# The adventures of radioactive ions between production and measurement

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FOM

RuG

# Contents

- Orientation: what’s all this about ?
- Production of exotic nuclei
- Selection:
  - overview
  - building blocks
  - examples
- Manipulation:
  - overview
  - building blocks
  - examples
- Summary

# An on-line experiment

after production target

measurement requires

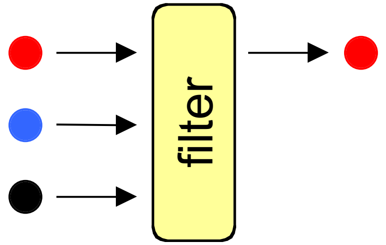
**products of interest** ●

**other products** ● ● ●

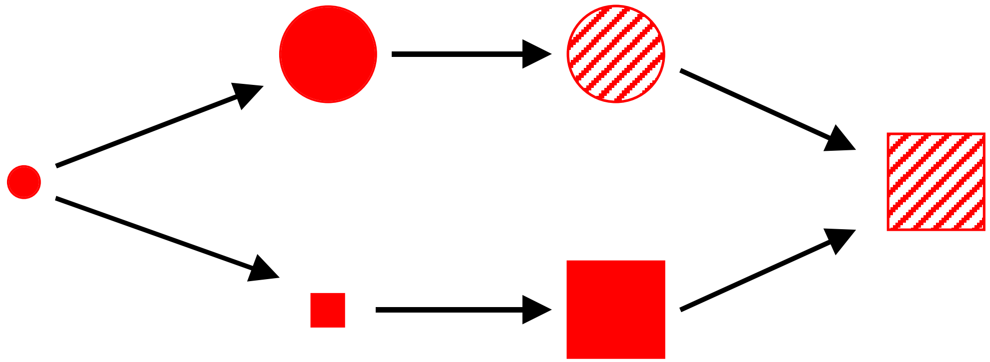
**primary beam** ● ● ● ● ● ●

selection & manipulation

selection



manipulation



# Special needs for radioactive ions

selection and manipulation techniques need to be

- **fast** (short half-life)

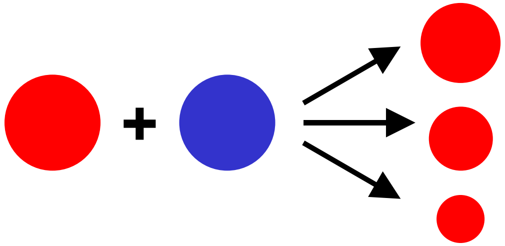
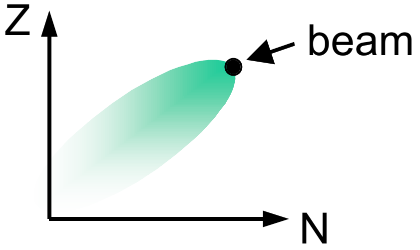
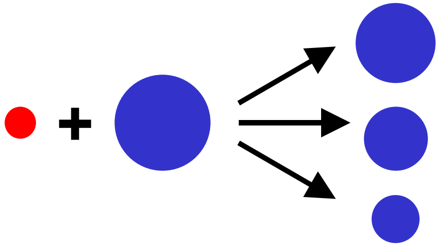
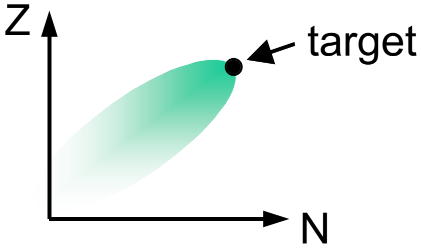
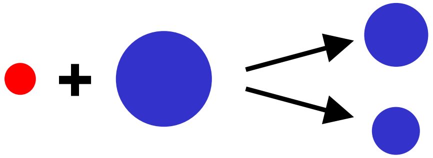
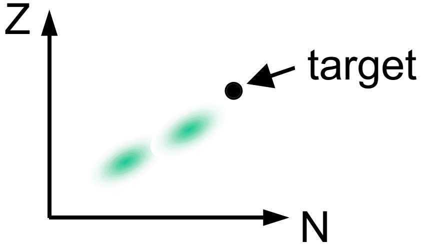
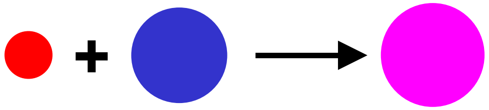
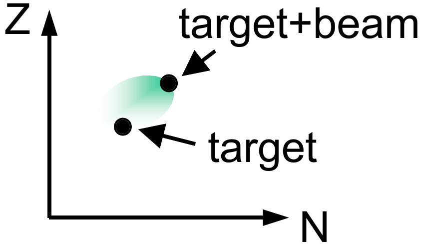
  down to μs

  ☞ “on-line”

- **efficient** (small cross section)

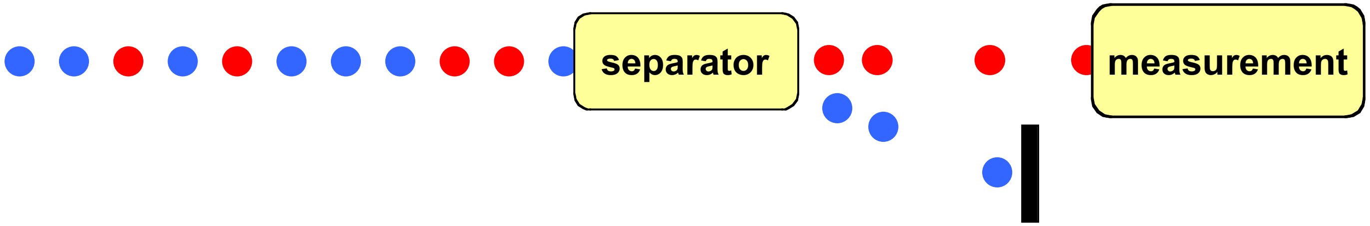
  aim for 100 %

# Producing exotic nuclei

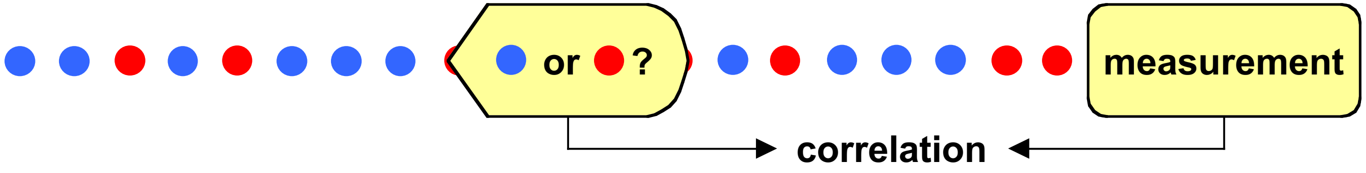
| | | high energy<br>>> *thermal energy* | many products | |
|---|---|---|---|---|
|  | fragmentation | $v_{product} = v_{beam}$ | up to 1000 |  |
|  | spallation | few MeV/u | up to 1000 |  |
|  | fission | ~1 MeV/u | few 100 |  |
|  | fusion-evaporation | $E_R = \frac{m_p}{m_p + m_t} E_P$ | few (≤ 20) |  |

# Selection techniques: 2 types

**separation**



**identification**

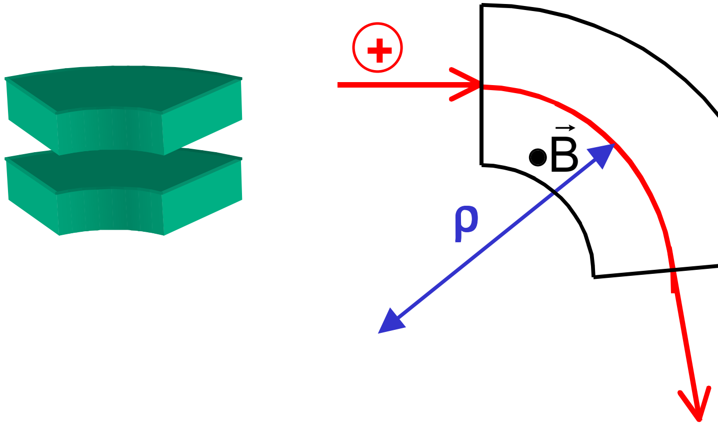


# Selection: building blocks

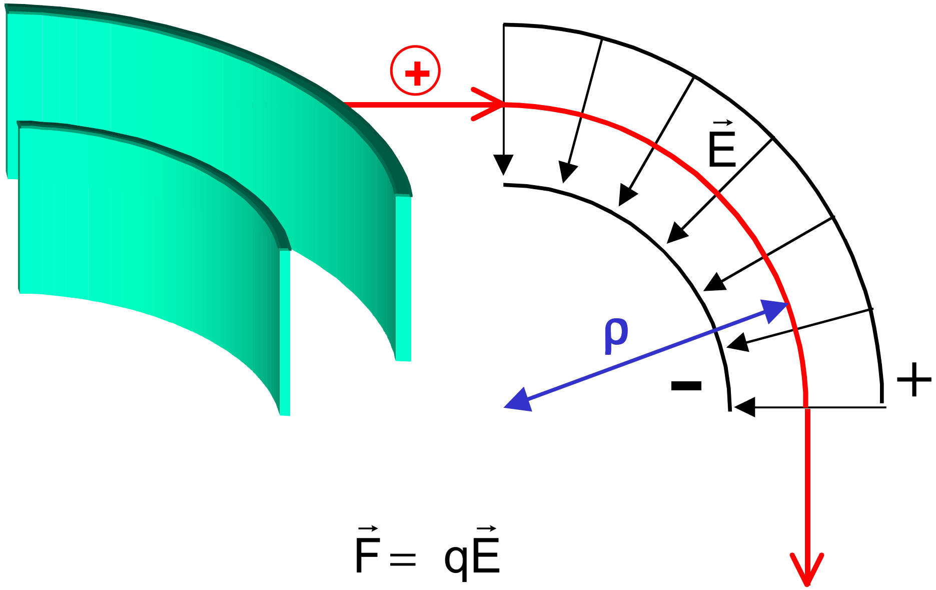
| | high energy<br>*beam* | thermal energy<br>*cloud* |
|---|---|---|
| separation | • magnetic dipole<br>• electric dipole<br>• velocity filter<br>• energy degrader | • ionization<br>• ion trap |
| identification | • time-of-flight (TOF)<br>• total energy<br>• energy loss (ΔE)<br>• magnetic rigidity | • stopping range<br>• radioactive decay |
| | in-flight | stop & go<br>**(ISOL)** |

# Separation at high energy

magnetic dipole



electric dipole



$$\vec{F} = q\vec{v}\times\vec{B}$$

$$\vec{F} = q\vec{E}$$

$$B\rho = \frac{mv}{q} \qquad [T\cdot m]$$

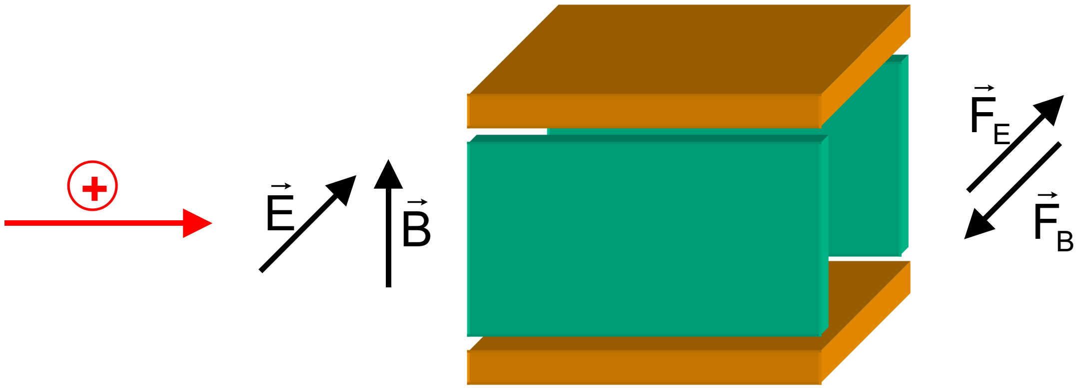
$$E\rho = \frac{mv^2}{q} \qquad \left[\frac{J}{C}\right]$$

magnetic rigidity

dispersion

electric rigidity

# Separation at high energy

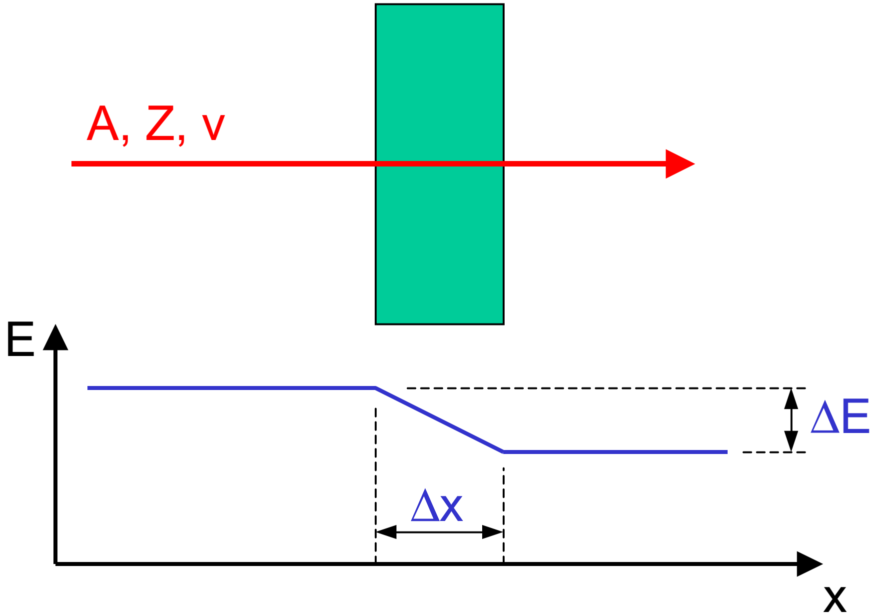


velocity filter

Wien filter, E-cross-B filter

charged particles with velocity $v = \frac{E}{B}$ are not deflected

# Energy degrader

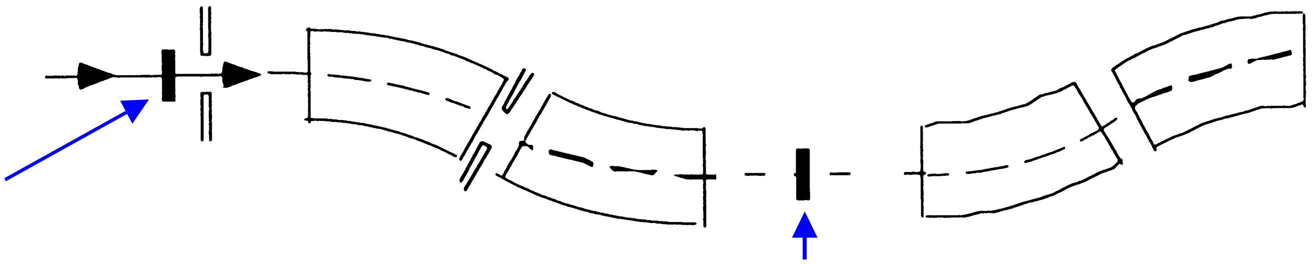


stopping power $S \equiv -\frac{dE}{dx} \propto \frac{Z^2}{v^2} \propto \frac{A\,Z^2}{E}$

→ straggling (spread) in energy and angle

# Momentum-loss achromatic fragment separator

example: FRS @ GSI



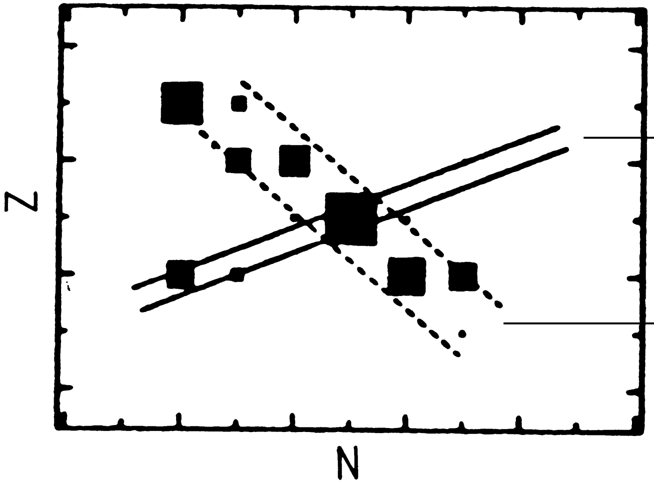
**A/Z separation**

**momentum loss separation**

**target**
**q=Ze**
**~constant v**

**energy degrader**
***non-Liouvillean optics***

$$\left(B\rho\right)_1 \propto \frac{Z+N}{Z} \qquad v_2^2 = v_1^2 - d\,\frac{Z^2}{Z+N} \qquad v_2 = v_1\,\frac{\left(B\rho\right)_2}{\left(B\rho\right)_1}$$



$(B\rho)_1$ Z = a N

$(B\rho)_2$ Z = b - N

# Identification at high energy

## measured quantities

time-of-flight (TOF) $T = \frac{L}{v}$

total energy $E = \frac{1}{2} m\, v^2 = \frac{1}{2} K\, A\, v^2$

magnetic rigidity $B\rho = \frac{m\, v}{q} = K\, \frac{A\, v}{q}$

energy loss $\Delta E \propto \frac{A\, Z^2}{E}$

## relationships

$$A = \frac{2}{K}\, \frac{E\, T^2}{L^2}$$

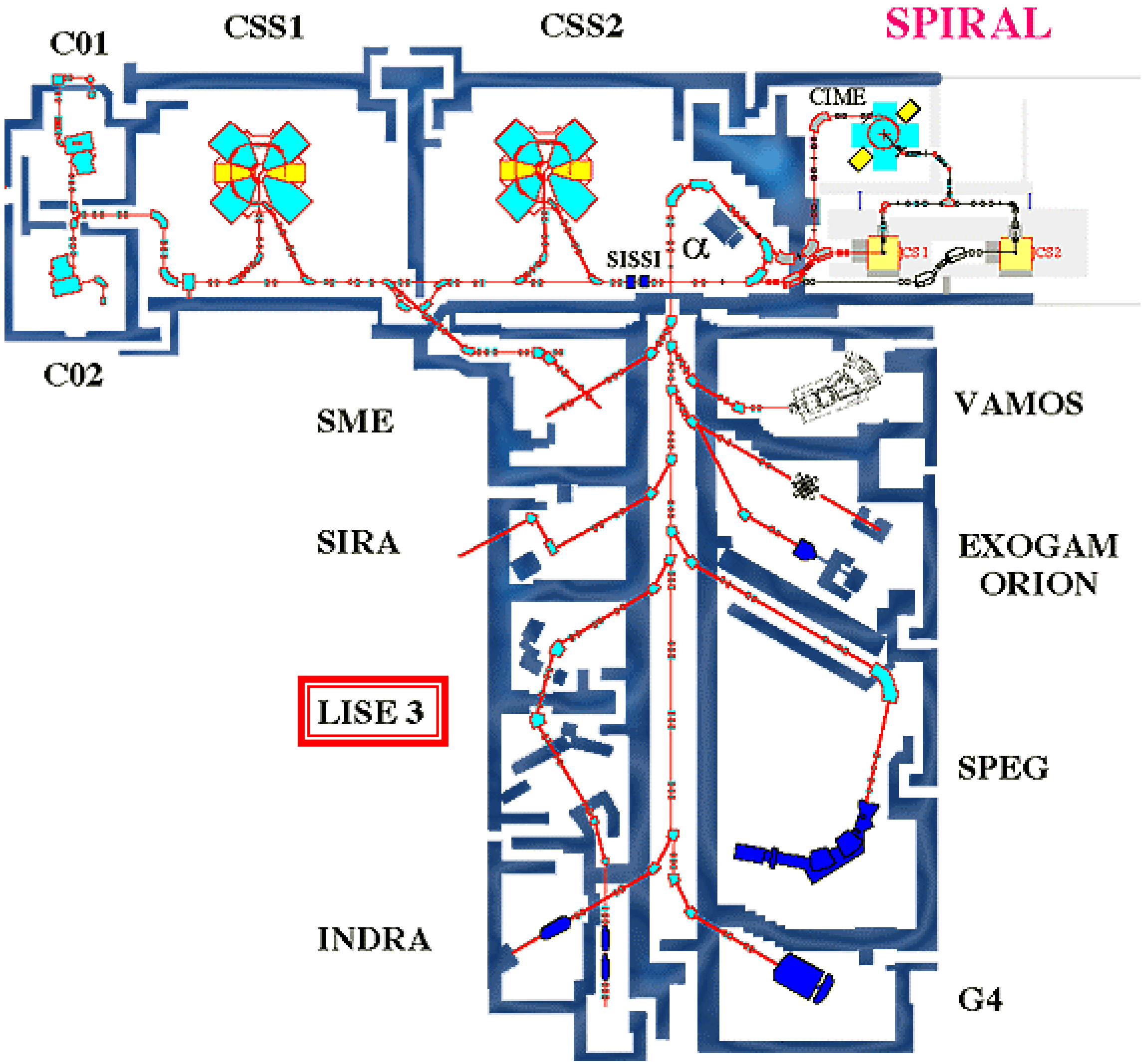
$$\frac{q^2}{A} = 2\, K\, \frac{E}{(B\rho)^2}$$

$$\frac{A}{q} = \frac{1}{K}\, \frac{B\rho\, T}{L}$$

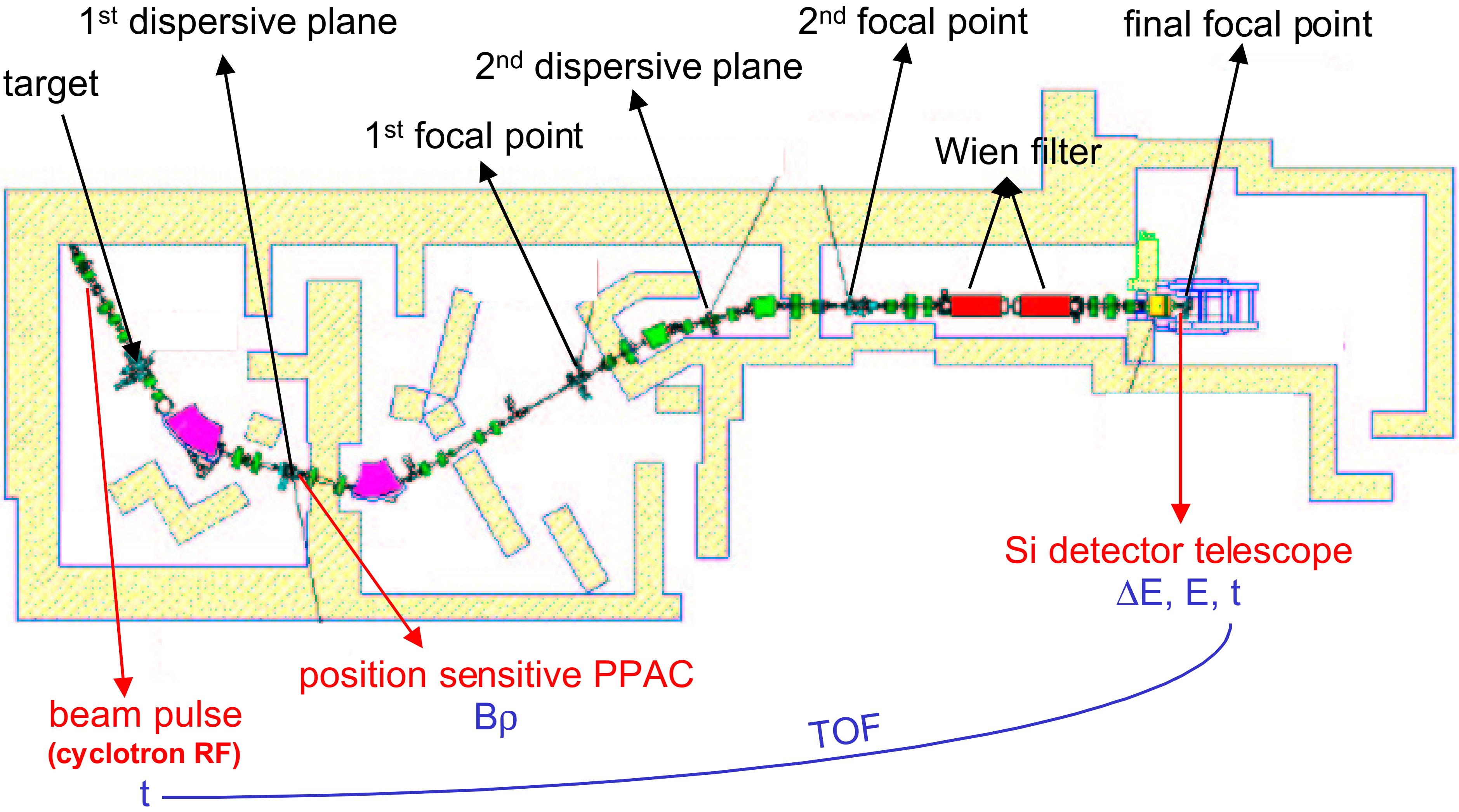
$$q = 2\, \frac{E\, T}{L\, B\rho}$$

A and q are discrete !

# Example: LISE 3 at GANIL



# Example: LISE 3 at GANIL



1st dispersive plane

2nd focal point

final focal point

target

2nd dispersive plane

1st focal point

Wien filter

Si detector telescope

$\Delta E$, E, t

beam pulse
**(cyclotron RF)**
t

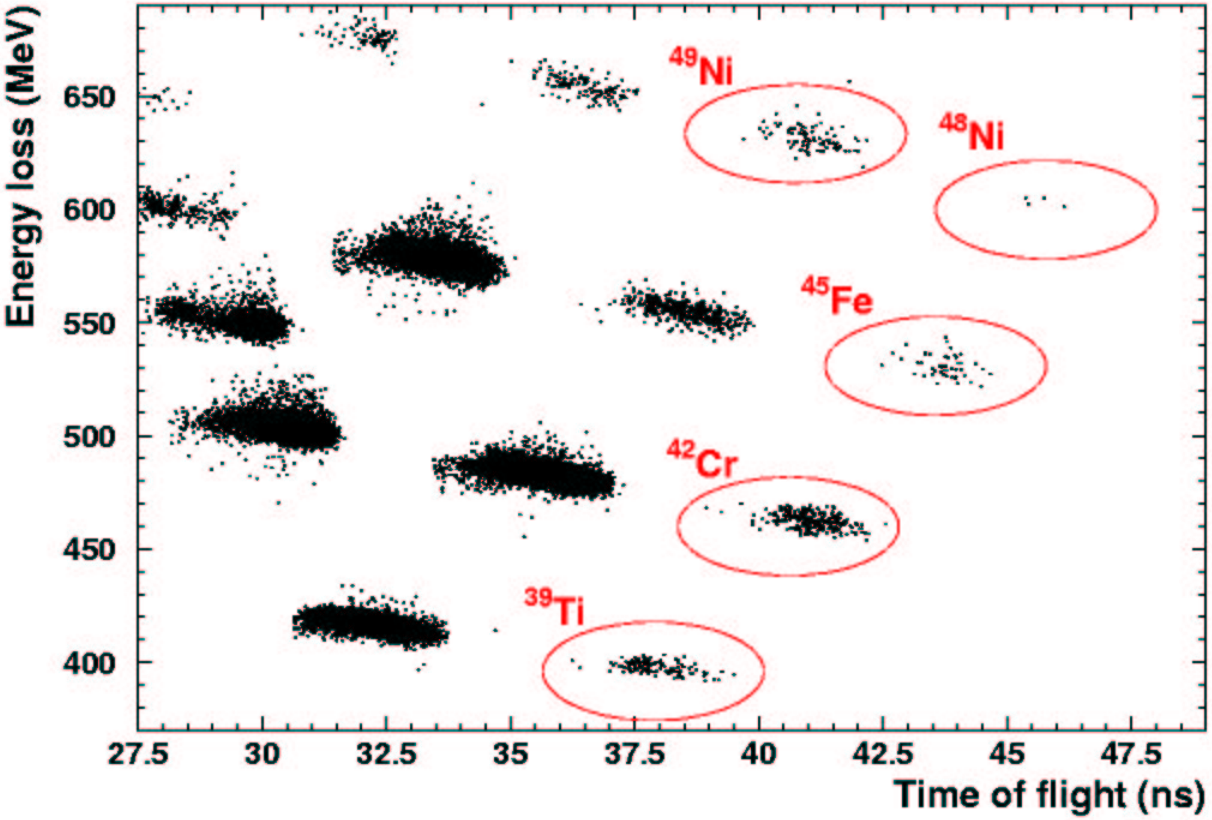
position sensitive PPAC
$B\rho$

TOF

# Identification plot: discovery of $^{48}$Ni

*B. Blank et al., Phys. Rev. Lett. 84 (2000) 1116*

115 pnA 74.5 A MeV $^{58}Ni^{26+}$ + 230 mg/cm$^2$ $^{nat}$Ni



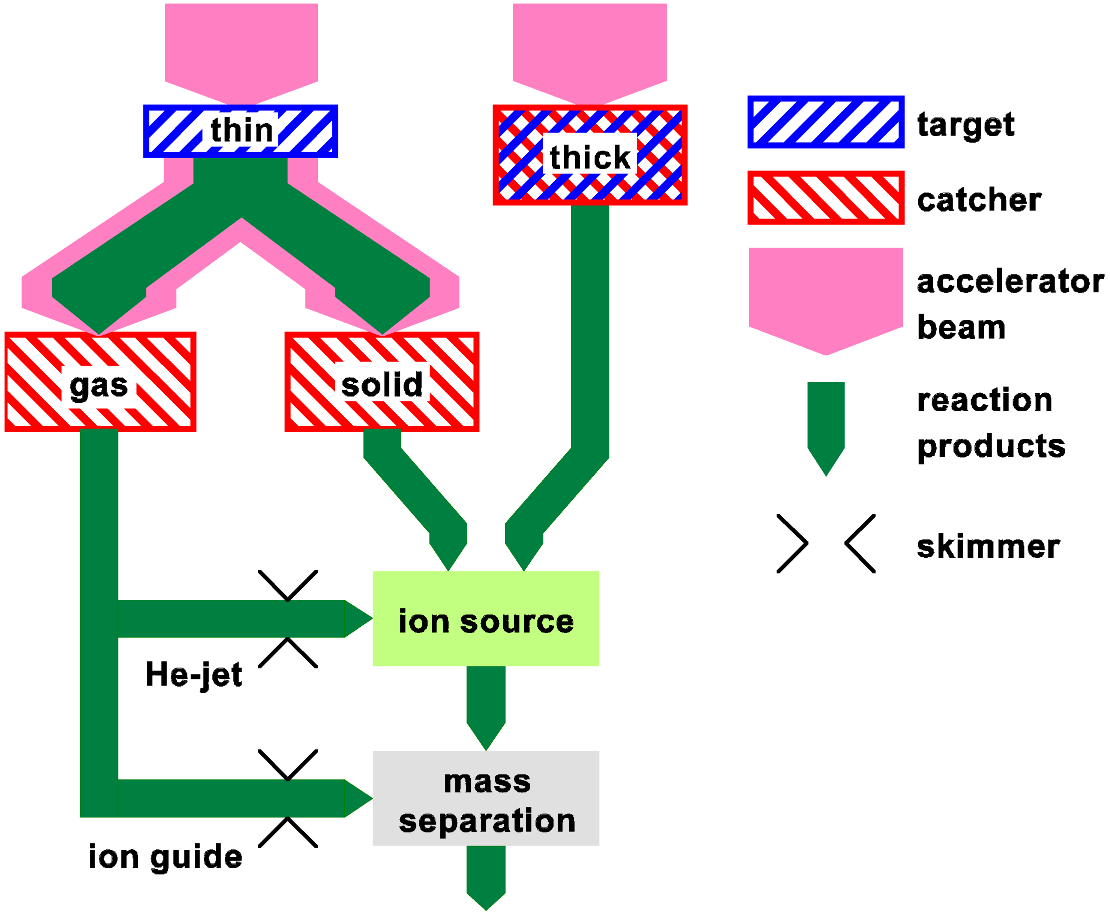
one $^{48}$Ni observed for every $10^{17}$ primary beam particles!

transmission efficiency: 10 % → cross section = 5 $10^{-14}$ b

# Separation at thermal energy: target-ion source systems

## the ISOL method

*Isotope Separator On-Line*



## target-ion "sourcery"

target-ion source systems can have:

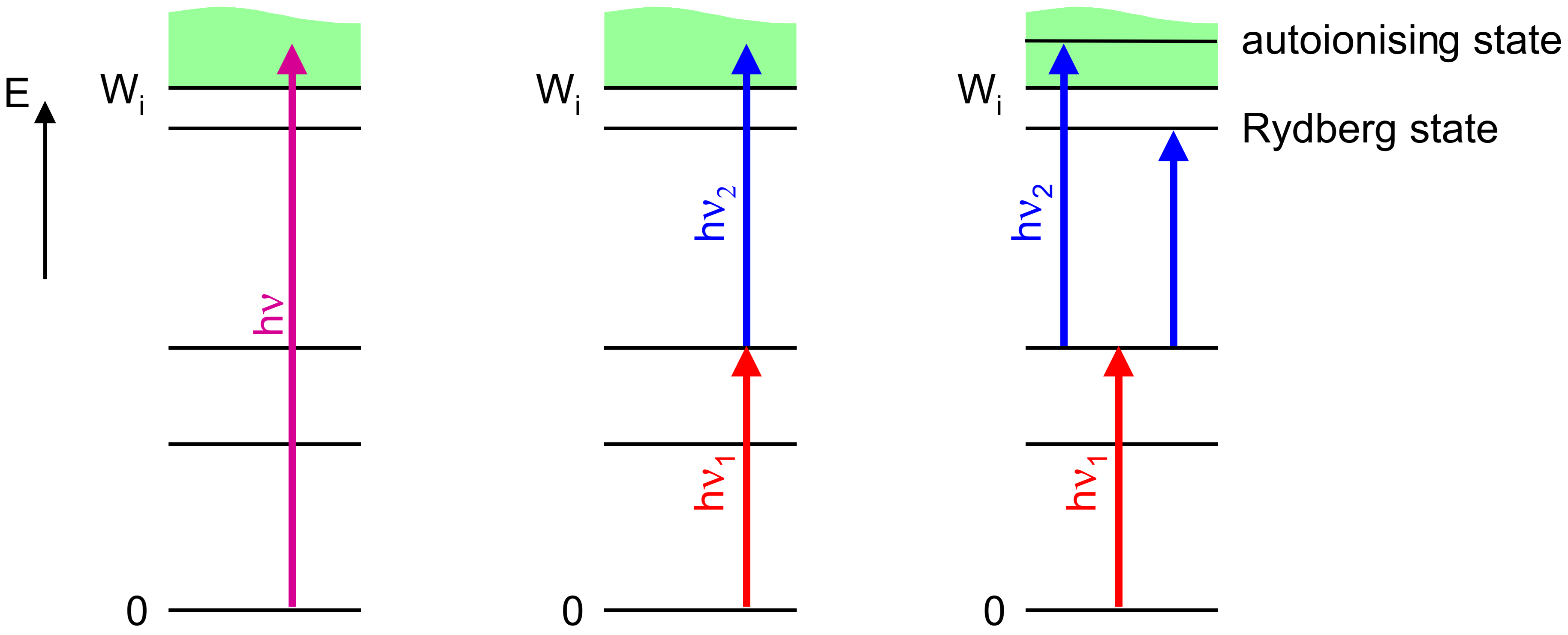
- chemical selectivity
  based on e.g. melting point, diffusion constant, ionization energy, oxidation state in compounds
- isotopic/isomeric selectivity
  laser ionization

# Laser ionization

1 step

2(3)-step

2(3)-step resonant

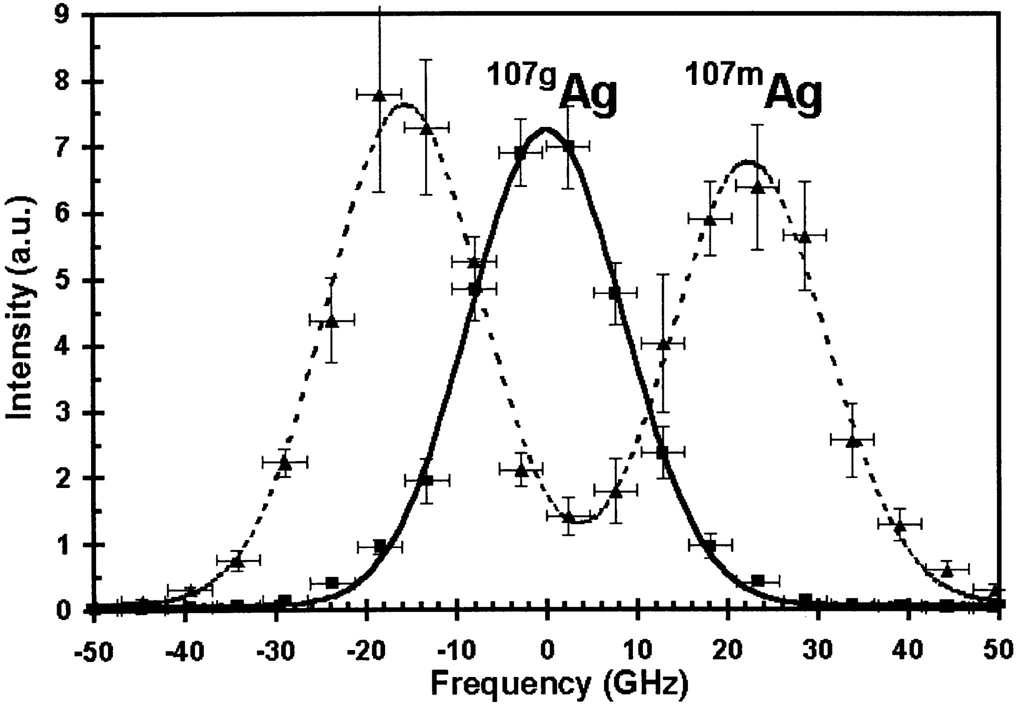


technically not feasible

resonant step gives selectivity
- chemical (=Z)
- isotopic (=Z, ≠A)
- isomeric (=Z, =A, ≠E*)

# Selectivity in laser ionization

|  | $E^*$ (keV) | $T_{1/2}$ (s) | $I^\pi$ |
|---|---|---|---|
| $^{107m}$Ag | 93 | 44 | $7/2^+$ |
| $^{107g}$Ag | 0 | stable | $1/2^-$ |



*ISOLDE-CERN*

# Manipulation of radioactive ions

## manipulation of ion group properties

| | *beam, cloud* |
|---|---|
| • energy | *energy degrading*<br>*stopping, trapping*<br>*acceleration* |
| • energy spread | *cooling, trapping* |
| • emittance | *cooling* |
| • size | *cooling, trapping* |
| • time structure | *pulsing*<br>*bunching* |

"ion beam cooler"
(gas-filled RF quadrupole)

## manipulation of ion properties

| | |
|---|---|
| • charge state | *ionization* |
| • ionic/atomic state | |
| • spin direction | *alignment*<br>*polarization* |

"charge breeder"
(ECRIS & EBIS)

# Ion beam cooler: principle

- reducing beam size, emittance, energy spread
- storing
- bunching

**the output does not depend on the input !**

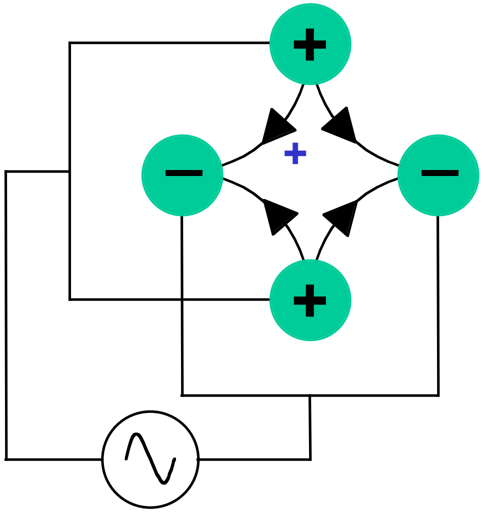
**principle**

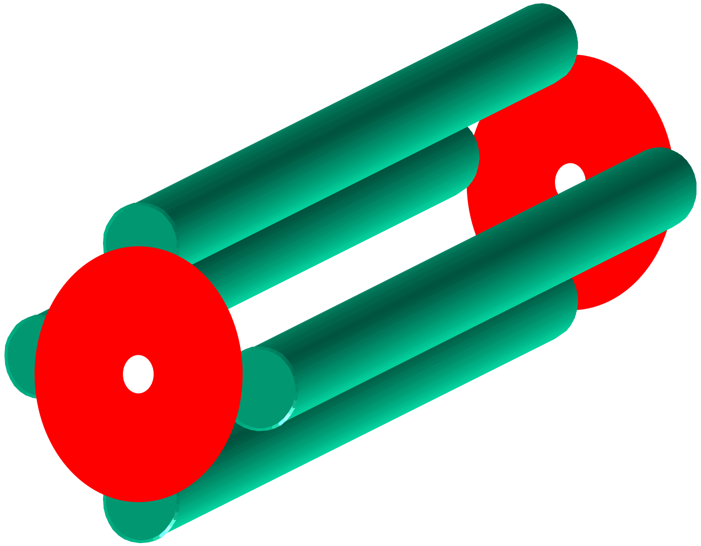
reducing energy spread:

thermalization in (helium) gas

confinement by electric fields

- RF multipole
- end electrodes



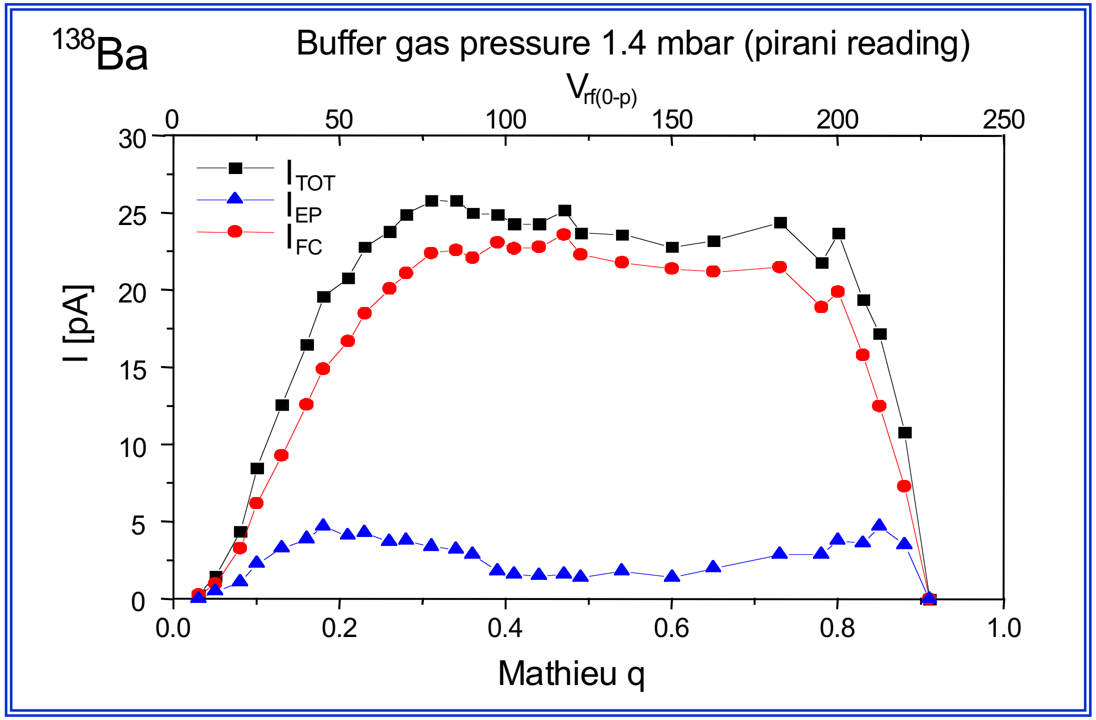


# Ion beam cooler: RF confinement

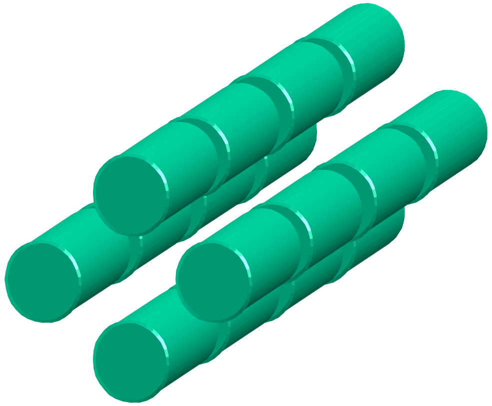
Mathieu parameter

$$q = \frac{4\ Q\ V_{RF}}{m\ r_0^2\ \Omega_{RF}^2}$$

Ion motion is stable when 0 < $q$ < 0.91

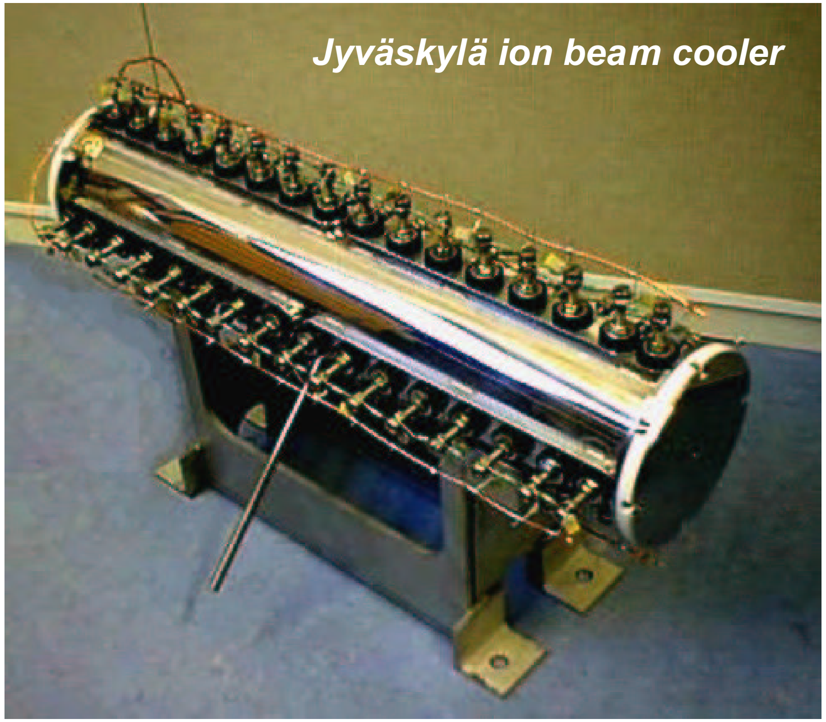


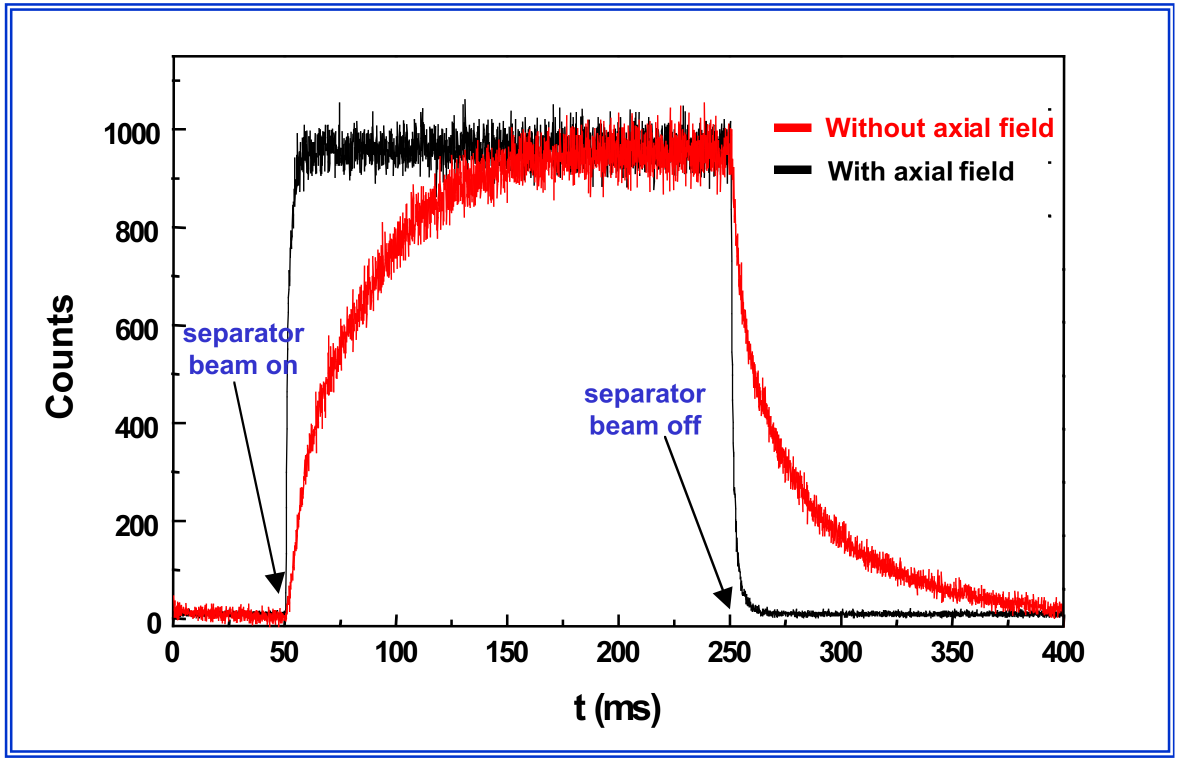
# Ion beam cooler: axial field



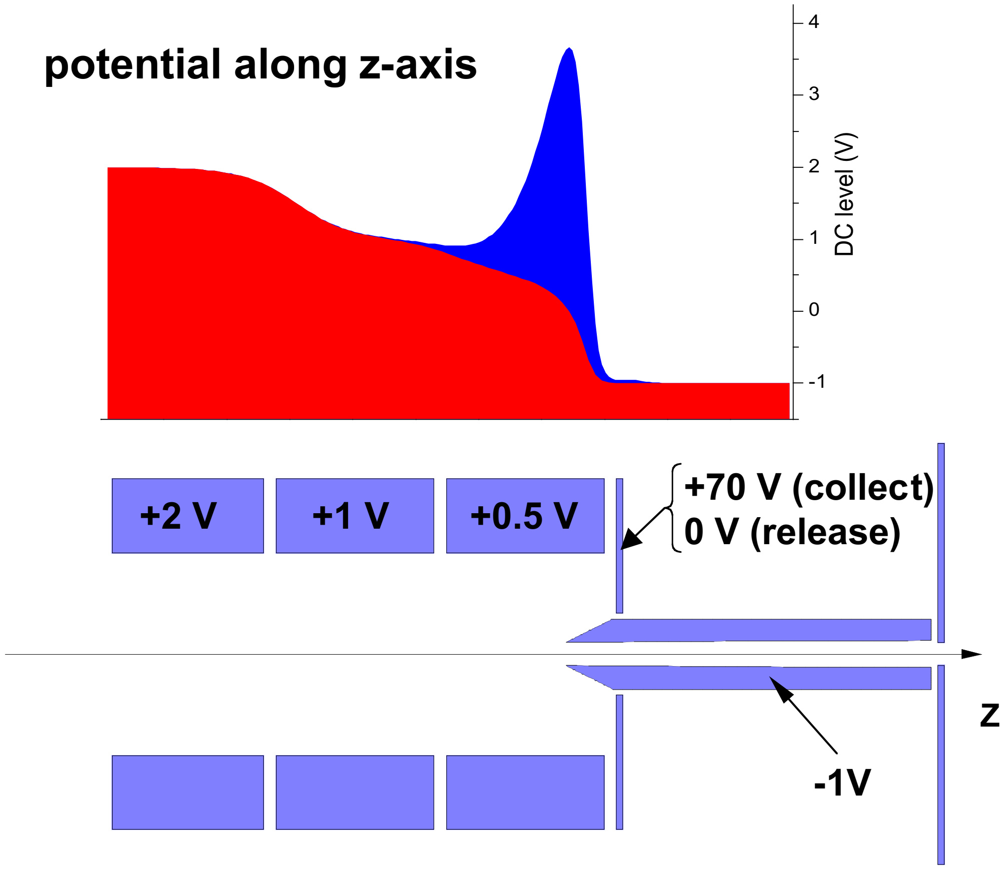
axial field due to segmentation of quadrupole rods

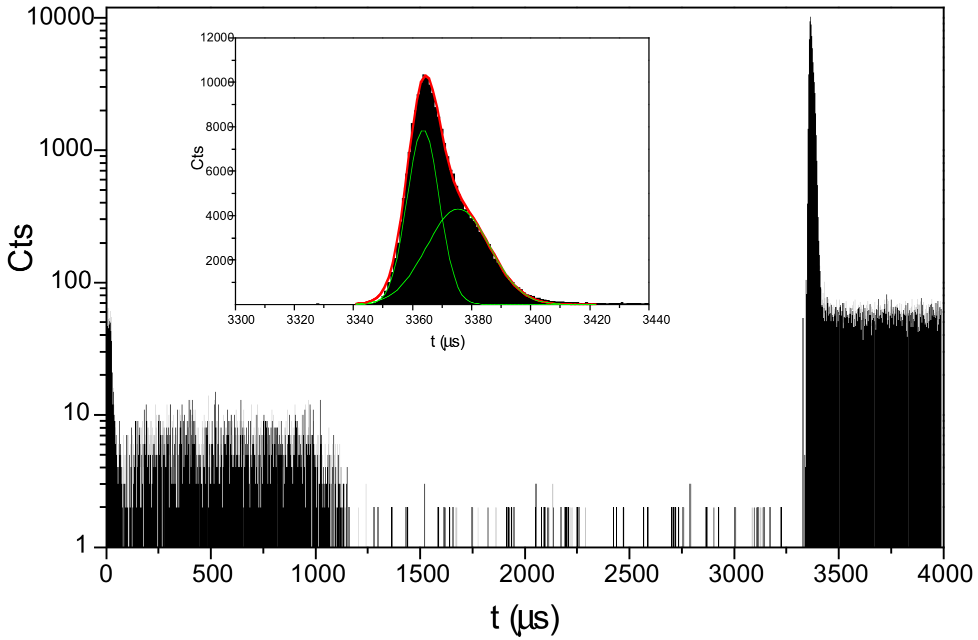
- speeds up transmission
- allows storing and bunching





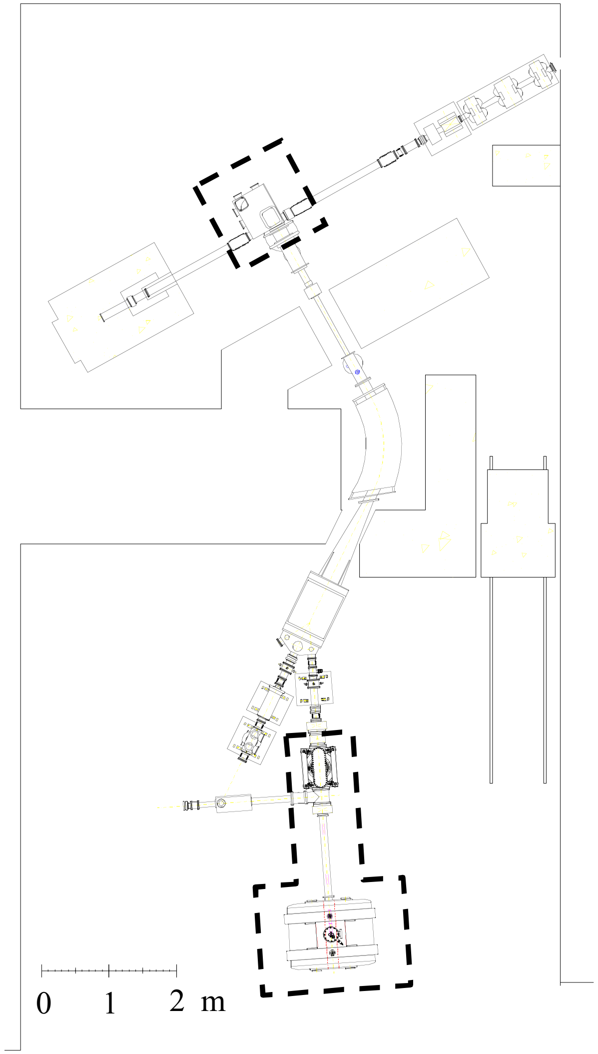
# Ion beam cooler: storing and bunching

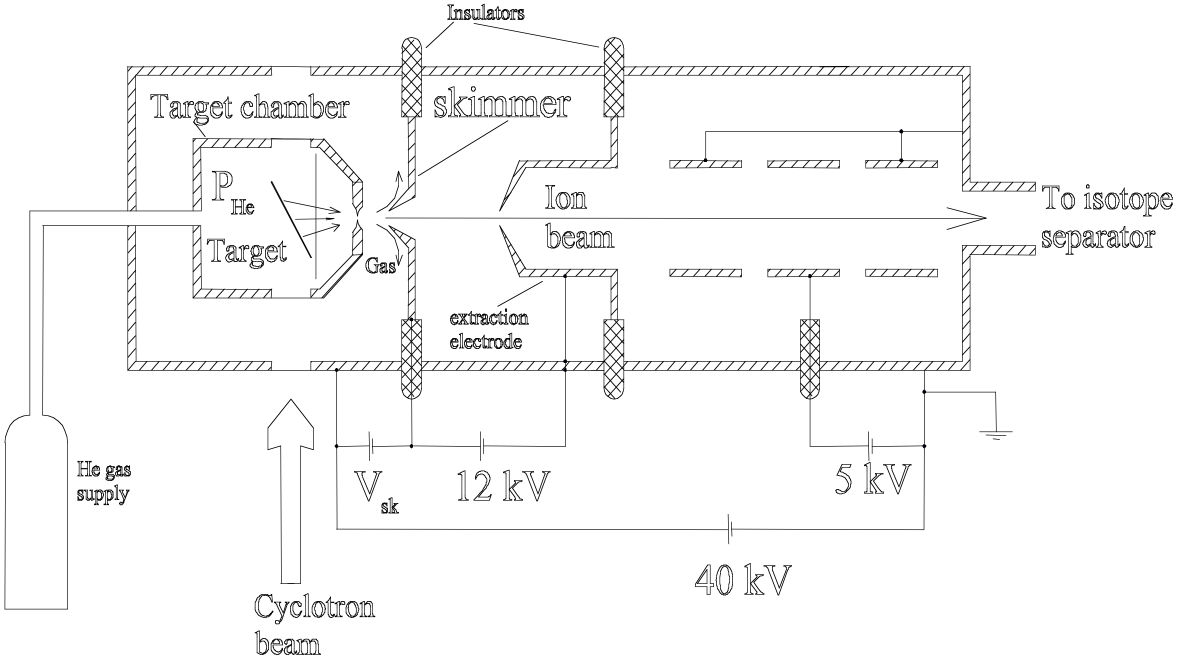




- separator beam on: t = 0 - 1000 μs
- cooler end plate voltage down t: = 3300-4000 μs

# The Jyväkylä IGISOL facility





## Specific features

- fast (sub ms)
- chemically non-selective
  → **access to all elements including refractory metals**

maximum yield
↑↓
high energy spread
⇓
on-line cooler-buncher

# Charge state breeding: basics

## What ?

from singly charged to multiply charged ions

" $1^+ \rightarrow n^+$ "

## Why ?

post-acceleration

$$E = q\,V \qquad \left(\text{cyclotron}: \; E = K\,\frac{q^2}{A}\right)$$

## In principle

electron impact stepwise ionization

### requirements

1) high enough electron energy

2) suitable combination of:
    - ionization time (→ confinement)
    - high electron density
    - good vacuum

## In practice

ECRIS

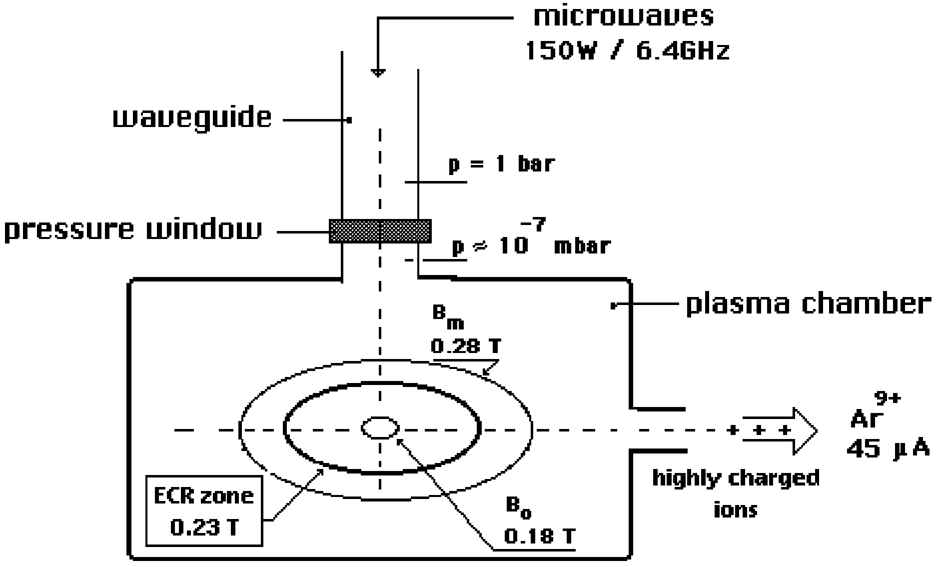
*electron cyclotron resonance ion source*

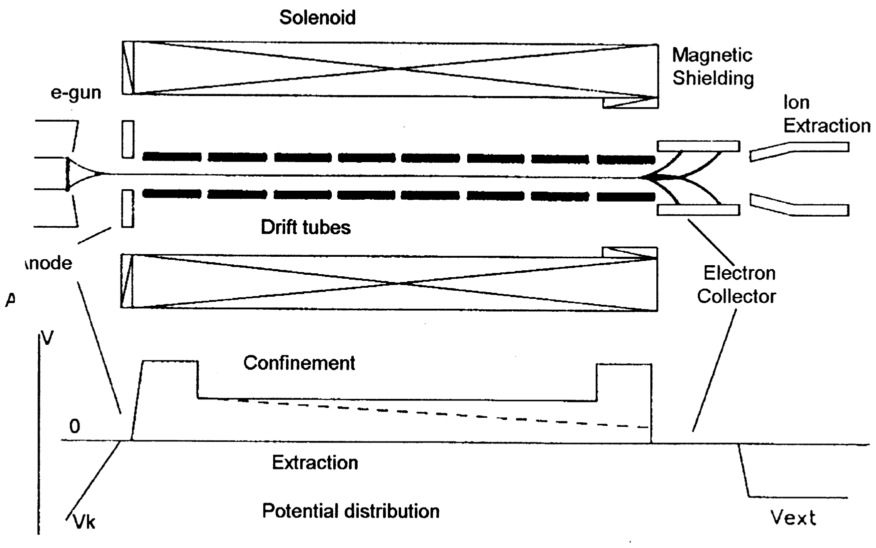
EBIS

*electron beam ion source*

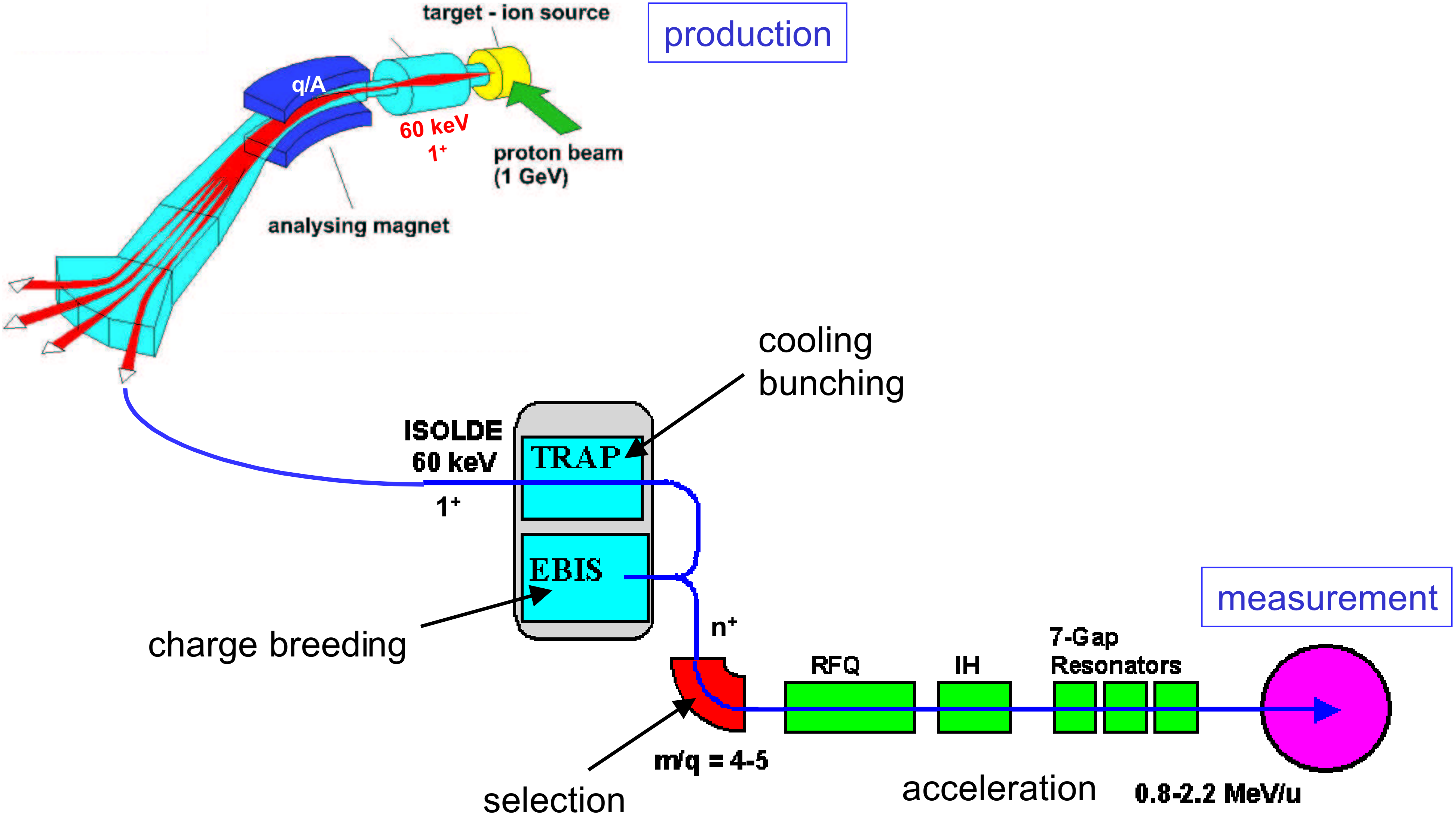
# Charge state breeding: ECRIS vs. EBIS

| | **ECRIS**<br>*Electron Cyclotron Resonance Ion Source* | **EBIS**<br>*Electron Beam Ion Source* |
|---|---|---|
| confinement | magnetic bottle / e$^-$-ion plasma<br>**minimum-B field**<br>**axial: solenoid, radial: multipole** | electrostatic / ions<br>**axial: potentials on drift tubes**<br>**radial: electron beam space charge** |
| electron energy | microwaves | electron gun |





# REX-ISOLDE



production

cooling
bunching

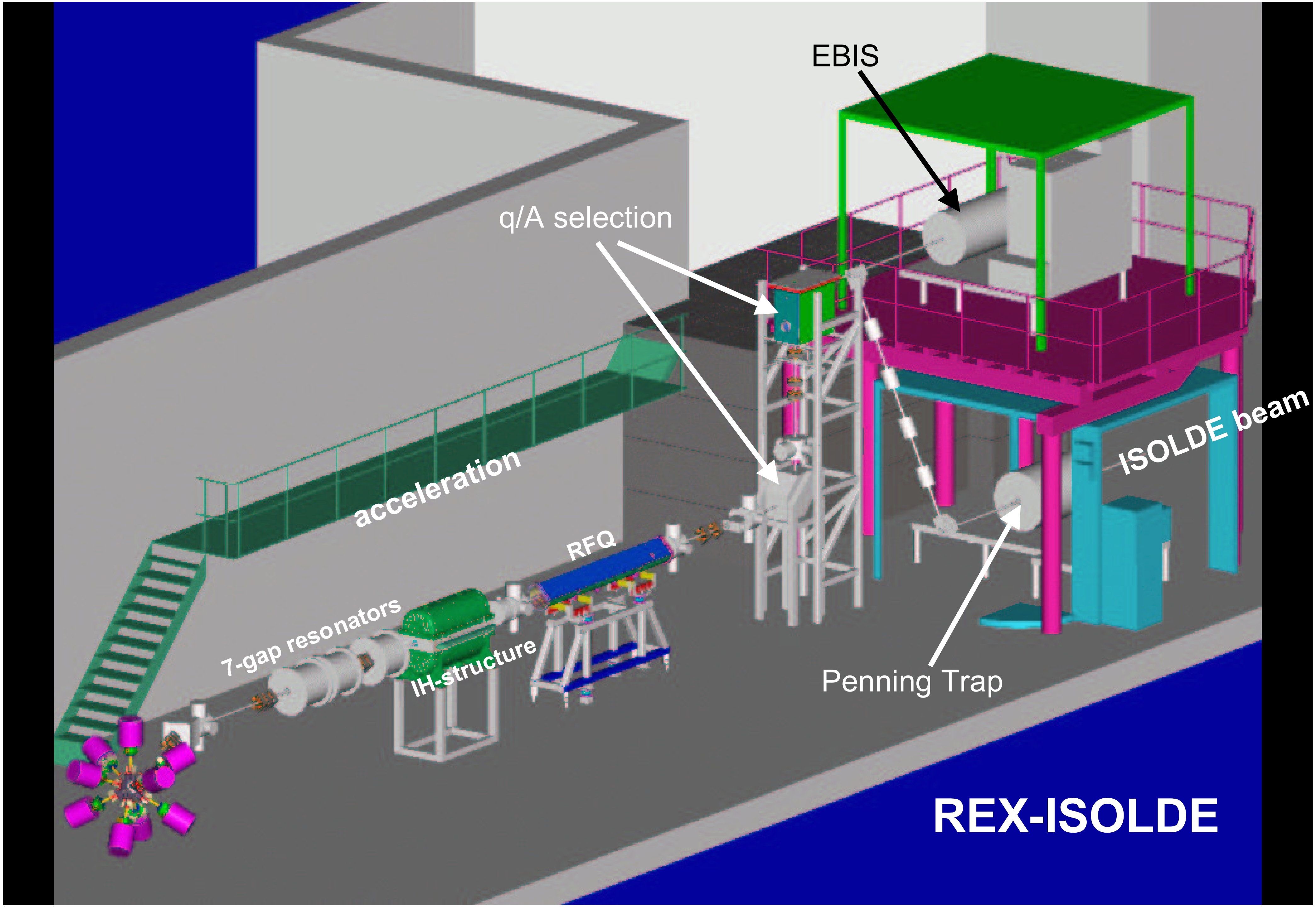
charge breeding

selection

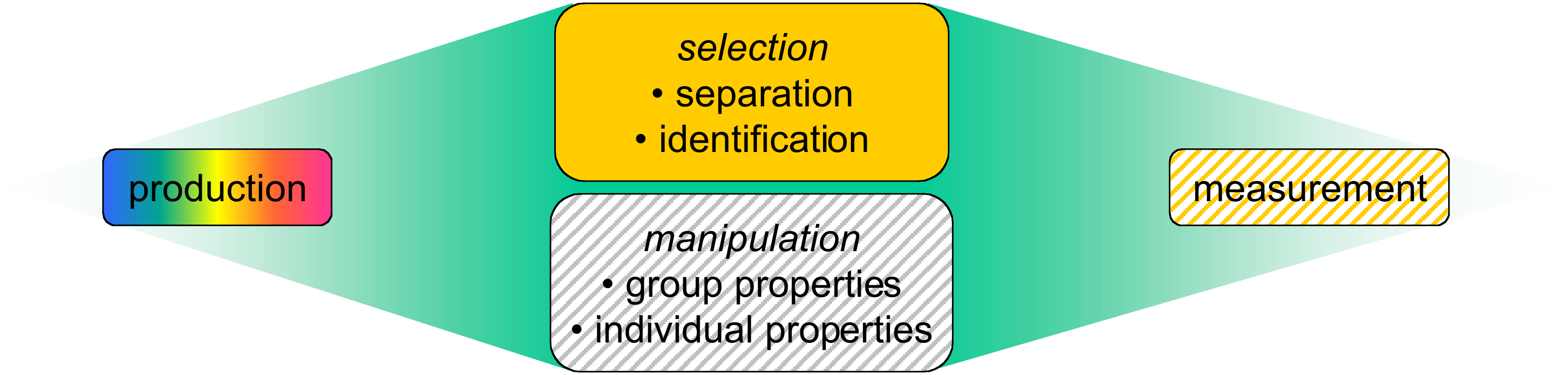
acceleration

measurement

# REX-ISOLDE


EBIS
q/A selection
ISOLDE beam
acceleration
RFQ
Penning Trap
7-gap resonators
IH-structure

# Summary



production

*selection*
- separation
- identification

*manipulation*
- group properties
- individual properties

measurement

many “building blocks” are available

studying exotic nuclei requires a clever combination of several building blocks

has to be fast and efficient !