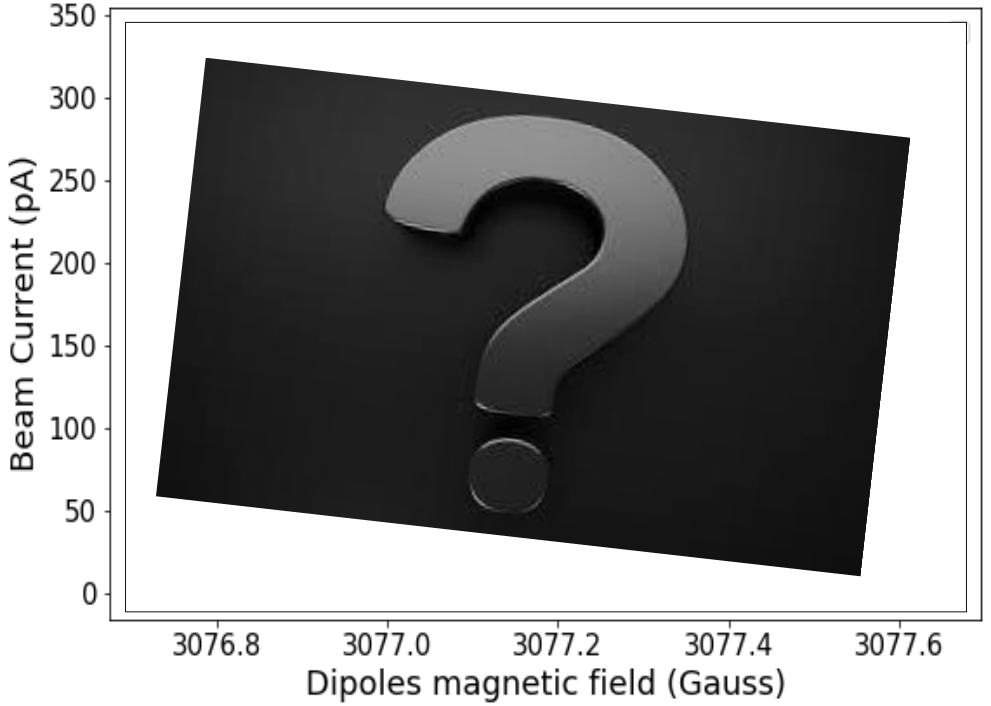


Signal generator : Guess who (square signal)

Square signal

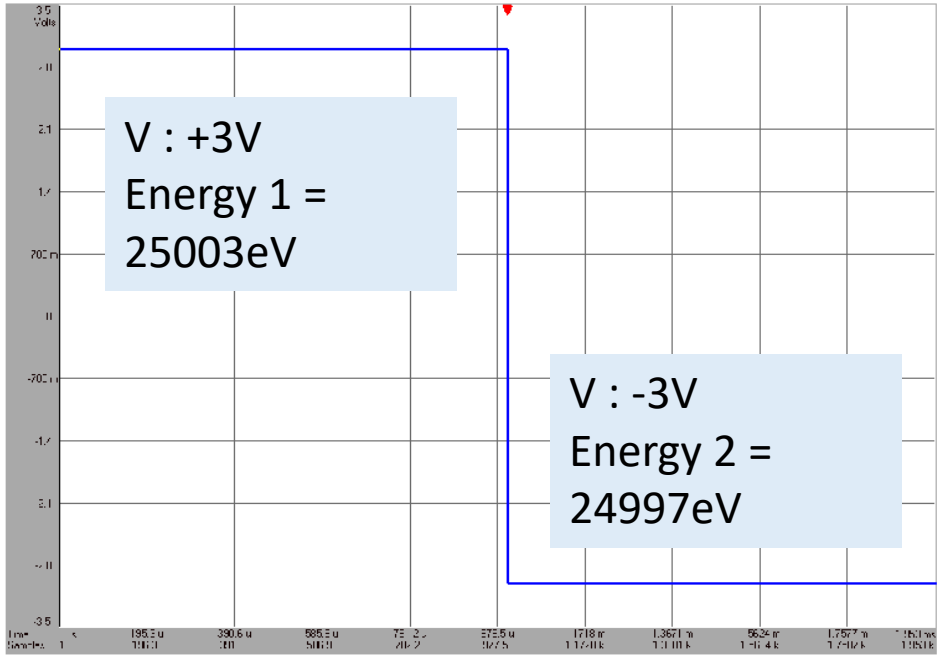
Populates ONLY two energies

??? beam



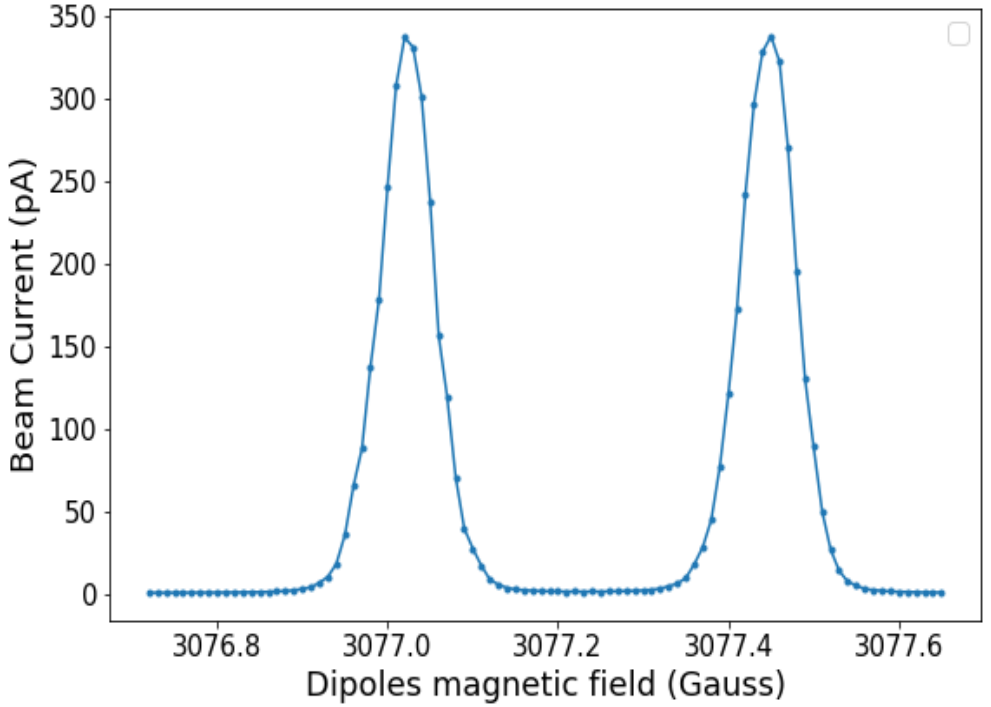
Signal generator : Guess who (square signal)

Square signal



Populates ONLY two energies

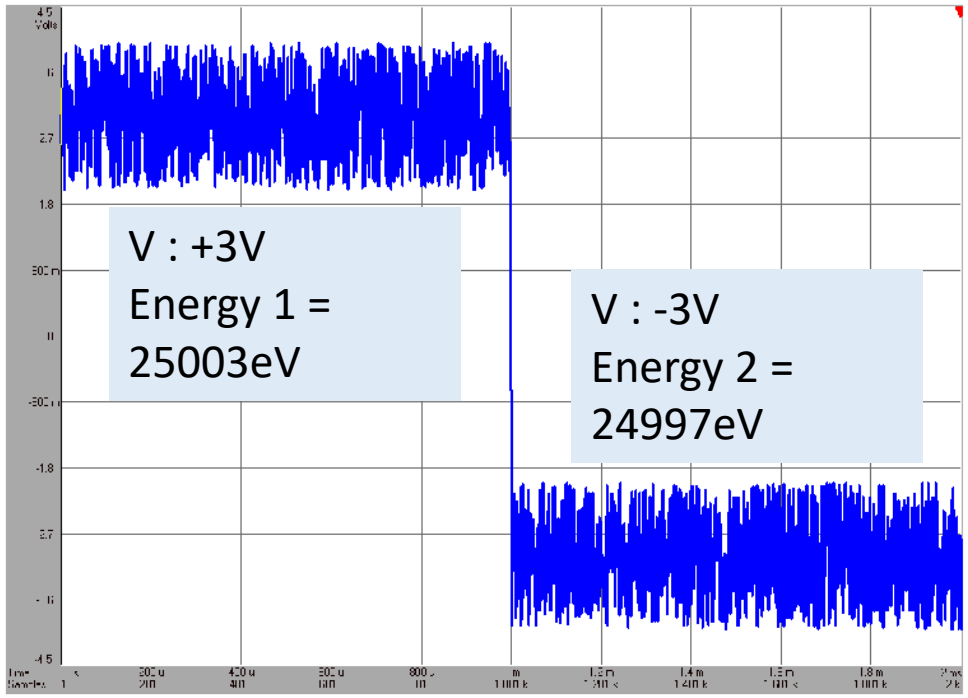
Duplicates the beam into 2 close energies beams

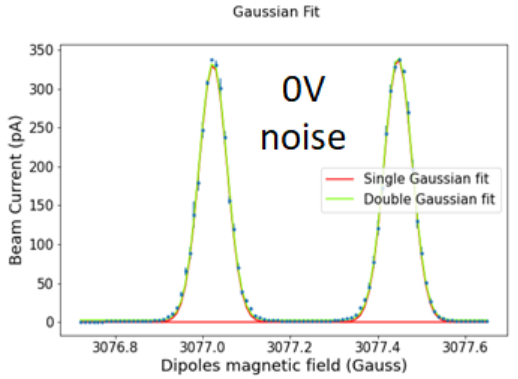


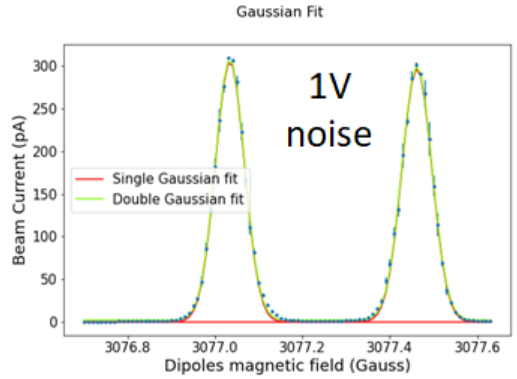
Energy separation can be arbitrary set

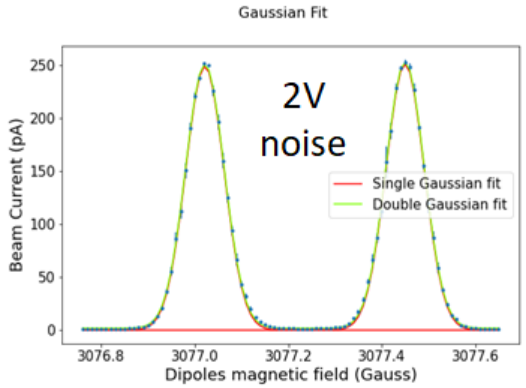
Square signal with noise

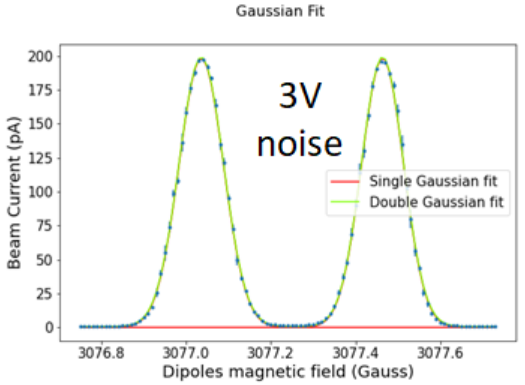
A square signal populates two and only two energies.
Adding noise to the signal increases the energy dispersion of the beam.





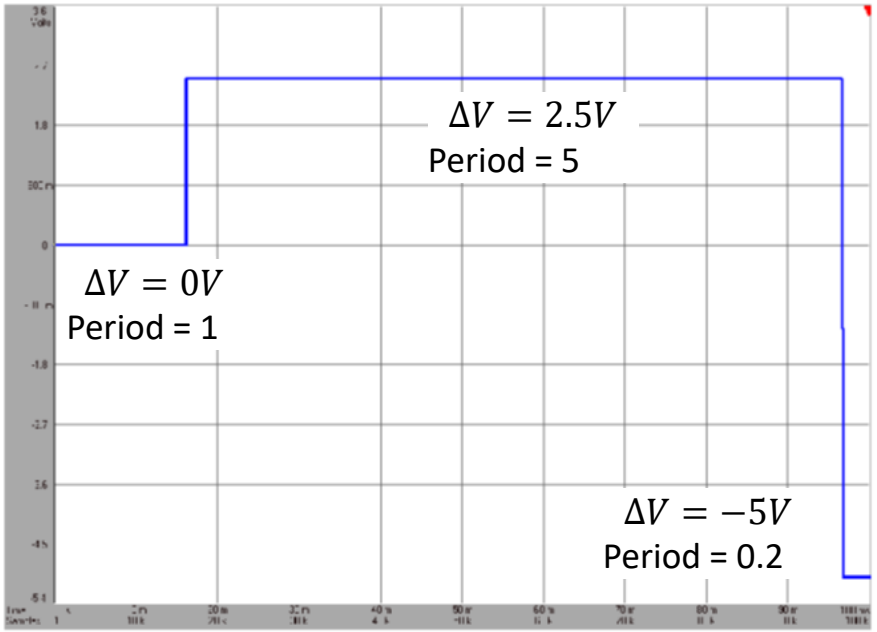




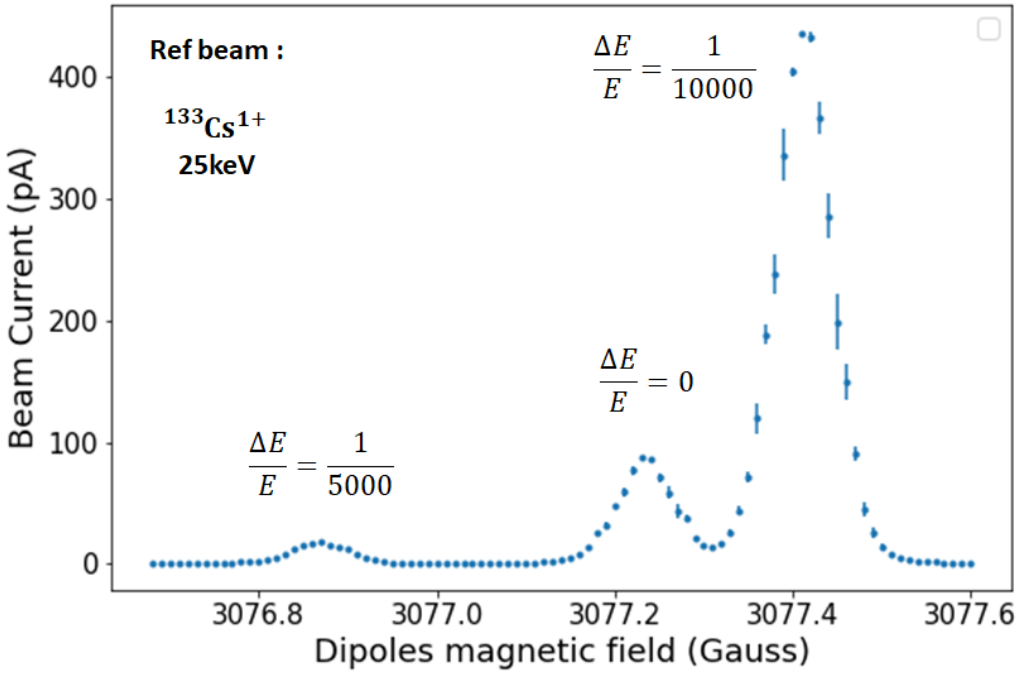


To go further…

A signal with multiple steps with adjustable amplitude and length can create (almost real) beam contaminants



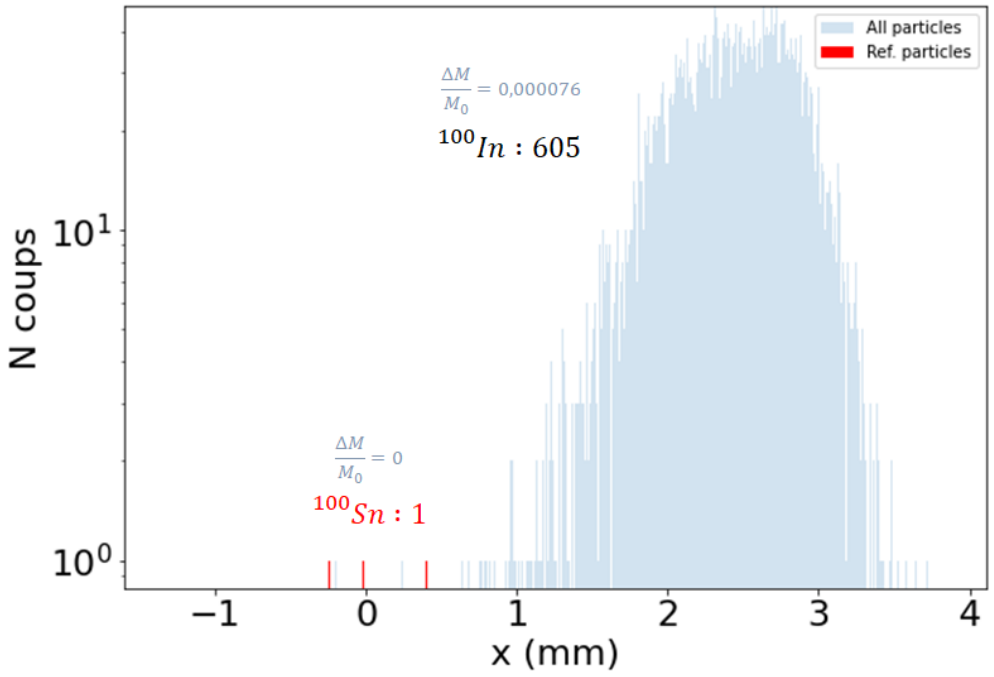
Create custom beam contaminants



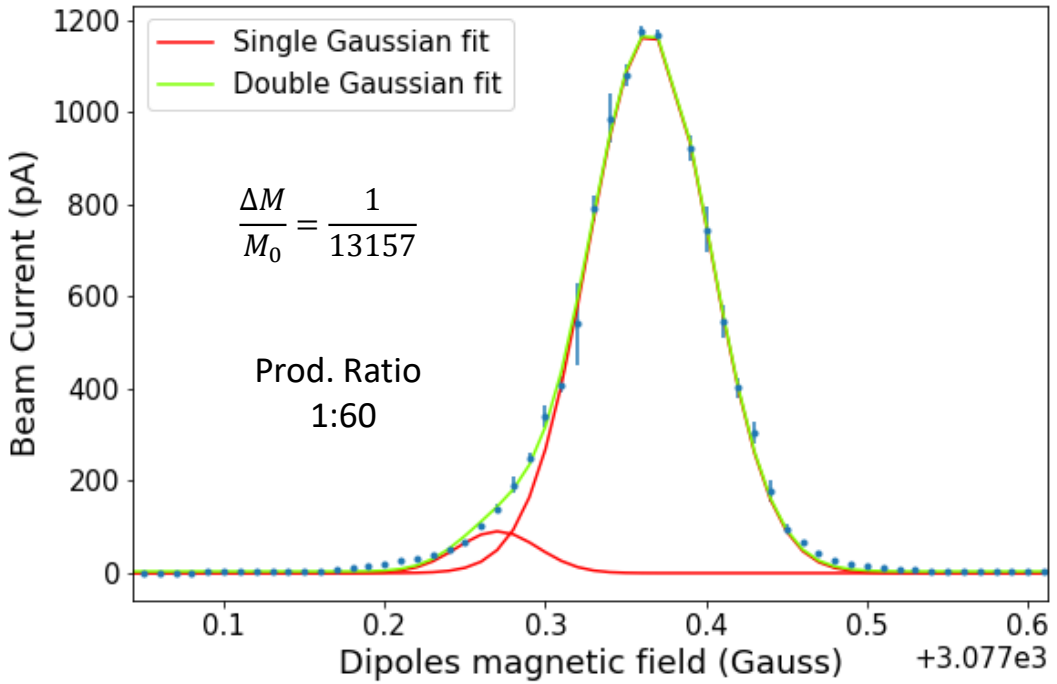
<u>The HRS can be commissioned in almost real operating conditions, with no radioactive beam and (relatively) high intensities</u>

A concrete example : separation of 100Sn and 100In

Simulation (COSY infinity)



Experimental separation



Highly produced contaminants with close masses are still difficult to separate, in this case :

- The major quantity of the contaminant can be separated.
- Beam can be almost totally purified by sacrifying a part of the beam of interest.
- Send the beam to a higher-level purification device (traps).

1. Mass separators – overwiew
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2. High resolution separators (HRS)
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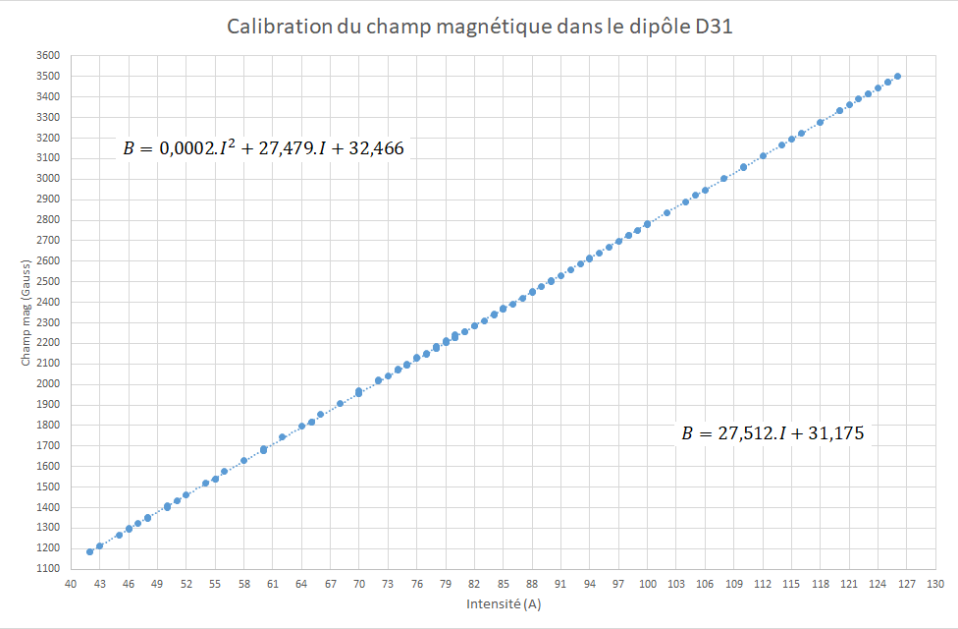
   - Optical aberrations and correction
3. **Characterisation and operation**
   - **Some operation issues**

Operating a spectrometer - Dipoles

Tuning a dipole :

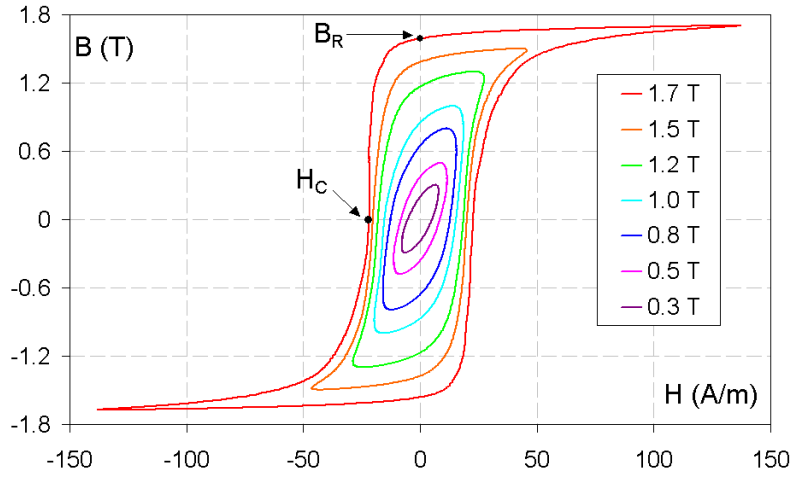


$$B = \frac{N \cdot \mu_0}{Gap} I = Cste \cdot I$$

Dipoles are controlled through current
Sometimes, CC asks for $B\rho$ directly

Hysteresis and cycling :

Hysteresis curve
$|B_{max}|$ level depend to μ_r



An external B-field, created by a current I, creates a B-field in iron by aligning tiny internal dipoles (electron spins) in the material.
However, if the current and external field are dropped to zero, the material remains partially magnetized. This gives rise to “hysteresis”.
➔ need for magnet cycling.

Operating a spectrometer - Find the right nuclei

I) If the nuclei of interest is highly produced ie :

- Its intensity is easily measurable by diagnostics (profilers and CF)
- Not so many (close) contaminants

➔ Easy case : compute nuclei's $B\rho$, then scan dipole current around this value.

II) If the nuclei of interest is **NOT** highly produced ie :

- Its intensity is too low to be measured by diagnostics
- It is « drowned » in contaminants

➔ Need scaling: tune the separator on a known close mass, then scale the field accordingly.

Conclusion

Summary about spectrometers :

$$B\rho = \frac{p}{q}$$

Thank you for listening !

References :

[1] Bertrand Jacquot, Introduction aux spectromètres et séparateurs en physique nucléaire
https://heberge.lp2ib.in2p3.fr/heberge/EcoleJoliotCurie/coursannee/cours/coursBertrandJacquot.pdf
[2] Ulli Köster, Electromagnetic separators, Institut Laue Langevin, Grenoble, France
[3] P. Chauveau, SPIRAL1 beams for DESIR status and development, DESIR Workshop, 2024
[4] J. Michaud et al., Commissioning of the DESIR high-resolution mass separator, NIM B
https://doi.org/10.1016/j.nimb.2023.05.013.

3.1 Experimental difficulties (low efficiency, charge state pollution)

Reactions around the Coulomb barrier induce phenomena of great diversity (nucleon transfer, elastic scattering, fusion-evaporation, inelastic scattering, fission,…).
The reaction kinematics are so different that the technical methods to optimize the efficiency, the selectivity and the identification are, as well, different. It therefore leads to a wide variety of separators and spectrometers.
Understanding these spectrometers rely mainly on the understanding of the experimental difficulties encountered in each type of reaction.

Problem A: Large emission angle of reaction products and low transmission

The solid angle in fission or multi-nucleon transfer reactions, i.e. the cone emission of reaction products, can be very large (1 steradian), while separators often have a small acceptance, around 10 mstrd, and their efficiency is often very limited (low transmission).However, in these reactions, the emission at a large solid angle of products of interest leaves the possibility of rotating the spectrometer around the target reaction in order to avoid beam scattered particles. This technique can often improve the selectivity of the spectrometer.

Problem B: Charge state distribution

At high energy (500 MeV/A) any ion leaving the target is fully stripped and the charge state corresponds to the atomic number (Q=Z). At lower energy, typically a few MeV/A, the primary beam and reaction products are not fully stripped. The distribution of the number of remaining electrons is generally large, since atomic collisions in a target generate numerous electron capture and stripping reactions.

For example, a nucleus with mass ~ 100, formed by fusion-evaporation, usually has 4 or 5 states charges for an average charge state <q0> ~25+. Furthermore, the velocity dispersion is of the order of several %.

Generally the charge states distribution created in a target and transported in a conventional magnetic separator generates two difficulties:

- All the different charge states of the interesting nuclei are not transported to the focal plane (Bρ acceptance). This results in a reduction of the spectrometer transmission:

$$\frac{\Delta B\rho}{B\rho} = \frac{\Delta q}{< q_0 >} + \frac{\Delta v}{< v_0 >} \quad >> 10\% \; > \; B\rho \text{ acceptance}$$

- The primary beam emerges from the target with so many charge states (with different Bρ), that the focal plane is polluted over a large range in Bρ, which often prevents to measure very rare events.

Problem C: Contaminants (beam charge states and other kinds)

The nuclei of interest are often polluted by particles whose intensity is often too large to be accepted by the detection system.

These particles to be eliminated (bad events) are of several types:
- Charge states of the primary ion beam (slowed down in the target by multiple interactions with the target atoms).
- Beam particles, elastically scattered by the Coulomb potential of target nuclei.
- Target ions, elastically scattered by the beam particles (recoil of target nuclei).
- Particles produced by nuclear reactions with a large cross section (fission, fusion, nucleon transfer, …).

Importance of an RFQ CB / gaz cell