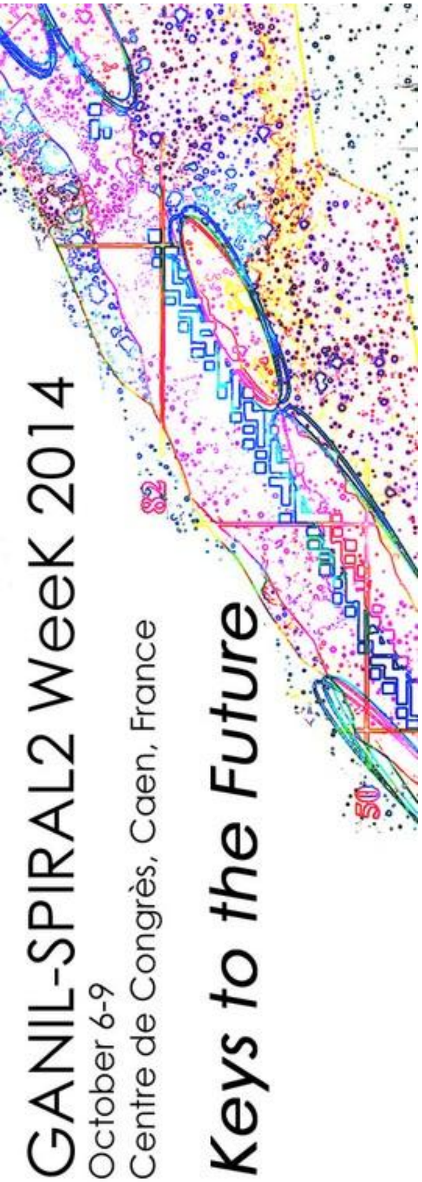


Purification techniques for low energy Radioactive Ion Beams at SPIRAL2

Stéphane Grévy
CENBG
grevy@in2p3.fr

Many thanks to :
Pierre Chauveau
Pierre Delahaye
Teresa Kurtukian-Nieto
Laurent Serani
Pauline Ascher
Enrique Minaya
and the PIPERADE team

Outlook

1- Purification techniques for low energy RIB's @ GANIL/SPIRAL2

- a- Magnetic spectrometer
- b- Multi-reflections time-of-flight spectrometer (MR-TOF-MS)
- c- Penning trap

2- Performances and Status of development of such devices @ GANIL/SPIRAL2

- a- HRS@DESIR
- b- PILGRIM @ S3-LEB
- c- PIPERADE@DESIR

3- Comparative performances / Complementarities

HRS : **H**igh **R**esolution **S**pectrometer
PILGRIM : **P**iège à **I**on **L**inéaire du **G**anil pour la **R**ésolution des **I**sobares et leur mesure de **M**asse
PIPERADE: **PI**ège de **PE**nning pour les ions **RA**dioactifs à **DE**sir

1- Purification techniques for low energy RIB's

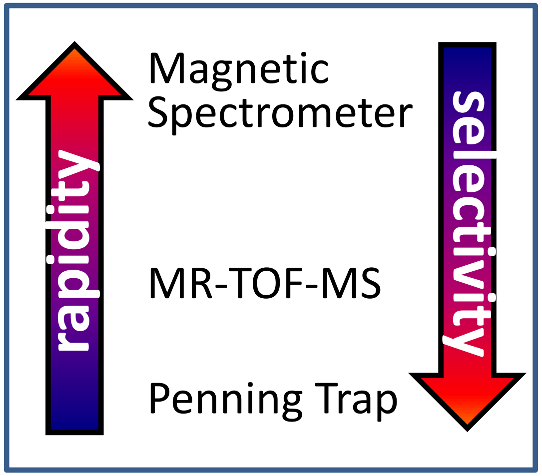
Introduction

- The production methods of radioactive beams are non selective

  → powerful selection methods are mandatory

- The important criteria are :

  - the selectivity — the capability to separate the ions of interest from contaminants
  - the efficiency — keep the maximum of the ions of interest
  - the rapidity — the time needed to separate the ions of interest from contaminants



- Main beam characteristics :

all nuclei are extracted from the source

- with the same charged state (usually 1+)
- with the same low energy (few to 60 keV)

  → no "universal" Z selection (depends of the source, use of lasers…)

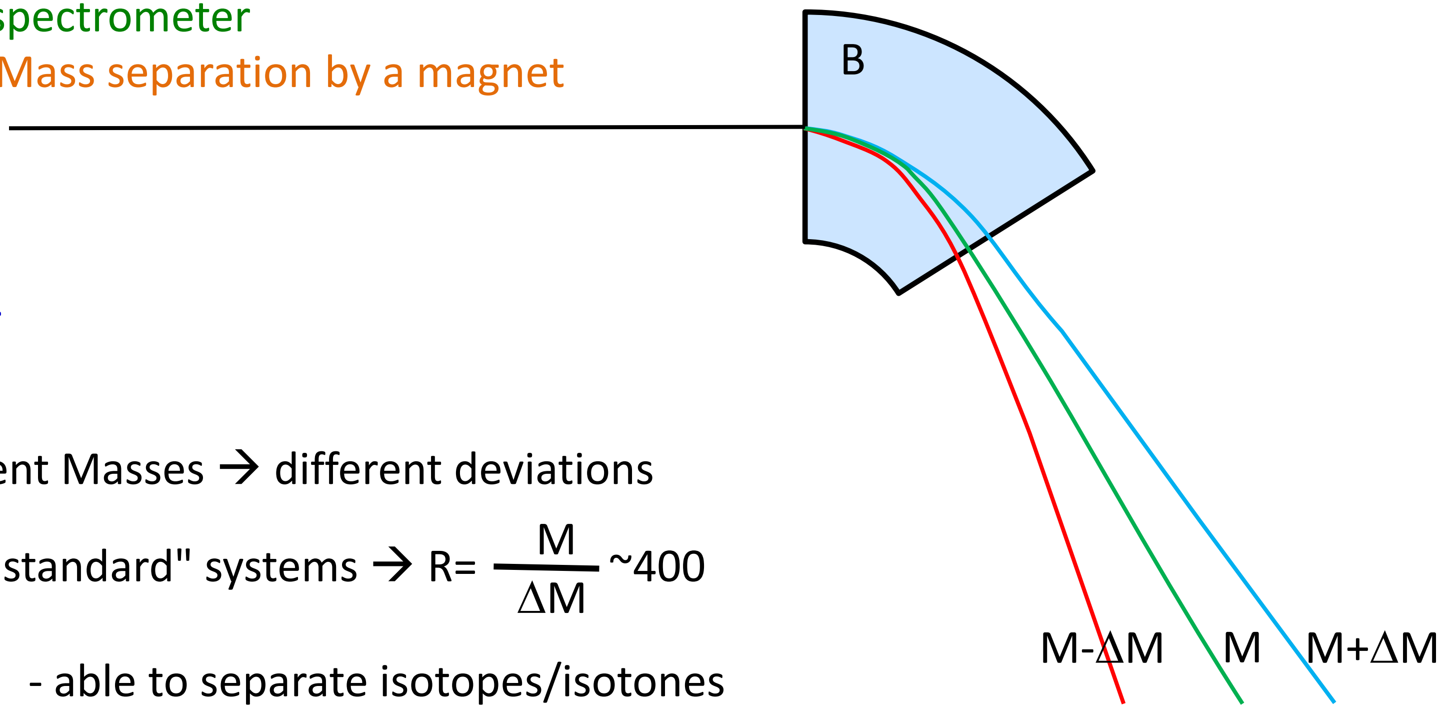
  → need for an isobaric selection through mass/velocity

- with "poor" optic qualities (emittance of few 10's of π.mm.mrad)

1- Purification techniques for low energy RIB's

a- Magnetic spectrometer

Principle : Mass separation by a magnet



$B\rho = M.v/Q$

$Q=1^+$

Different Masses → different deviations

With "standard" systems → $R = \frac{M}{\Delta M}$ ~400

- able to separate isotopes/isotones
  OK if Z selection
- not able to separate isobares

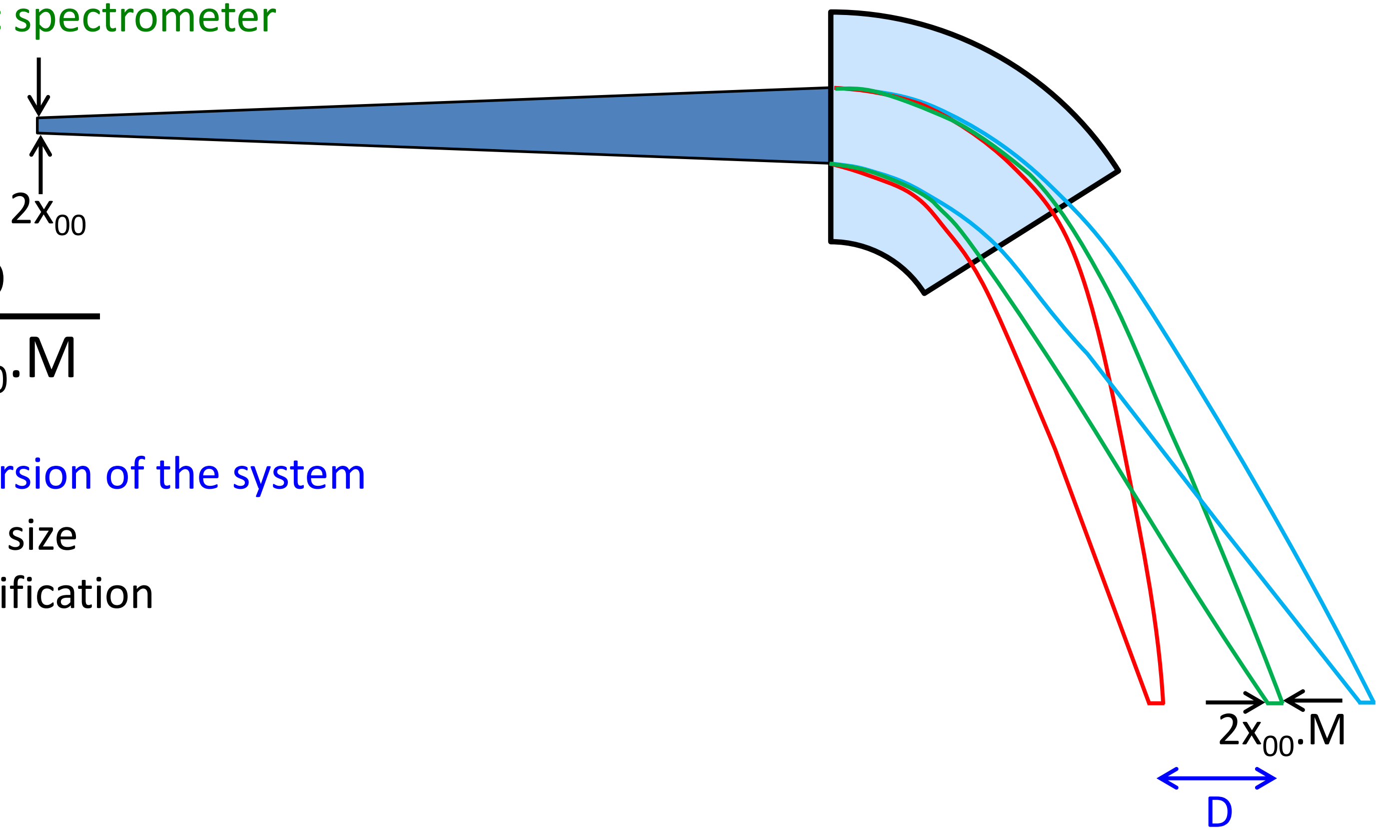
^{132}Sn : mass = 131.9178157

^{132}Sb : mass = 131.9144669

R=39392 → gain of ~100 needed on R

how to obtain this factor ? → HRS

a- Magnetic spectrometer



$$R = \frac{D}{2x_{00}.M}$$

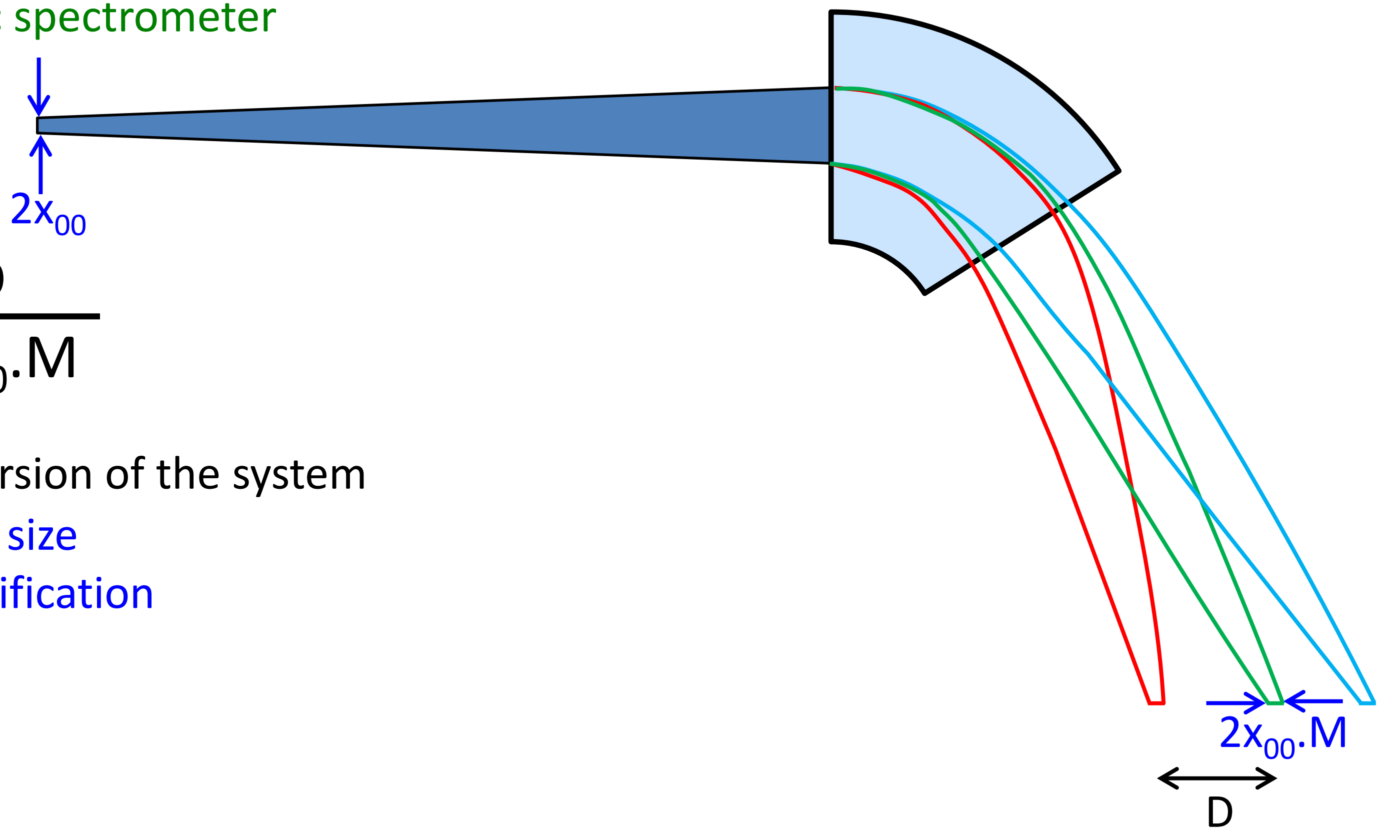
D : dispersion of the system

$2x_{00}$: beam size

M : magnification

1- Purification techniques for low energy RIB's

a- Magnetic spectrometer



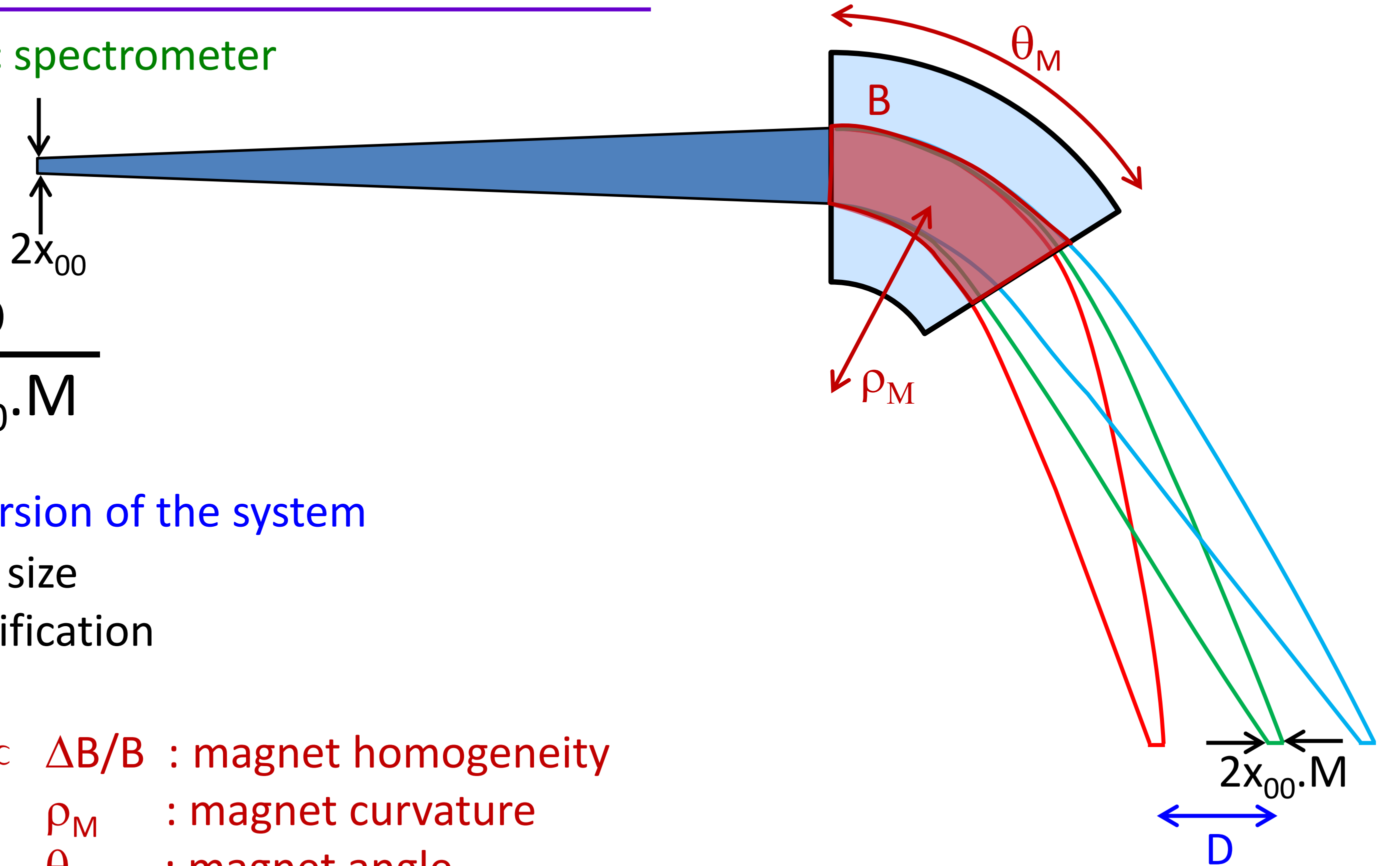
$$R = \frac{D}{2x_{00}.M}$$

D : dispersion of the system

$2x_{00}$: beam size

M : magnification

a- Magnetic spectrometer



$$R = \frac{D}{2x_{00}.M}$$

D : dispersion of the system

$2x_{00}$: beam size

M : magnification

$D \propto$ $\Delta B/B$: magnet homogeneity

ρ_M : magnet curvature

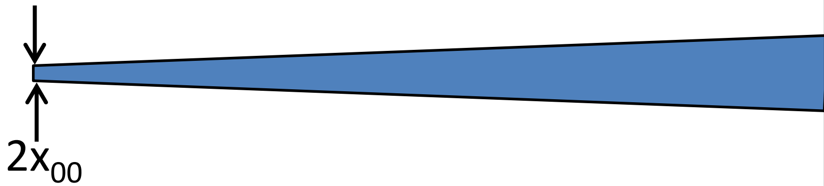
θ_M : magnet angle

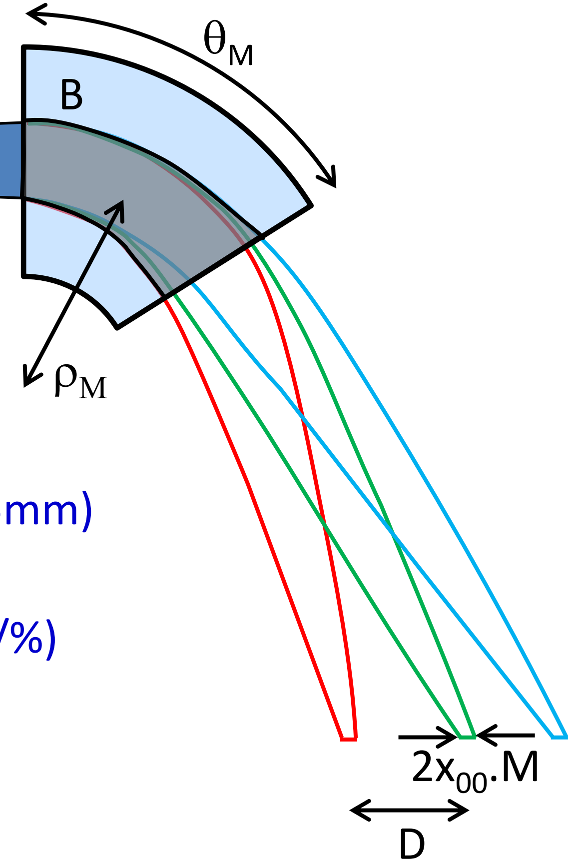
A_M : "filled" area of the magnet

…

1- Purification techniques for low energy RIB's

a- Magnetic spectrometer





$$R = \frac{D}{2x_{00}.M}$$

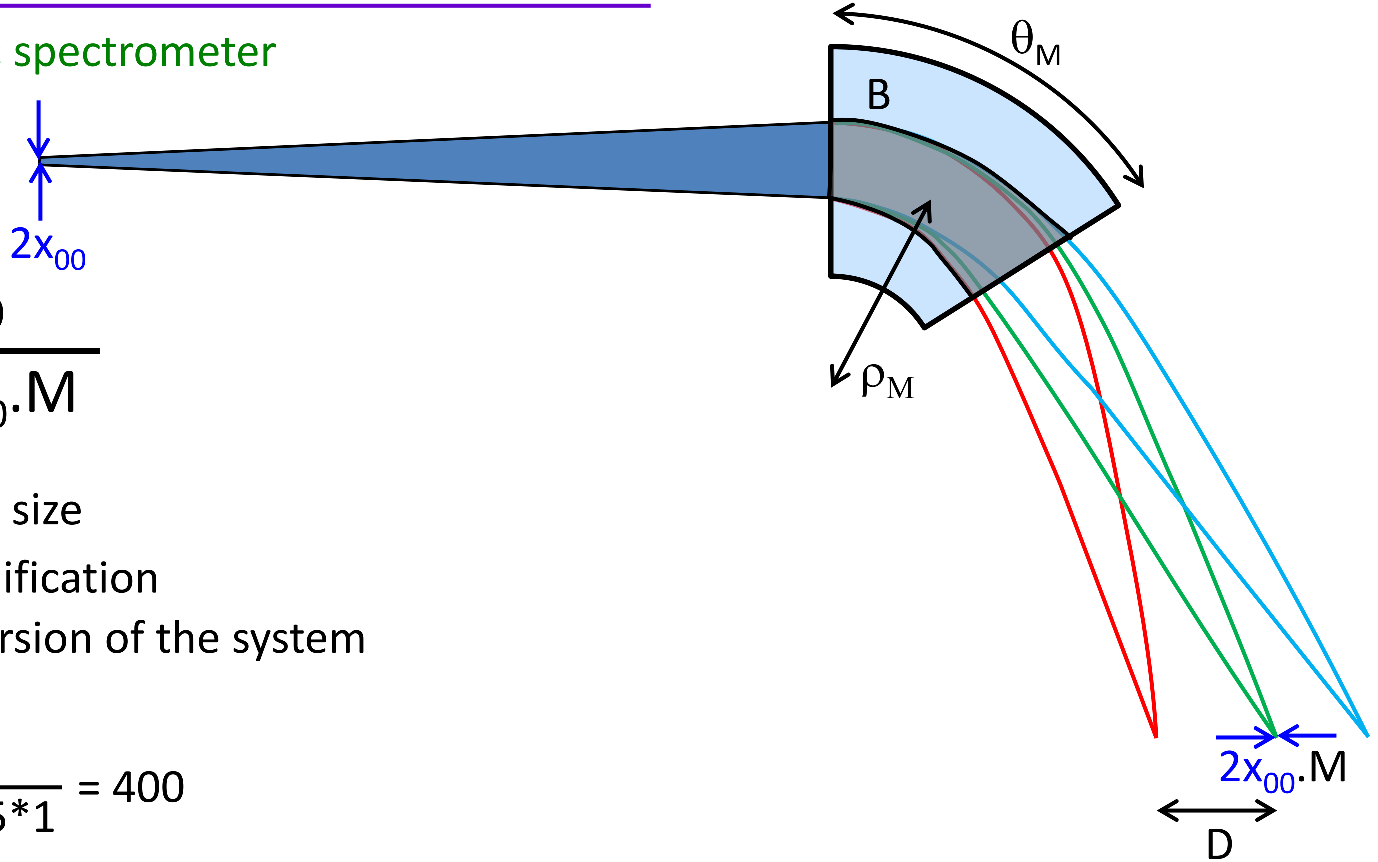
$2x_{00}$: beam size — standard 0.005m (5mm)

M : magnification — standard M=1

D : dispersion of the system — standard 2m (2cm/%)

$$R = \frac{2}{0.005*1} = 400$$

a- Magnetic spectrometer



$$R = \frac{D}{2x_{00}.M}$$

$2x_{00}$: beam size

M : magnification

D : dispersion of the system

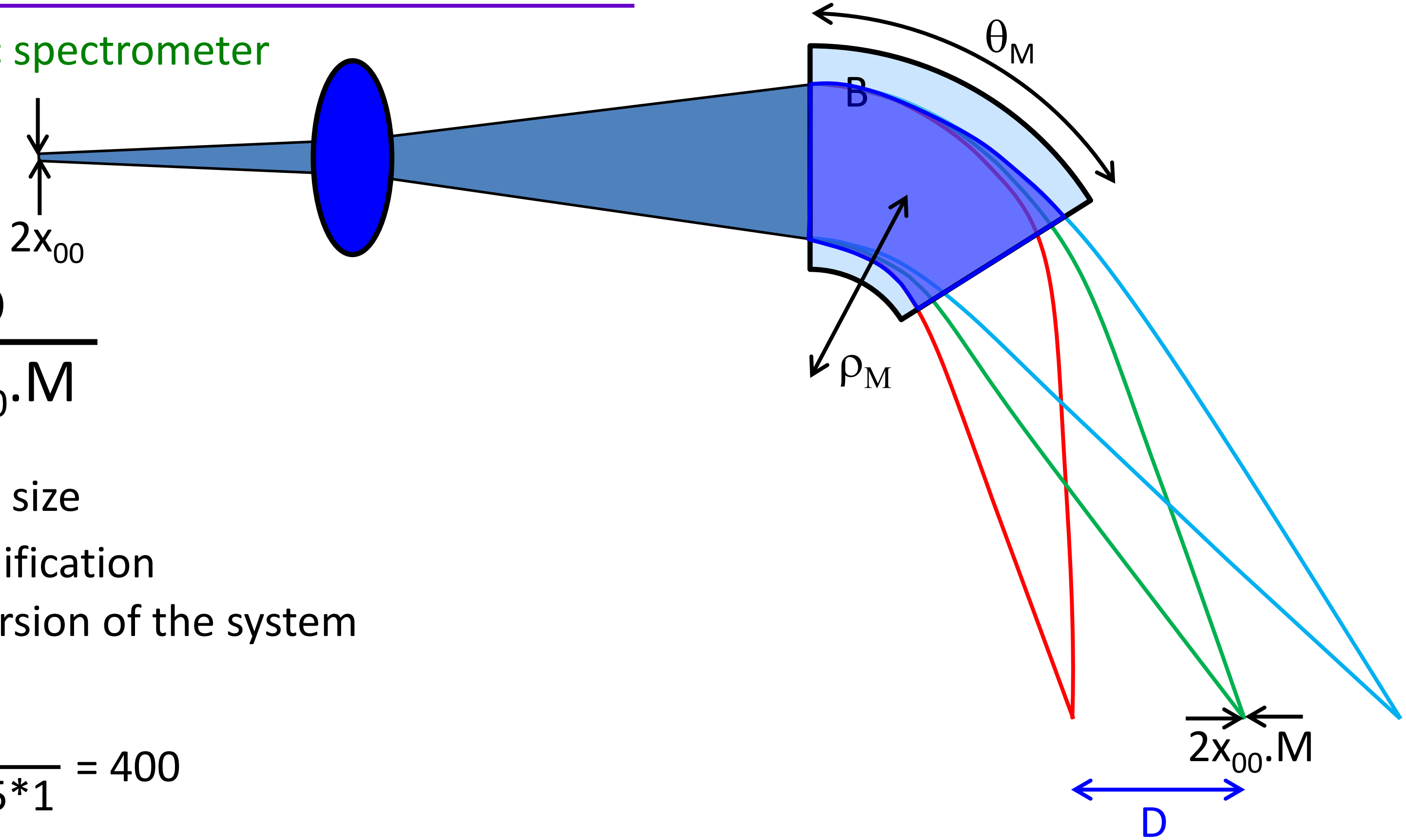
$$R = \frac{2}{0.005*1} = 400$$

HRS • $2x_{00}$: 1mm

$$R = \frac{2}{0.001*1} = 2000$$

→ need to cool the beam before the HRS : RFQ SHIRaC

a- Magnetic spectrometer



$$R = \frac{D}{2x_{00}.M}$$

$2x_{00}$: beam size

M : magnification

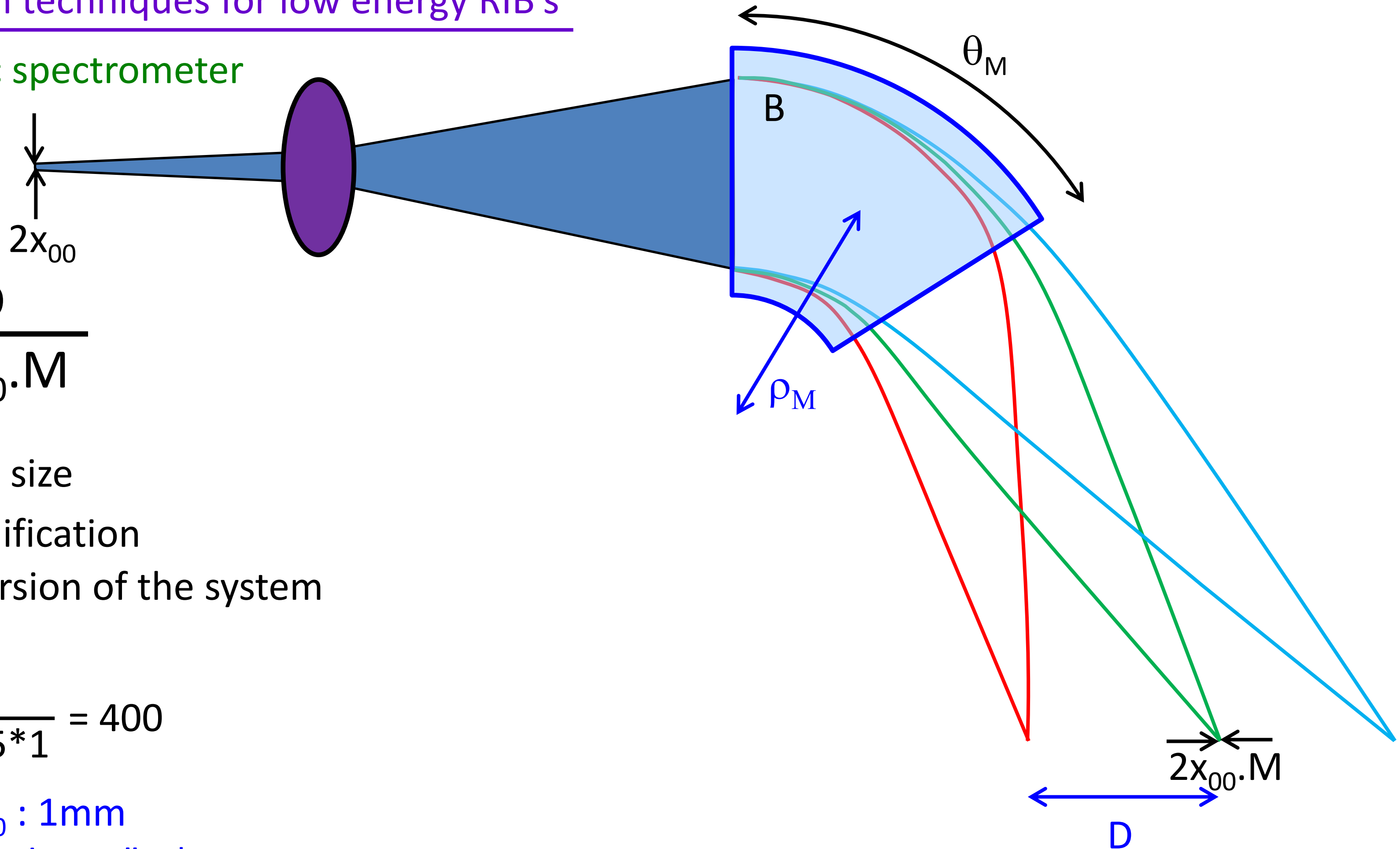
D : dispersion of the system

$$R = \frac{2}{0.005*1} = 400$$

HRS
- $2x_{00}$: 1mm
- "used area" : *3 → "dedicated" optics between SHIRaC and the first magnet

$$R = \frac{2*3}{0.001*1} = 6000$$

a- Magnetic spectrometer



$$R = \frac{D}{2x_{00}.M}$$

$2x_{00}$: beam size

M : magnification

D : dispersion of the system

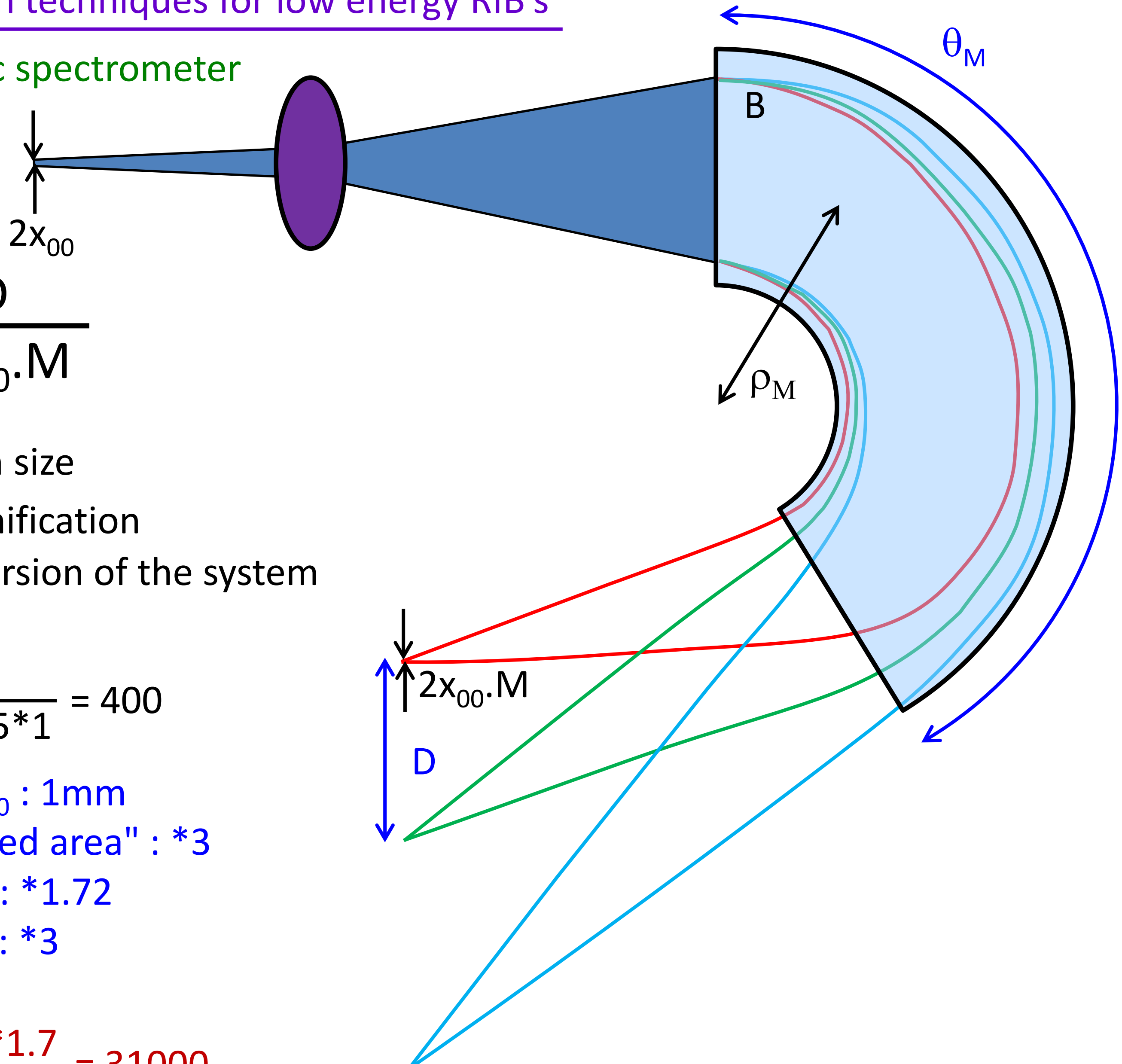
$$R = \frac{2}{0.005*1} = 400$$

HRS
- $2x_{00}$: 1mm
- "used area" : *3
- ρ : *1.7

$$R = \frac{2*3*1.7}{0.001*1} = 10200$$

1- Purification techniques for low energy RIB's

a- Magnetic spectrometer



$$R = \frac{D}{2x_{00}.M}$$

$2x_{00}$: beam size

M : magnification

D : dispersion of the system

$$R = \frac{2}{0.005*1} = 400$$

HRS
- $2x_{00}$: 1mm
- "used area" : *3
- ρ_M : *1.72
- θ_M : *3

$$R = \frac{2*3*1.7}{0.001*1} = 31000$$

b- MR-TOF-MS

Principle : Time-of-Flight separation in a linear trap

Nuclei extrated with the same energy → $\Delta M \leftrightarrow \Delta v$

^{132}Sn : mass = 131.9178157 → v = 0.0209486 cm/ns

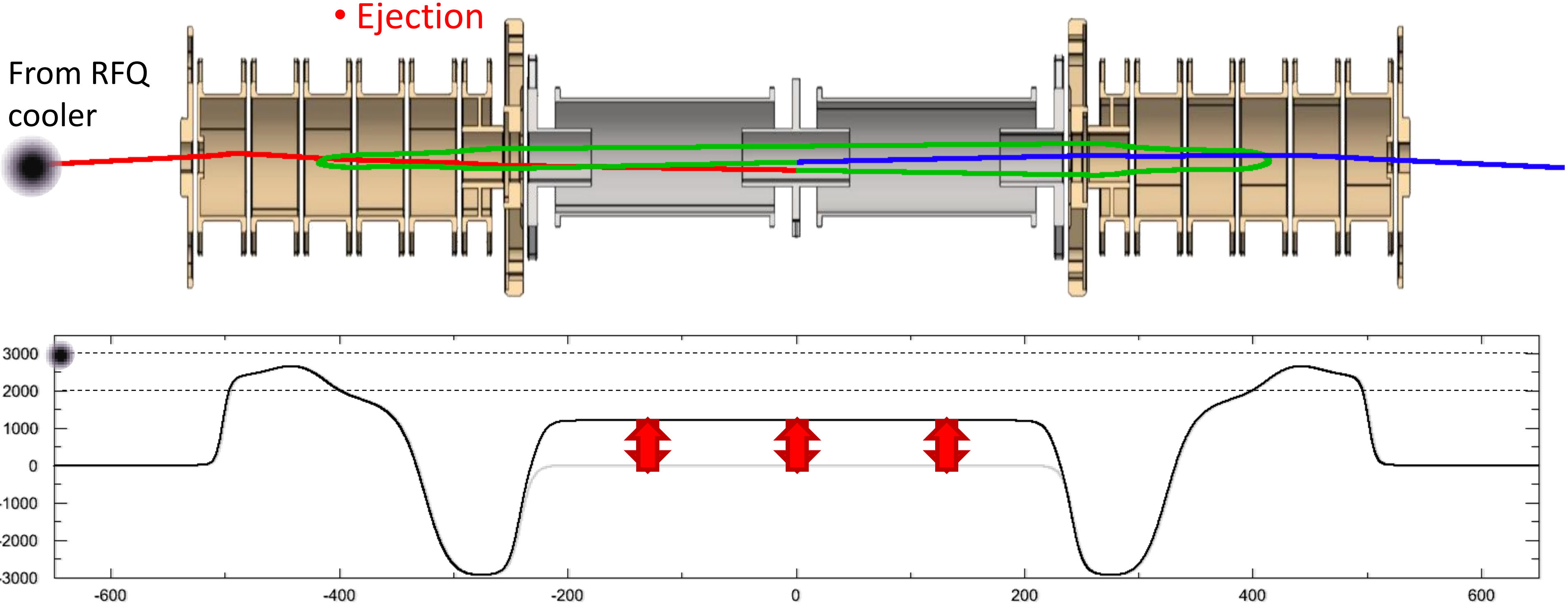
^{132}Sb : mass = 131.9144669 → v = 0.0209488 cm/ns

@ 5 keV

In 10 msec →

- Flight pass : 2 km ! → multi reflections (~4000) in a trap
- Δ_L : 2 cm
- Δ_TOF : 100 ns

- Injection
- Trapping
- ToF separation
- Ejection



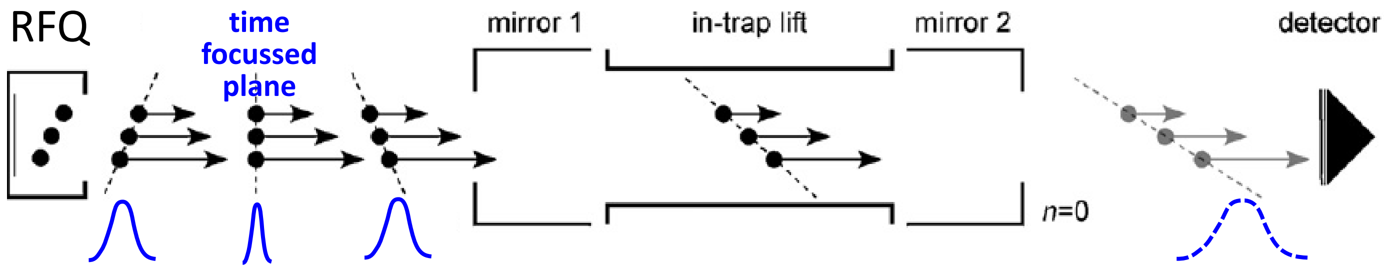
b- MR-TOF-MS

- Energy spread → need "time focussing"

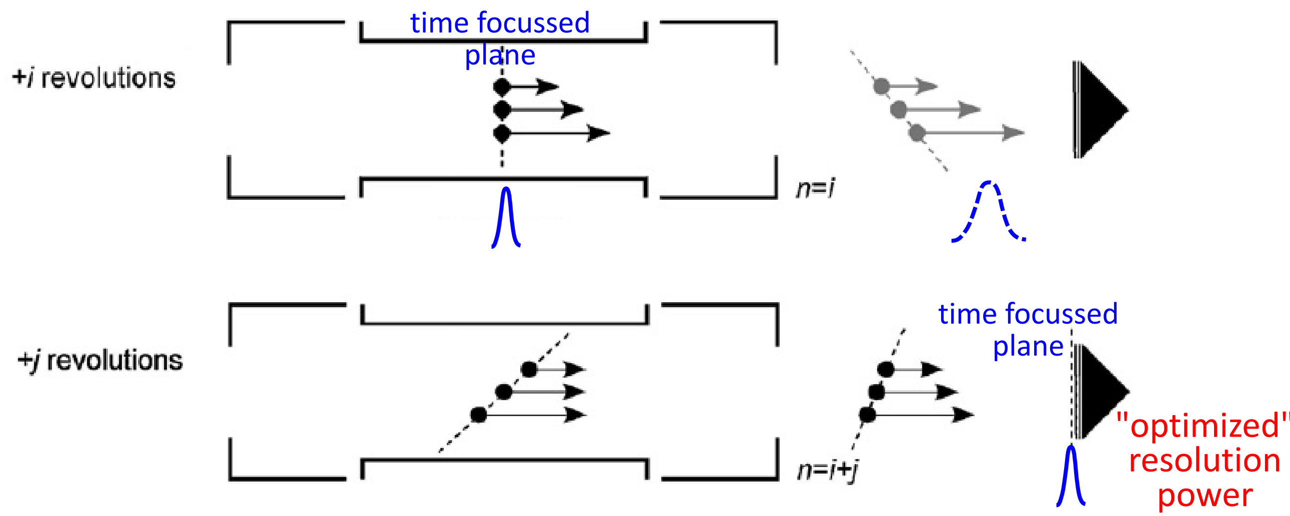
ToF focussing

Ions extracted from RFQ have (small) energy and position distributions…

$\Updownarrow$ ΔT



Need : Nuclei with higher energy to have longer revolution time
→ adjustment of the slope of the mirror voltage



Wolf *et al.*, IJMS 313, 8 (2012)

Generalization : Mirrors optimization to have a Flight time independant from :
- energy
- transverse position
- divergence

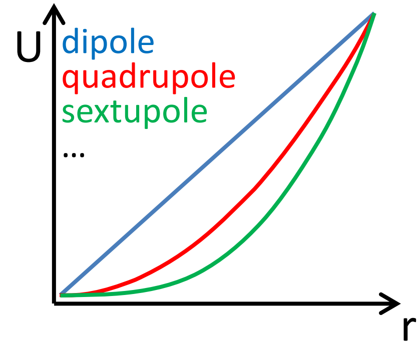
c- Penning trap

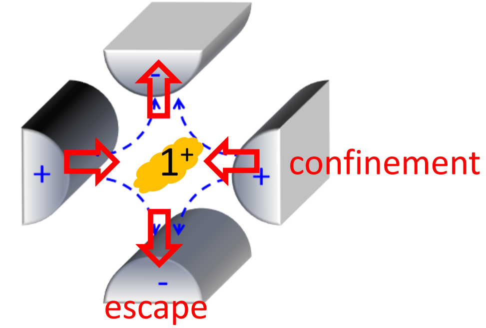
Principle : Mass separation in a trap

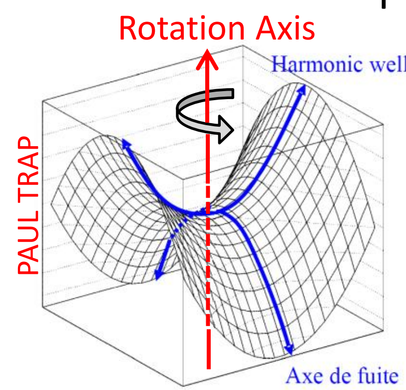
1) trapping in x, y and z

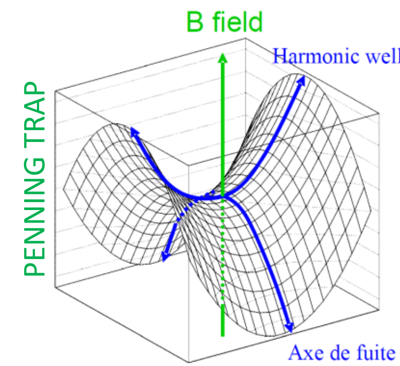
- use of a quadrupolar potential
- Laplace law : $\Delta\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0$

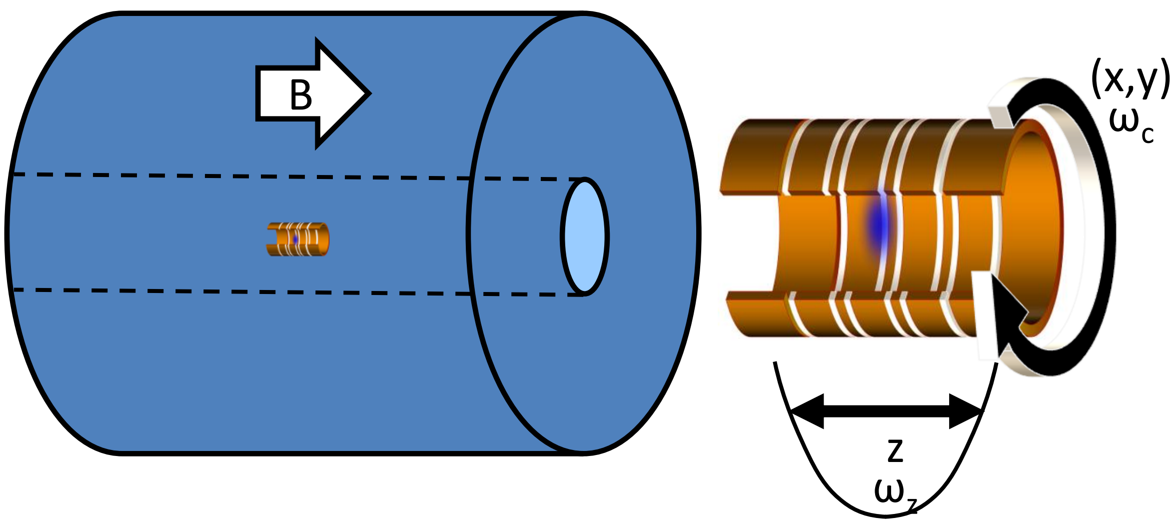
→ cannot confine in all the directions with a single potential (escape axis)











$$\Phi(z,r) = \frac{U_{dc}}{2d^2}\left(z^2 - \frac{1}{2}r^2\right)$$

coupled radial equations :

$$\frac{d^2x}{dt^2} = \omega_c\frac{dy}{dt} + \frac{\omega_{0z}^2}{2}x$$

$$\frac{d^2y}{dt^2} = -\omega_c\frac{dx}{dt} + \frac{\omega_{0z}^2}{2}y$$

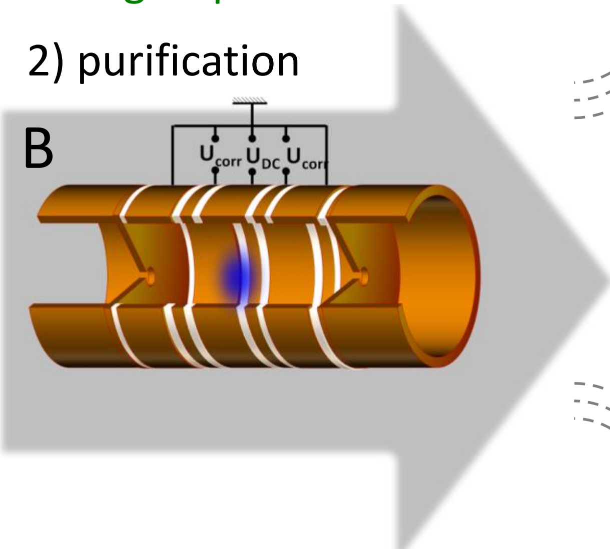
harmonic oscillation in z

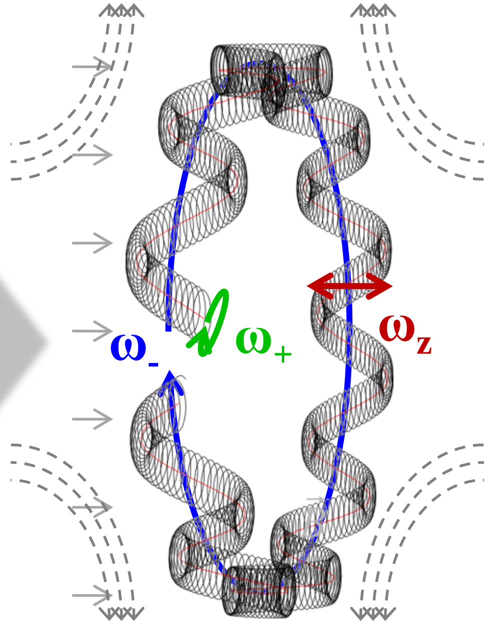
$$\omega_{0z} = \sqrt{\frac{2qU}{mr_0^2}}$$

1- Purification techniques for low energy RIB's

c- Penning trap

2) purification





axial motion

$$\omega_z = \sqrt{\frac{qU_{dc}}{md^2}}$$

ω_z ~ 100 kHz

magnetron motion

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

ω_- ~ kHz

modified cyclotron motion

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

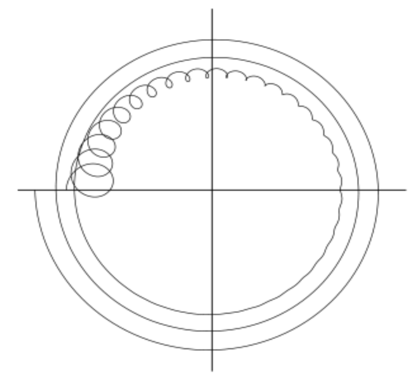
ω_+ ~ 10MHz

3 independent motions at 3 eigenfrequencies

Mass selection by sideband buffer gas cooling :

- Dipolar excitation at the magnetron frequency : $\omega_- \approx \frac{U_{dc}}{2d^2 B}$

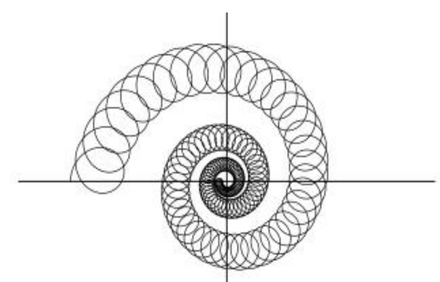
  mass independant → all ions to a higher radius



- Combining the effect of buffer gas and a quadrupolar excitation at ($\omega_+ + \omega_-$)
  - buffer gas: cyclotron motion is cooled, magnetron motion increases
  - quadrupolar excitation: coupling the two radial modes

  → radii of both motions are cooled

  → mass-selective centering



Outlook

1- Purification techniques for low energy RIB's @ GANIL/SPIRAL2

a- Magnetic spectrometer

b- Multi-reflections time-of-flight spectrometer (MR-TOF-MS)

c- Penning trap

2- Performances and Status of development of such devices @ GANIL/SPIRAL2

a- HRS@DESIR

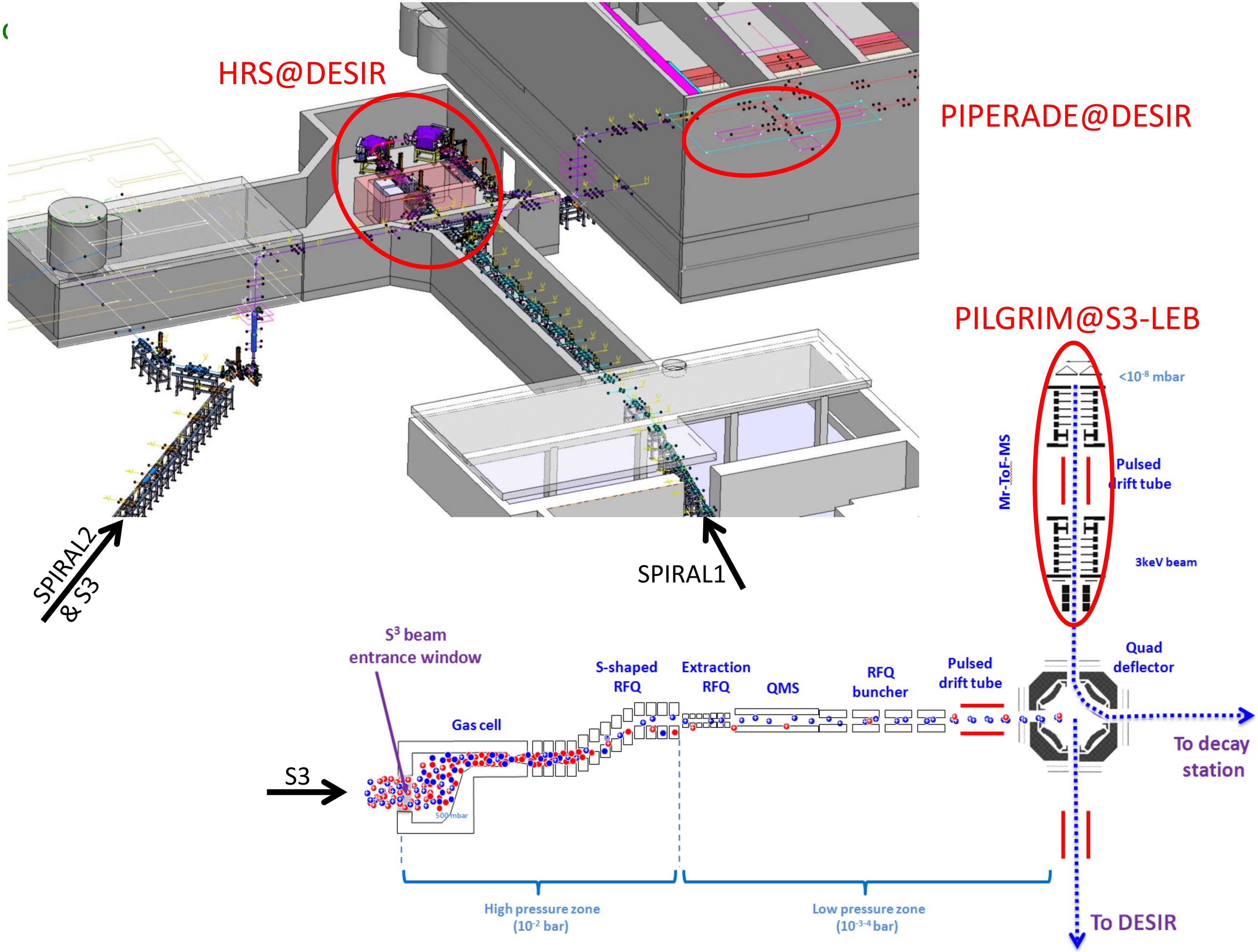
b- PILGRIM @ S3-LEB

c- PIPERADE@DESIR

3- Comparative performances / Complementarities

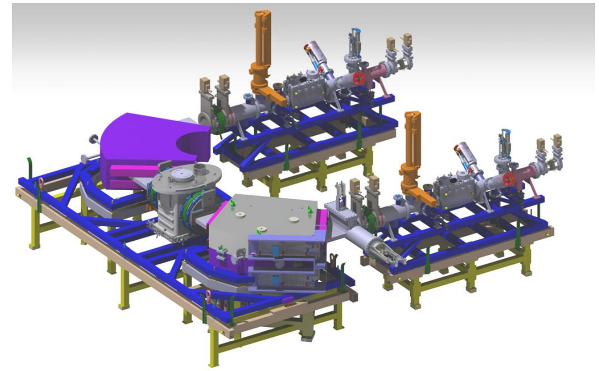
2- Performances and Status of development of such devices @ GANIL/SPIRAL2

Locati

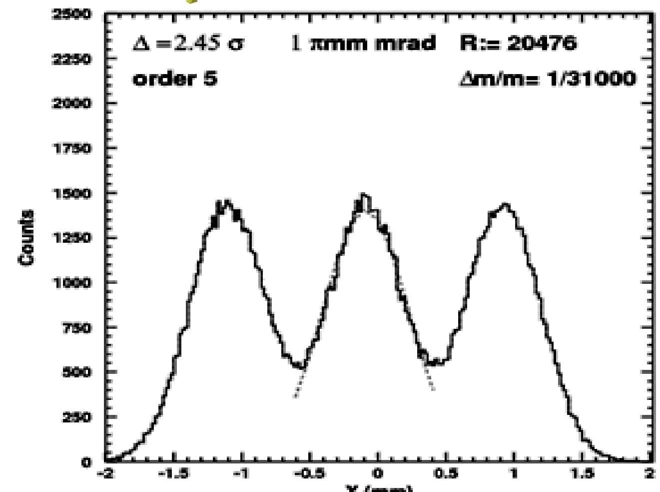


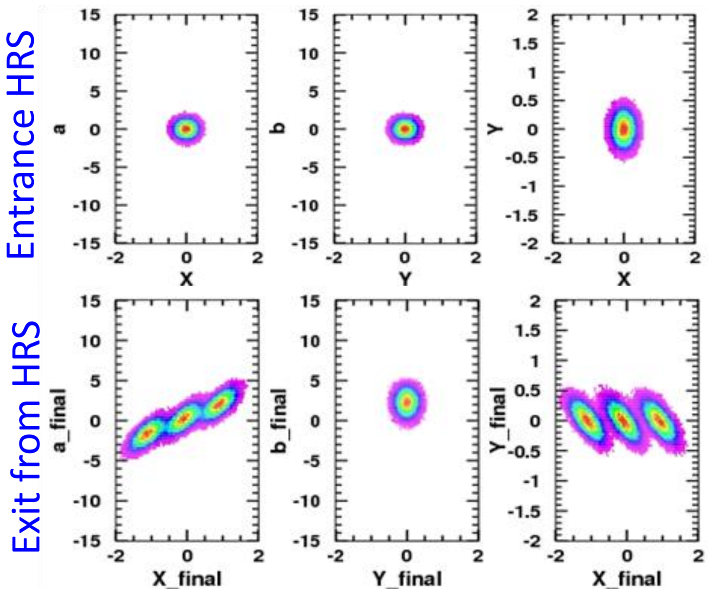
a- SHIRaC+HRS@DESIR

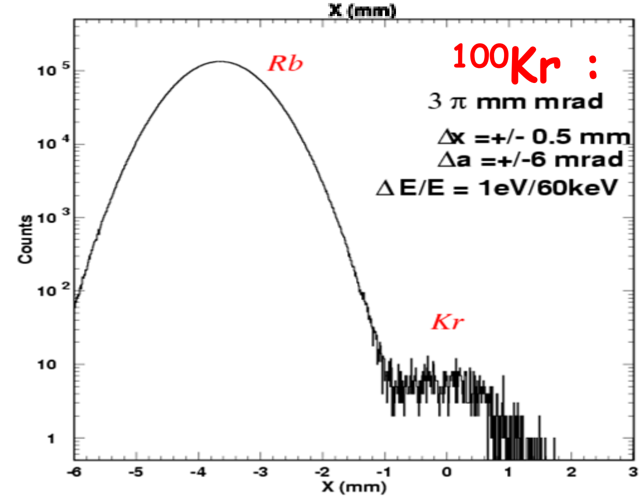
- Goal : "on-line" isobar purification
- Intensity : up to 1μA
- Cooling time ~ msec
- Design resolution : M/ΔM = 31 000
  + Misalignments → M/ΔM > 20 000



	X shift (mm)	Y shift (mm)	X Tilt (mrad)	Y Tilt (mrad)	Θ (mrad)
QQ1	±0.1	±0.1	±3.5	±3.5	±3.5
HQ1	±0.1	±0.1	±0.35	±3.5	±3.5
D1	±0.1	±0.1	±0.35	±3.5	±3.5
M	±0.1	±0.1	±3.5	±3.5	±3.5
D2	±0.1	±0.1	±0.35	±3.5	±3.5
HQ2	±0.1	±0.1	±0.35	±3.5	±3.5
QQ2	±0.1	±0.1	±3.5	±3.5	±3.5





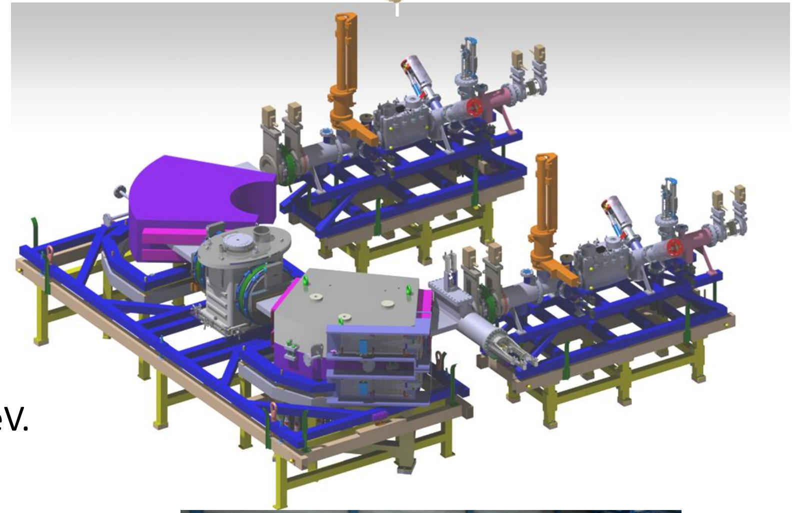


2- Performances and Status of development of such devices @ GANIL/SPIRAL2

a- SHIRaC+HRS@DESIR

Shiracq RFQ

- New measurements for emittances and energy spread
  - Transmission : above 70%
  - Emittance : 2 π.mm.mrad @60 keV and up to 1 µA
  - Energy spread : around 1,5 eV for 1 µA
- Gas recycling tested. To be implemented
- Modifications of design to fullfil 'ALARA' environment to be done

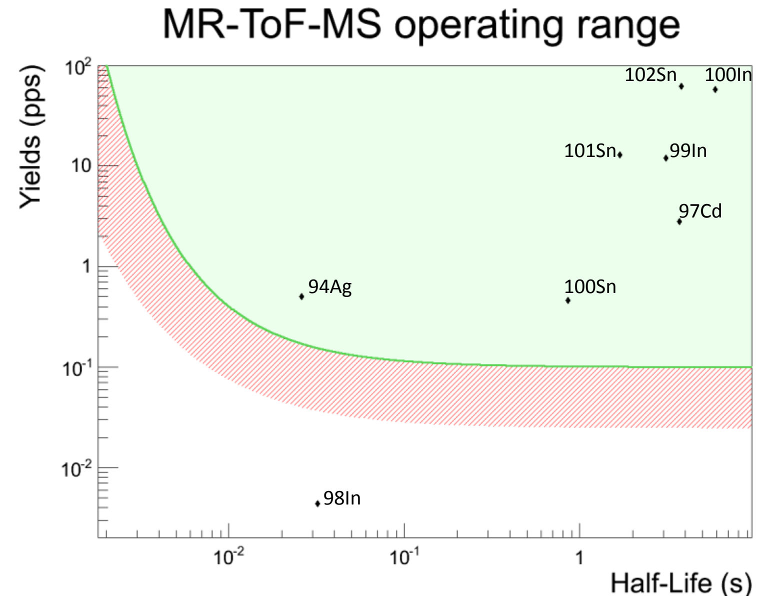


HRS

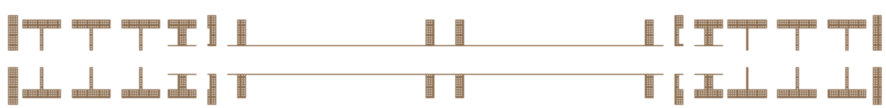
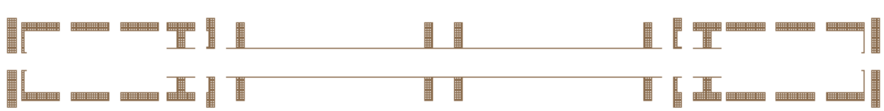
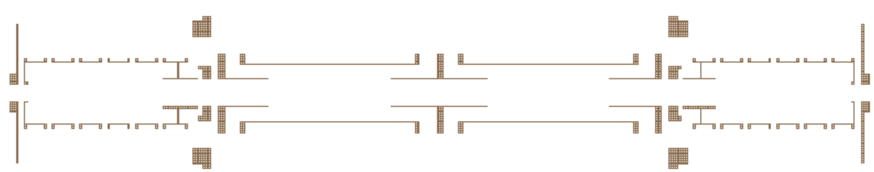
- Global optical design published
  EMIS2012, Japan. T. Kurtukian-Nieto et al.,
  NIMB 2013, DOI: 10.1016/j.nimb.2013.07.066.
- Performance of the HRS considering misalignment /positioning precision of different elements
  m/Δm =20,000 for a 3π mm mrad 60keV beam and energy spread ~1 eV.
- Mechanical design and integration ready
- Dipoles delivered @ GANIL (july2014)
  Magnetic field mapping scheduled for 2015
- Manufacturing of other elements by CENBG
- Setup completed @ CENBG end of 2015
- Tests @ CENBG up to 2018

b- PILGRIM @ S3-LEB

- goal : isobar purification + mass measurement
- intensity : 10^3 ions/pulse
- cycle time : 10 msec
- Design resolution : $M/\Delta M = 10^5$ and $\sigma M/M \approx 5.10^{-7}$



Simulations on SIMION :
- Potentials
- Geometry

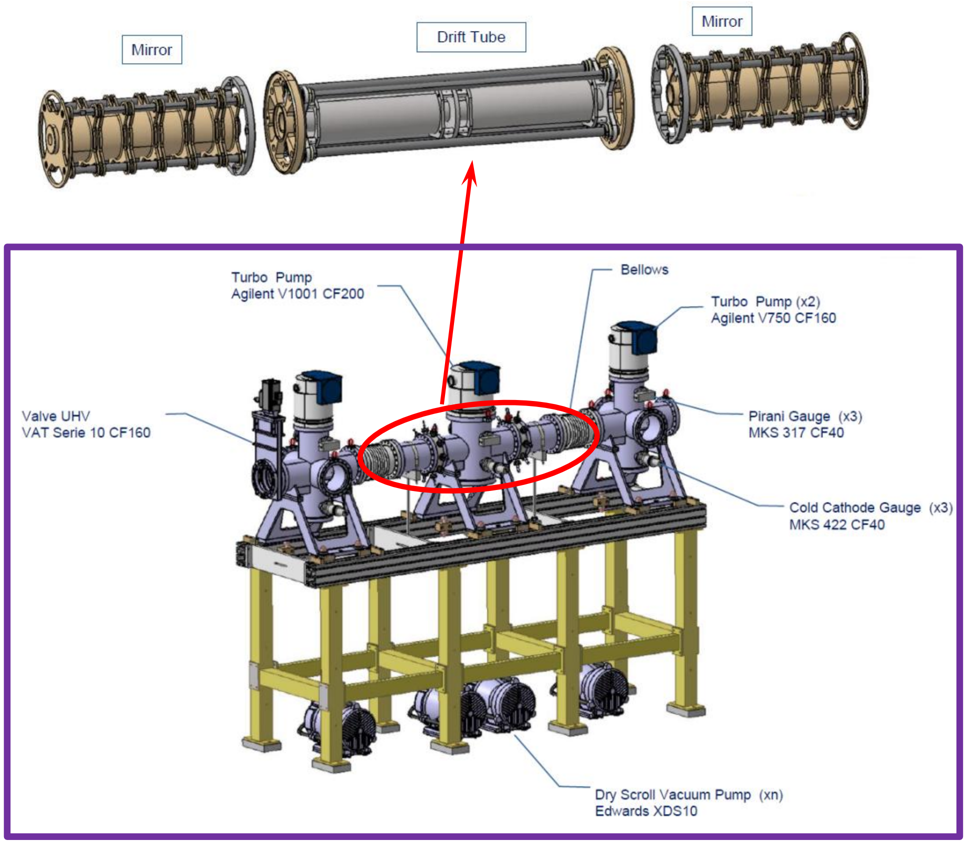
Geometry	R
	**2226.5**
	**29048.0**
	**42181.4**

B.Kansal

P.Chauveau

R>3.10^5 have been obtained in simulation for **realistic beams** (B.Kansal)

b- PILGRIM @ S3-LEB



Planning

PILGRIM :

- 10/2015 : end of mechanical design
- 10->12/2015 : production/purchase of mechanical parts
- 01->06/2016 : assembly of PLIGRIM
- 09->12/2016 : tests at LIRAT ?

c- PIPERADE@DESIR

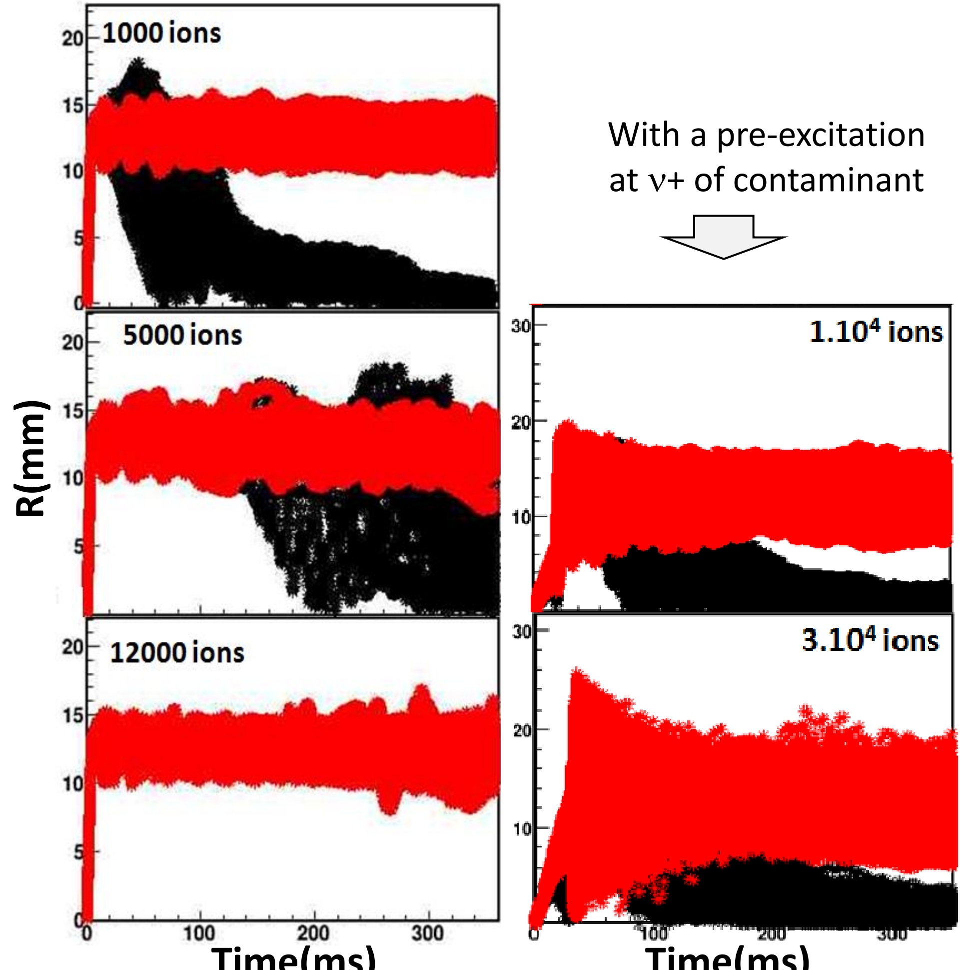
- goal : isobaric purification + accumulation for precision measurements
- intensity : up to 10^6 ions/pulse
- cycle time : 100-300 msec
- Design resolution : $M/\Delta M > 10^5$

90% ^{136}Te, 10% ^{136}Sb   P = 10^{-4} mbar   B = 7T

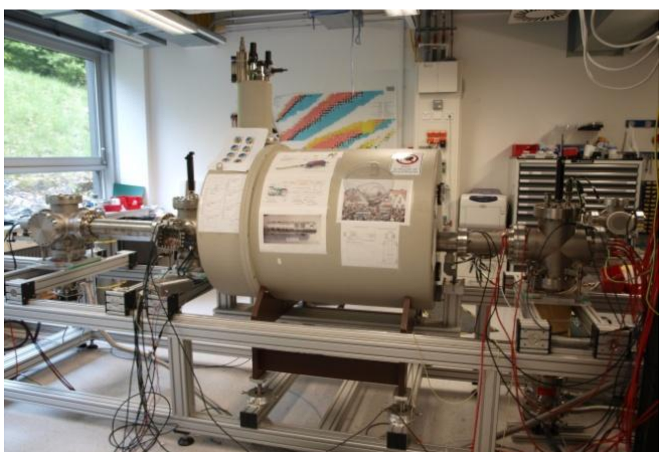
SIMBUCA code, *S. Van Gorp et al., NIM A 638, 192200 (2011)*

Increasing the number of ions makes the re-centering inefficient

Additional potential created by the cloud itself
→ f-shifts, peak broadening, screening effects



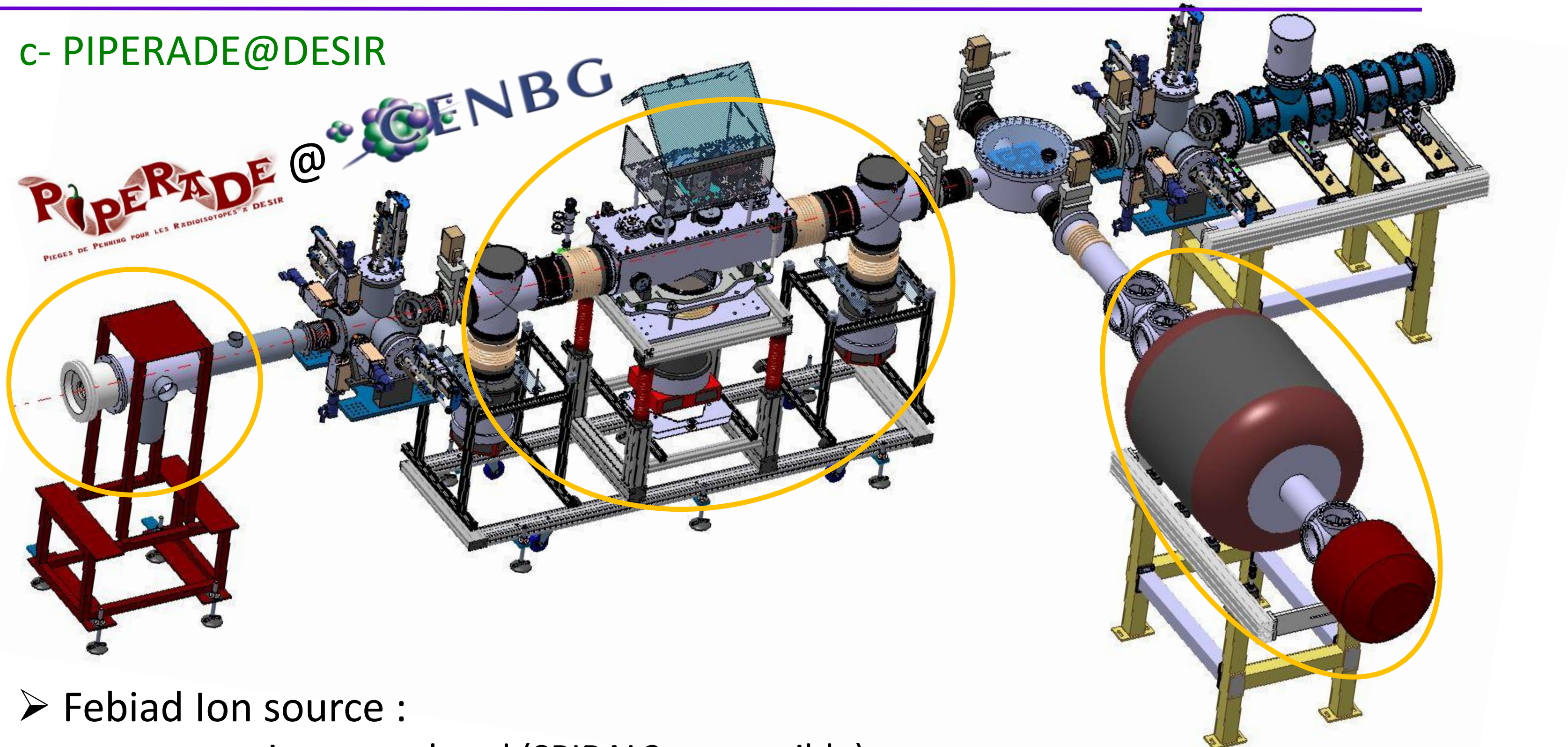
Alternative techniques…
-simulations @ CSNSM and MPIK
- experimental tests @ MPIK



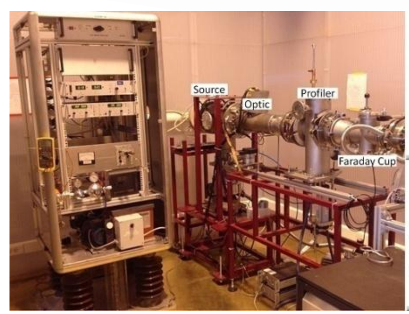
P. Ascher. S. Naimi. A. de Roubin. E. Minava - MPIK. P. Dupré CSNSM

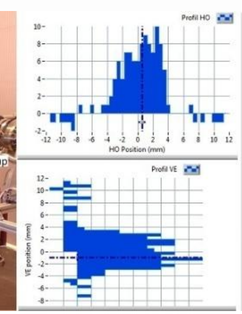
c- PIPERADE@DESIR

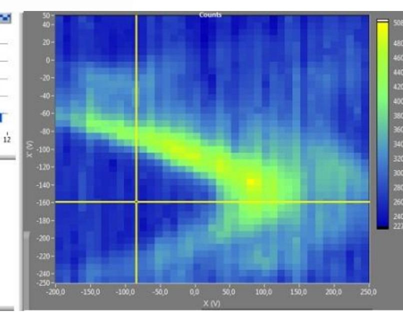
PIPERADE @ CENBG



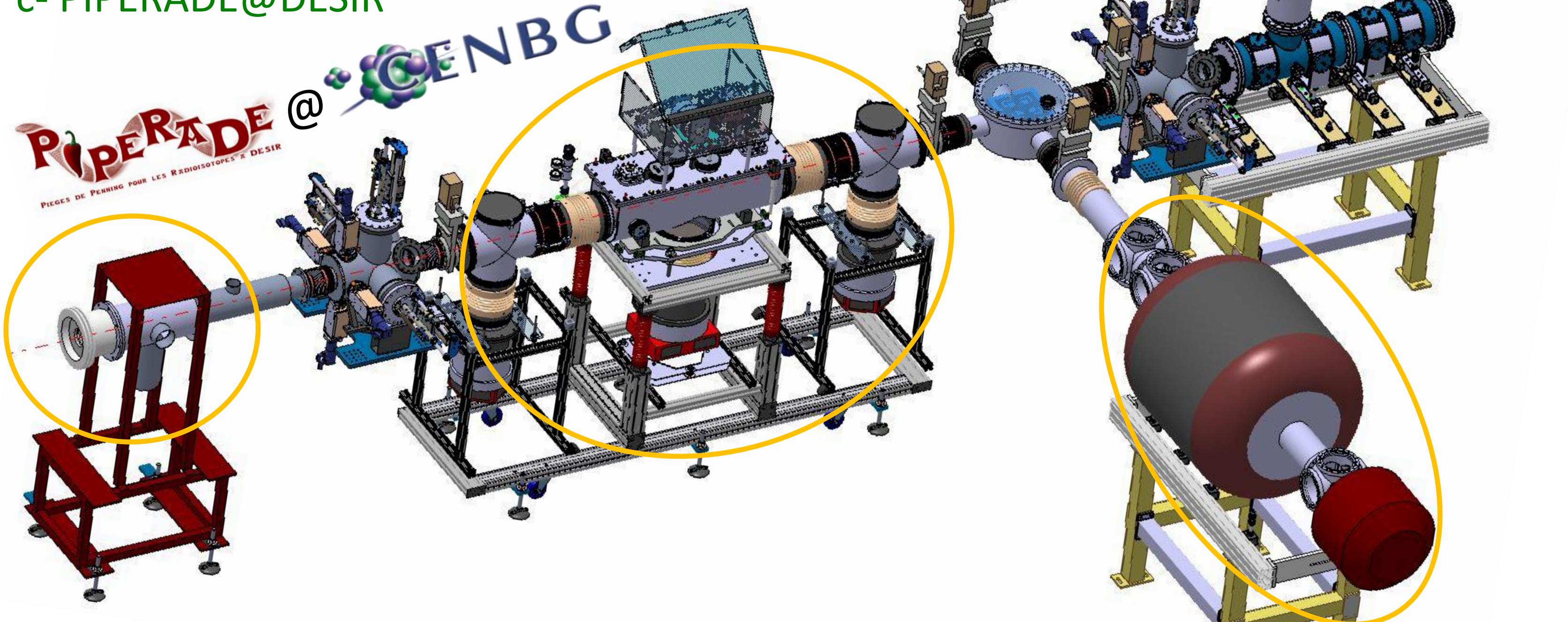
- Febiad Ion source :
  - renovation completed (SPIRAL2 compatible)
  - emittance caracterized
- General Purpose Ion Buncher :
  - mechanics and electronics completed
  - ready to be tested
- Penning Trap
  - simulations underway
  - mechanical design ready
  - construction beginning of 2015
  - magnet ordered (delivery expected 10/15)
  - tests@CENBG in 2016



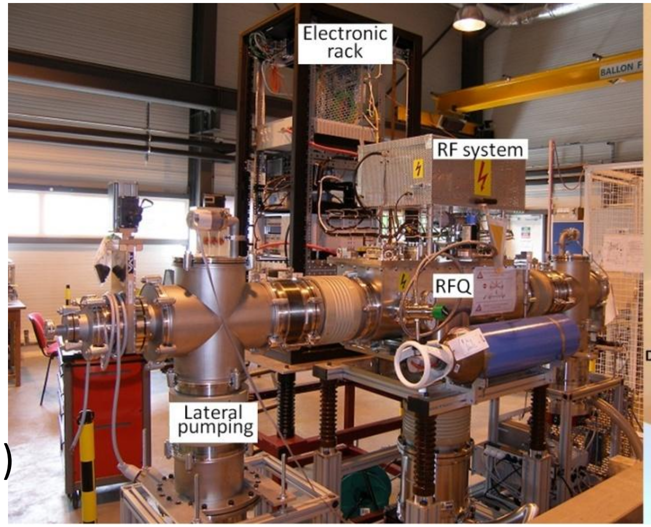


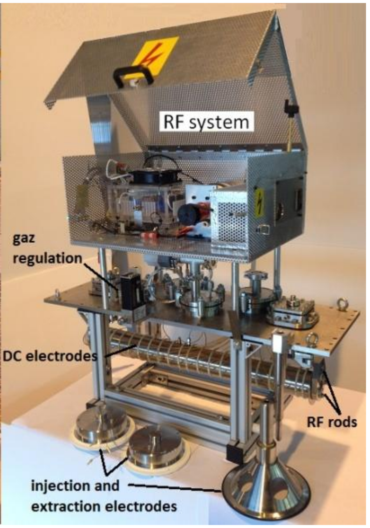


c- PIPERADE@DESIR

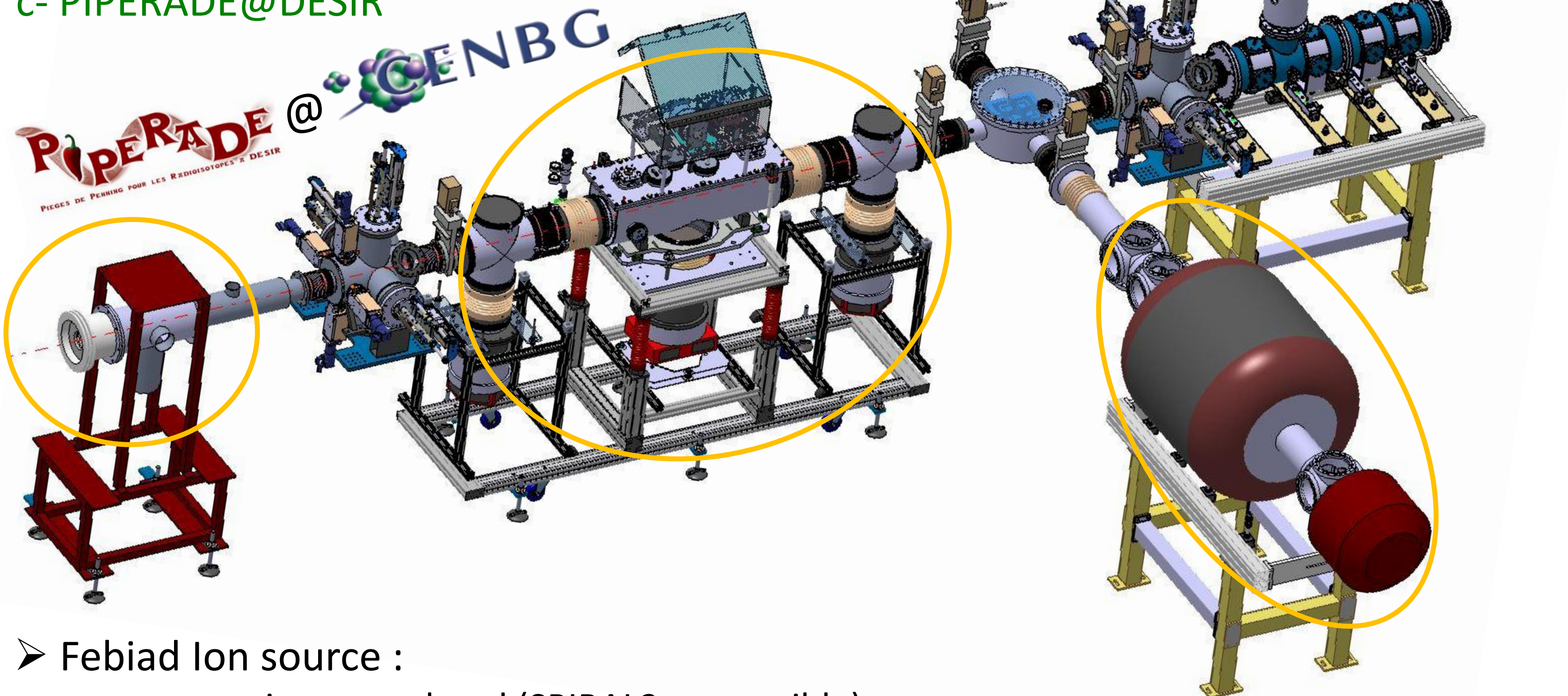


- Febiad Ion source :
  - renovation completed (SPIRAL2 compatible)
  - emittance caracterized
- General Purpose Ion Buncher :
  - mechanics and electronics completed
  - ready to be tested
- Penning Trap
  - simulations underway
  - mechanical design ready
  - construction beginning of 2015
  - magnet ordered (delivery expected 10/15)
  - tests@CENBG in 2016

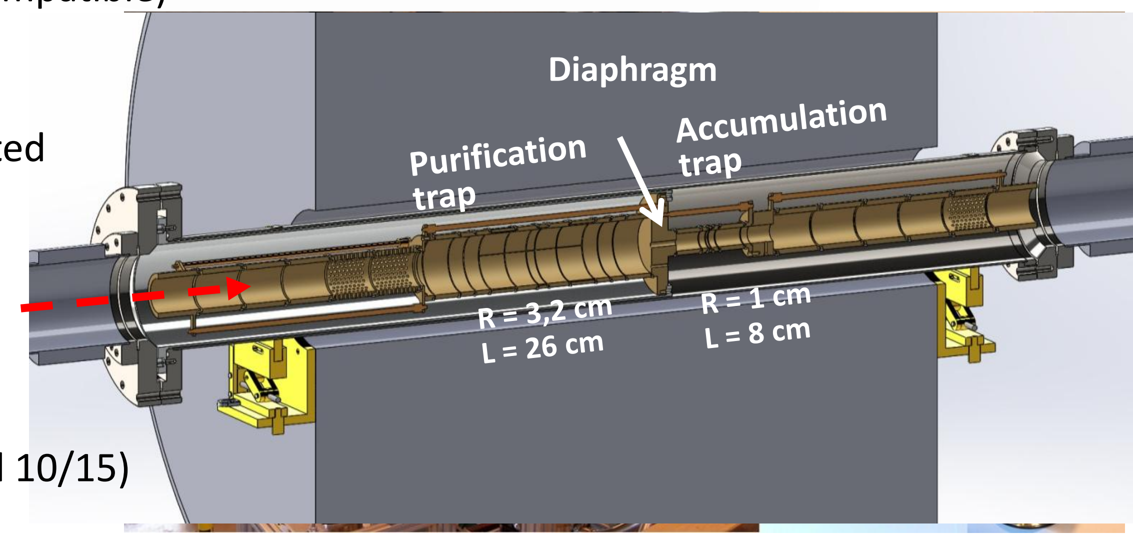




c- PIPERADE@DESIR



- Febiad Ion source :
  - renovation completed (SPIRAL2 compatible)
  - emittance caracterized
- General Purpose Ion Buncher :
  - mechanics and electronics completed
  - ready to be tested
- Penning Trap
  - simulations underway
  - mechanical design ready
  - construction beginning of 2015
  - magnet ordered (delivery expected 10/15)
  - tests@CENBG in 2016



3- Comparative performances / Complementarities

- HRS and MR-TOF-MS/Penning Trap have different philosophy
- MR-TOF-MS and Penning Trap are complementary

	HRS	MR-TOF-MS PILGRIM	Penning Trap PIPERADE
Goals	Isobaric purification	Isobaric purification Mass measurement	Isobaric/Isomeric purification and accumulation
Intensity	10^{13}pps	10^3 ions/pulse - 100Hz	10^5 ions/pulse - 5/10Hz
Timing	N/A	10 msec	100-200 msec
Resolution M/ΔM	>20 000	10^5	>10^5
Efficiency	100%	>50%	>50%
Possible developments	N/A	identification device ("tagging")	In trap decay spectroscopy …

Rq1 : HRS would be able to make a "pre"-purification before PIPERADE
Rq2 : a MR-TOF-MS device could be installed in the DESIR hall in the future