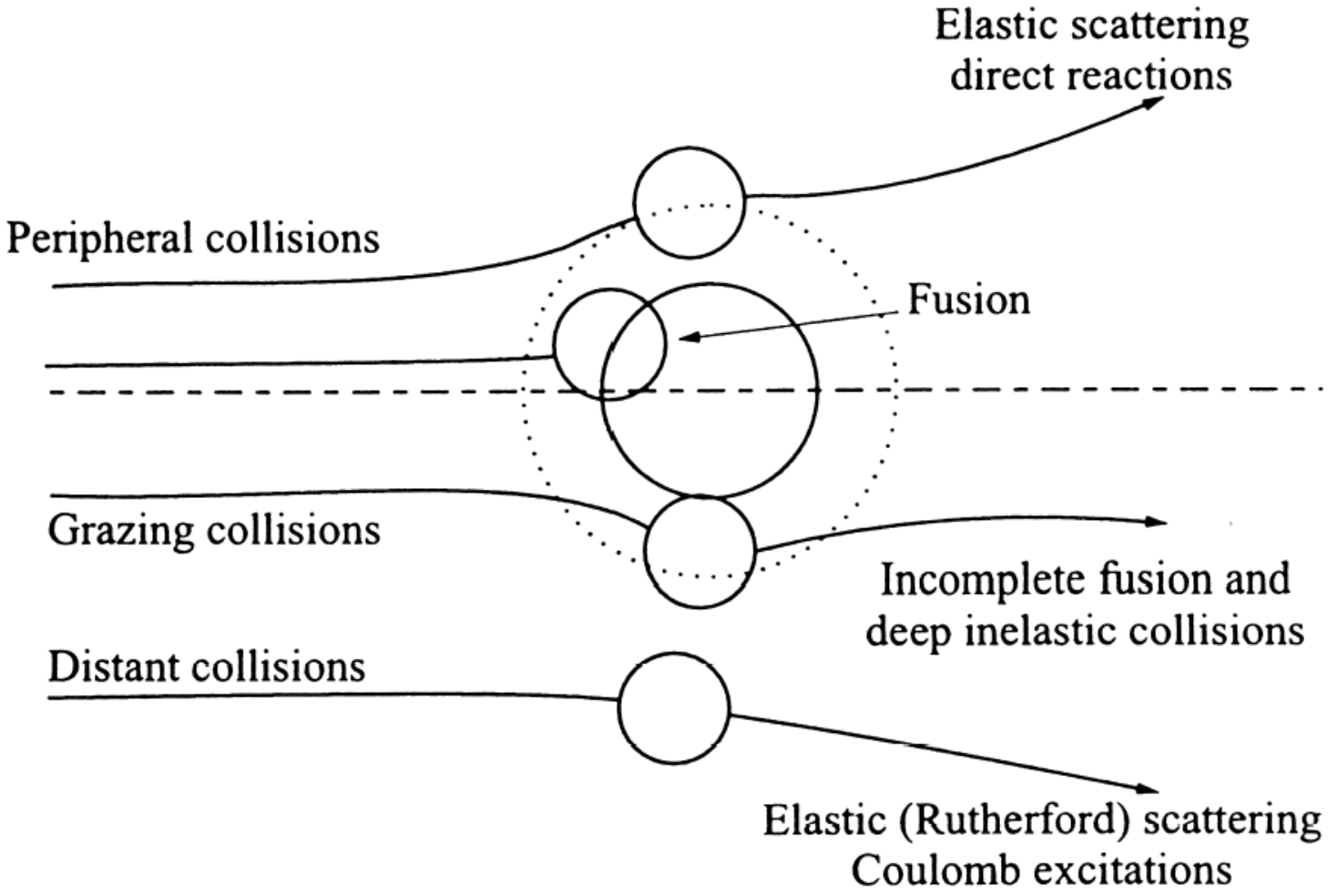
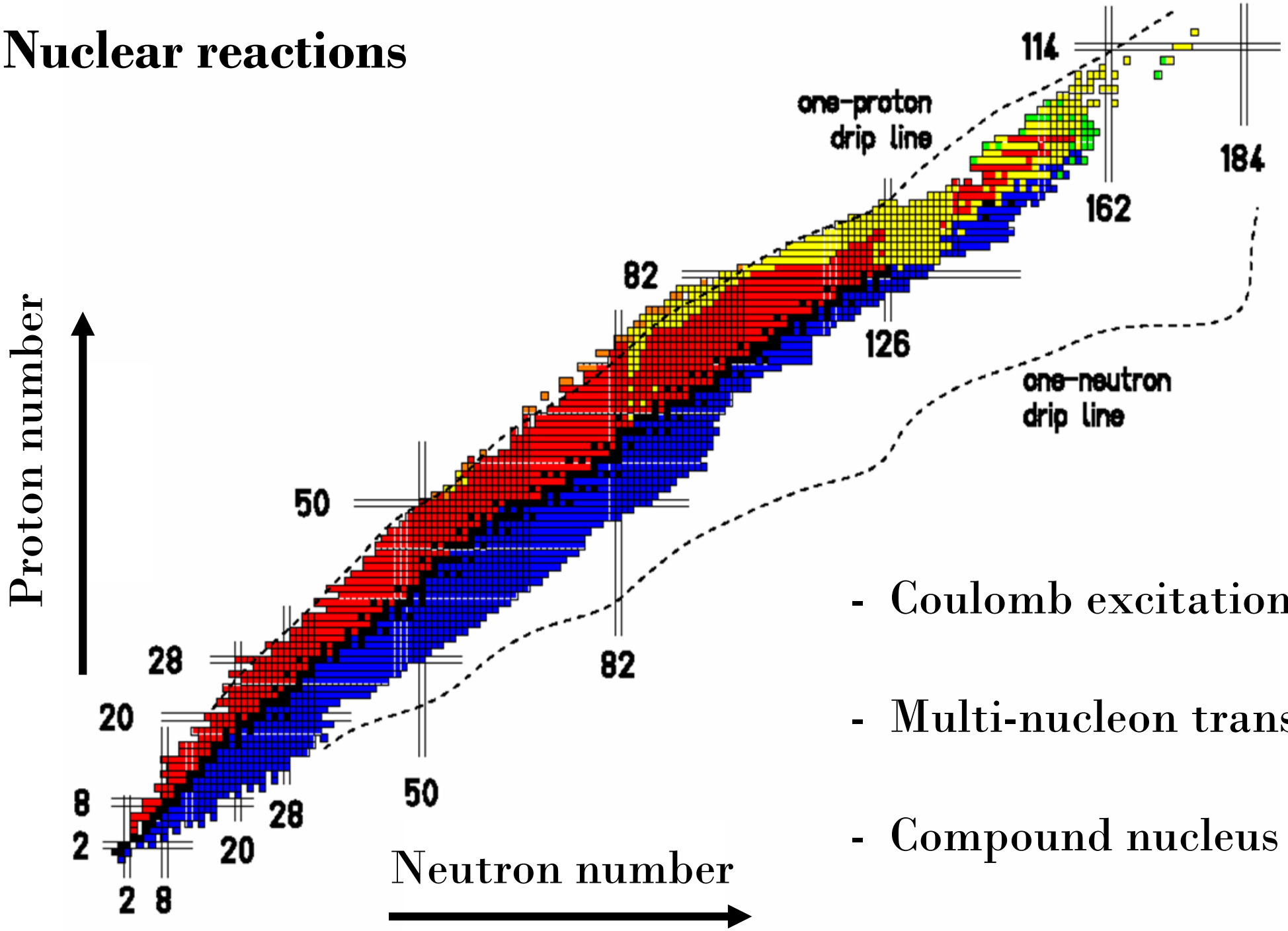
Classification of nuclear reactions around Coulomb barrier

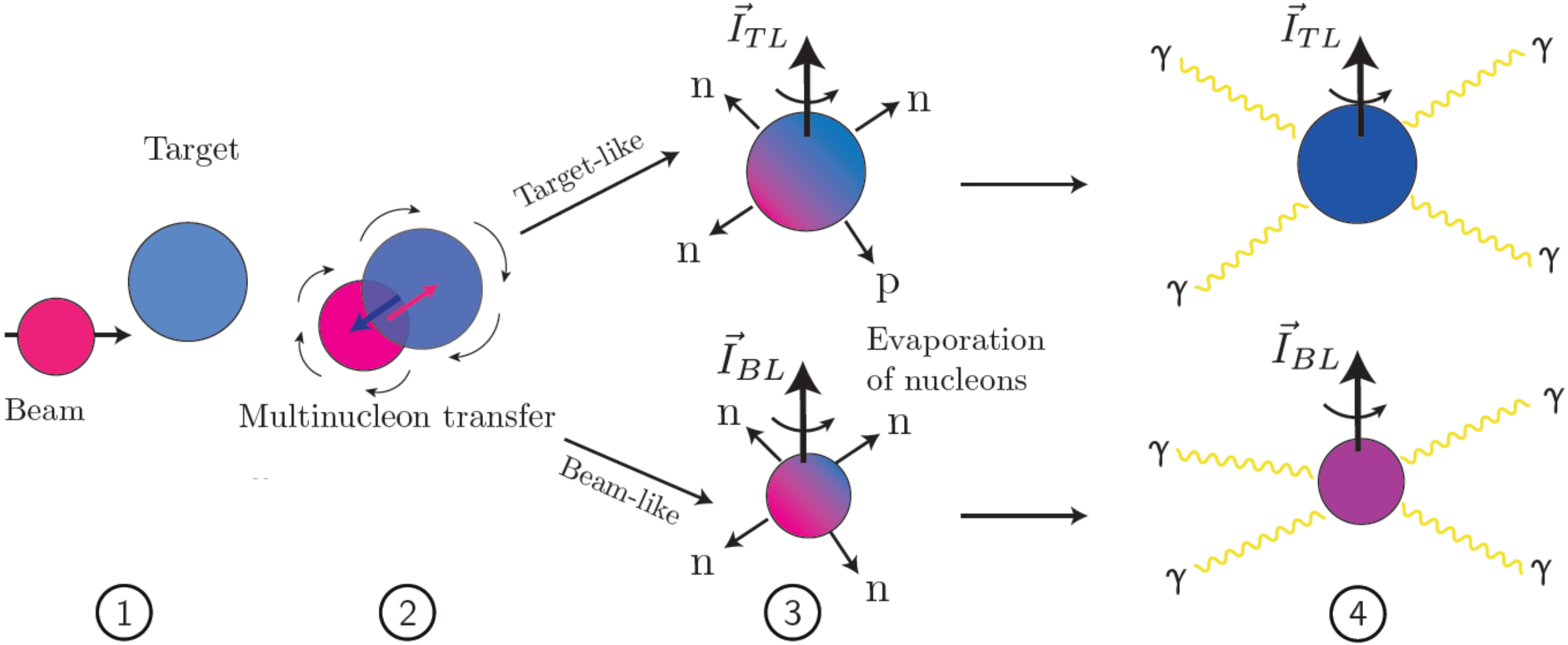


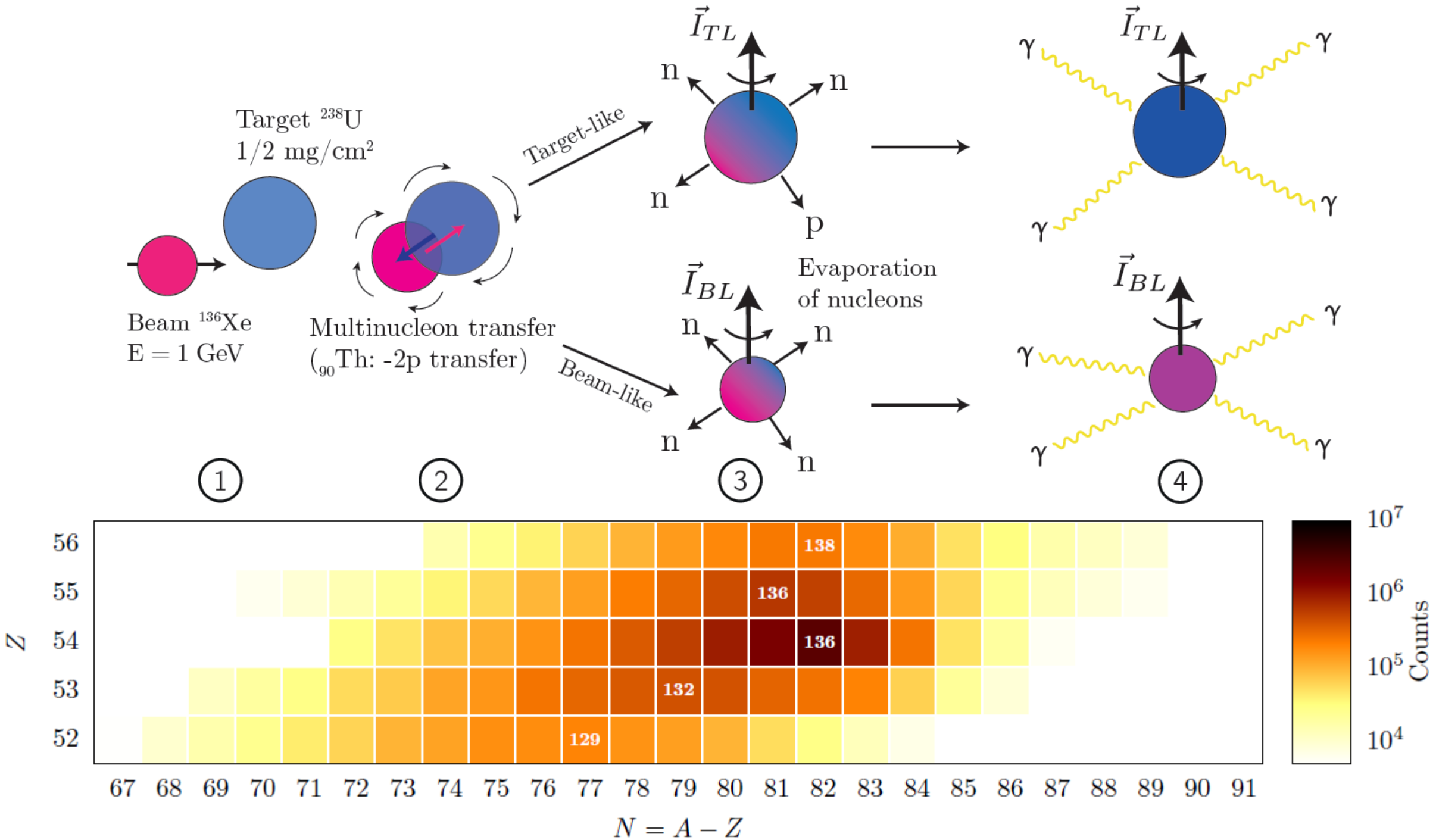
Nuclear reactions

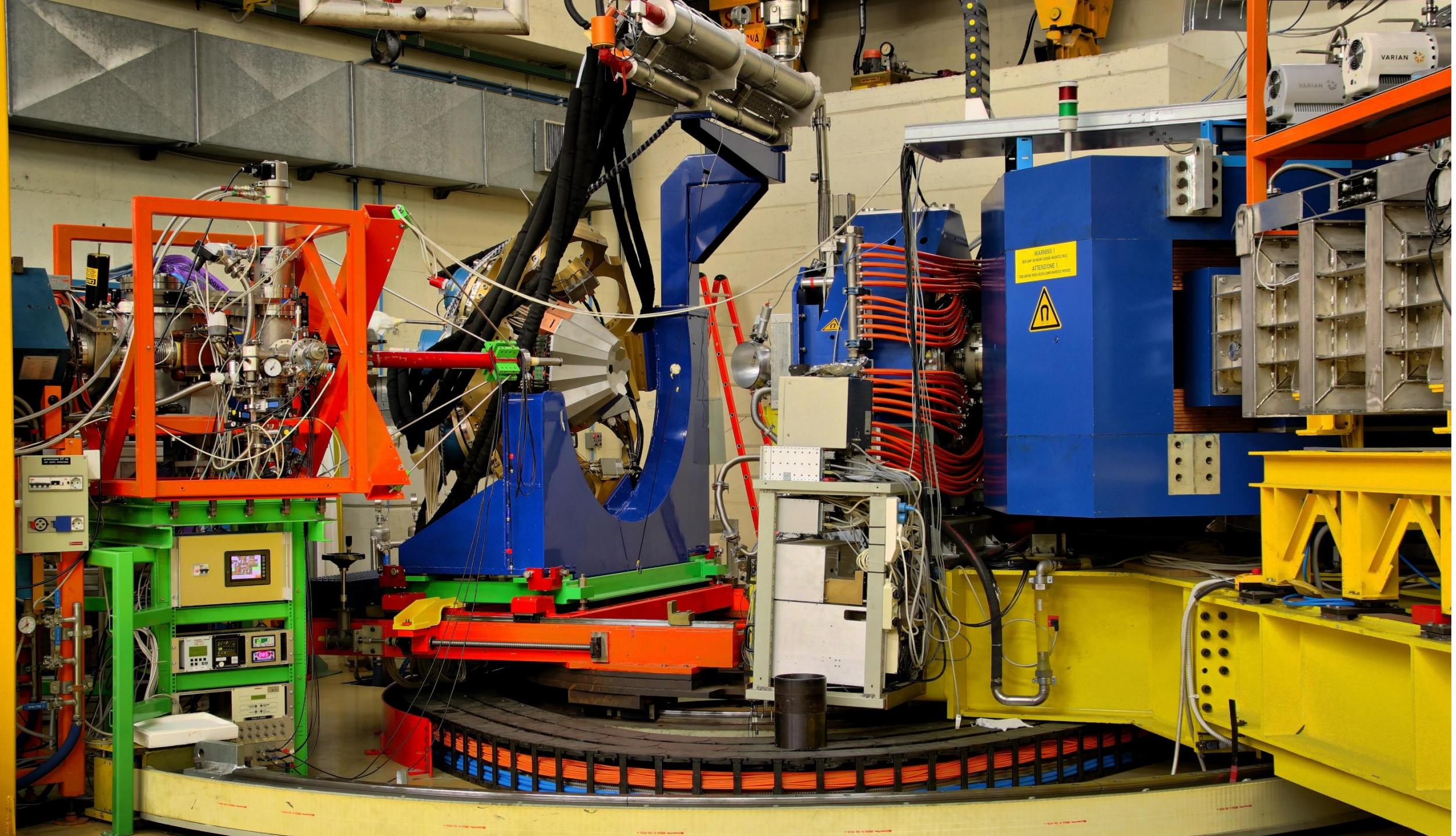


- Coulomb excitation
- Multi-nucleon transfer reaction
- Compound nucleus reaction

Multi-nucleon Transfer




Target ^{238}U
1/2 mg/cm^2
Beam ^{136}Xe
E = 1 GeV
Multinucleon transfer
($_{90}$Th: -2p transfer)
Target-like
Beam-like
$\vec{I}_{TL}$
$\vec{I}_{BL}$
n
p
γ
Evaporation
of nucleons
1
2
3
4
Z
N = A − Z
Counts
138
136
136
132
129

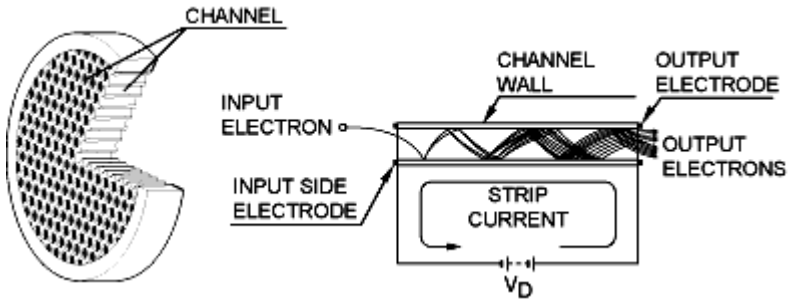

WARNING !
ATTENZIONE !
VARIAN

Magnet spectrometer PRISMA

- large solid angle (80 msr)
- large momentum acceptance (+/-10%)
- high mass resolution (1/300)
- high energy resolution (1/1000)

National laboratory Legnaro, Italy (LNL)

PRISMA - MCP

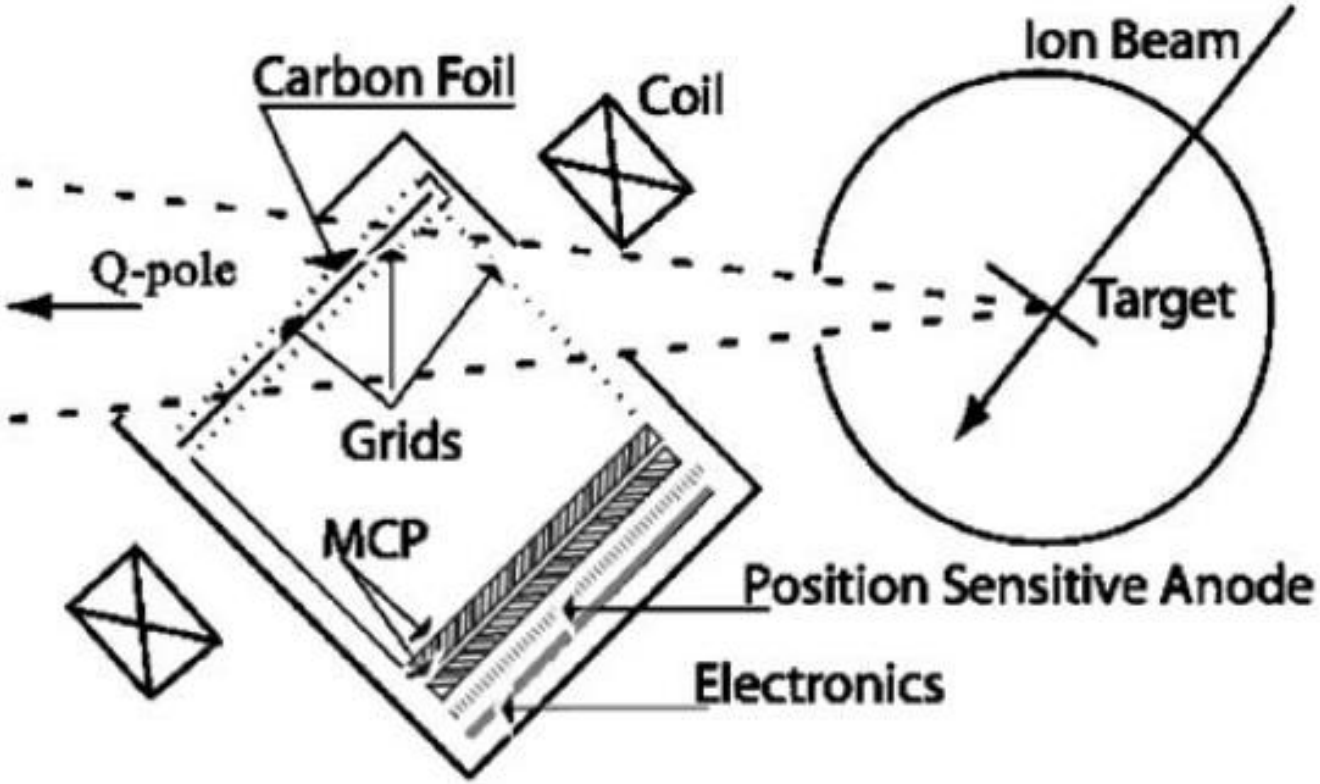


Micro Channel Plate (MCP)

- Electron multiplier high gain (10^6 – 10^8)
- 10^7 micro channels
- diameter 10 μm

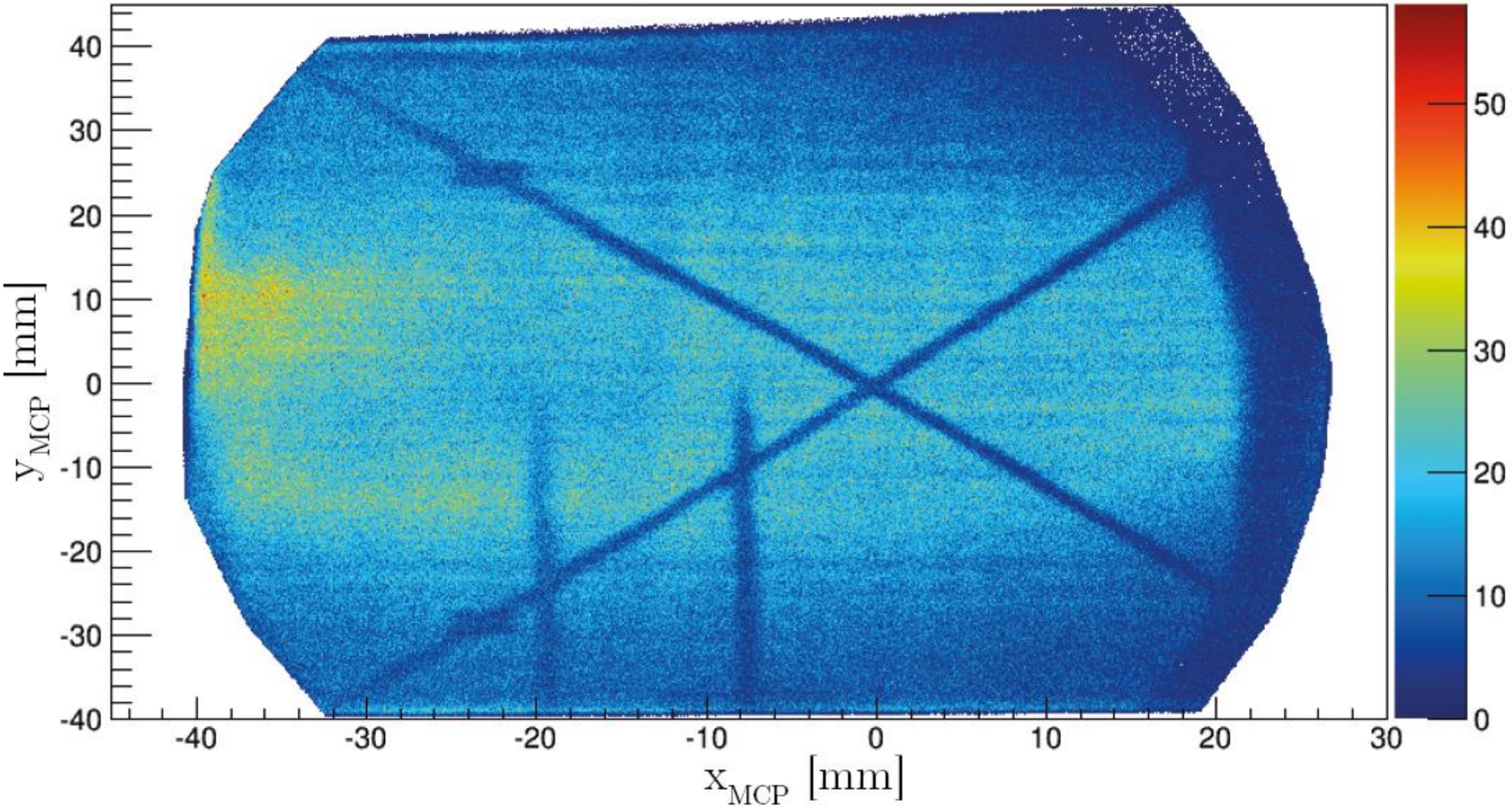
MCP performance

- position resolution (≤ 1 mm)
- timing (≤ 400 ps)
- Large area (80x100 mm^2)

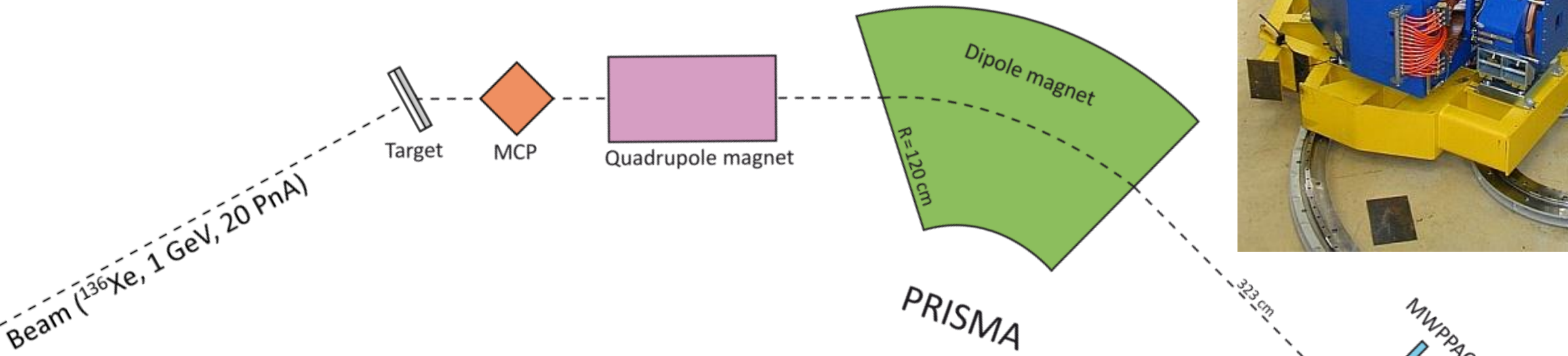


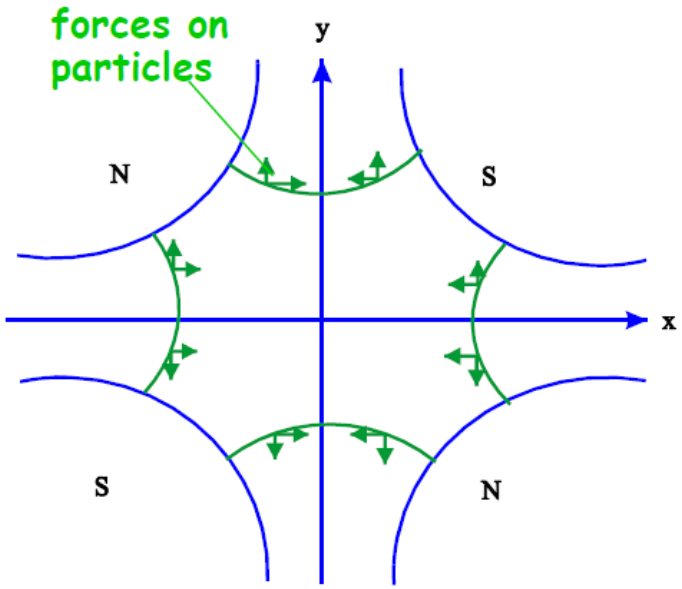
- 3 grids
- Thin carbon foil (20 μg/cm^2) at -2300 V

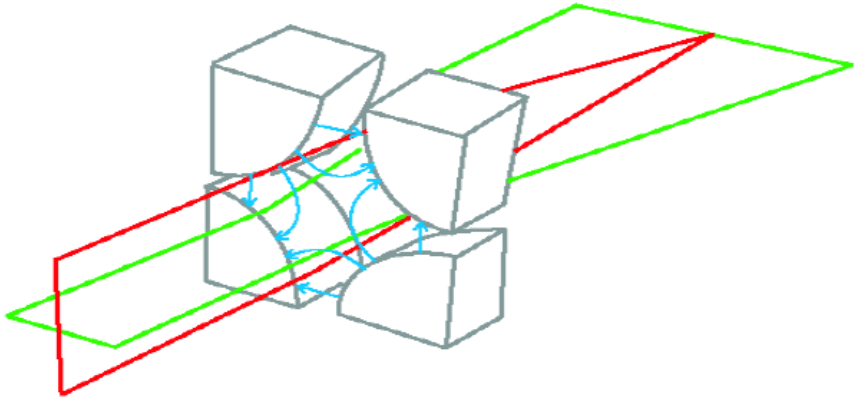
PRISMA - MCP


40
30
20
10
0
-10
-20
-30
-40
y_{MCP} [mm]
-40
-30
-20
-10
0
10
20
30
x_{MCP} [mm]
50
40
30
20
10
0

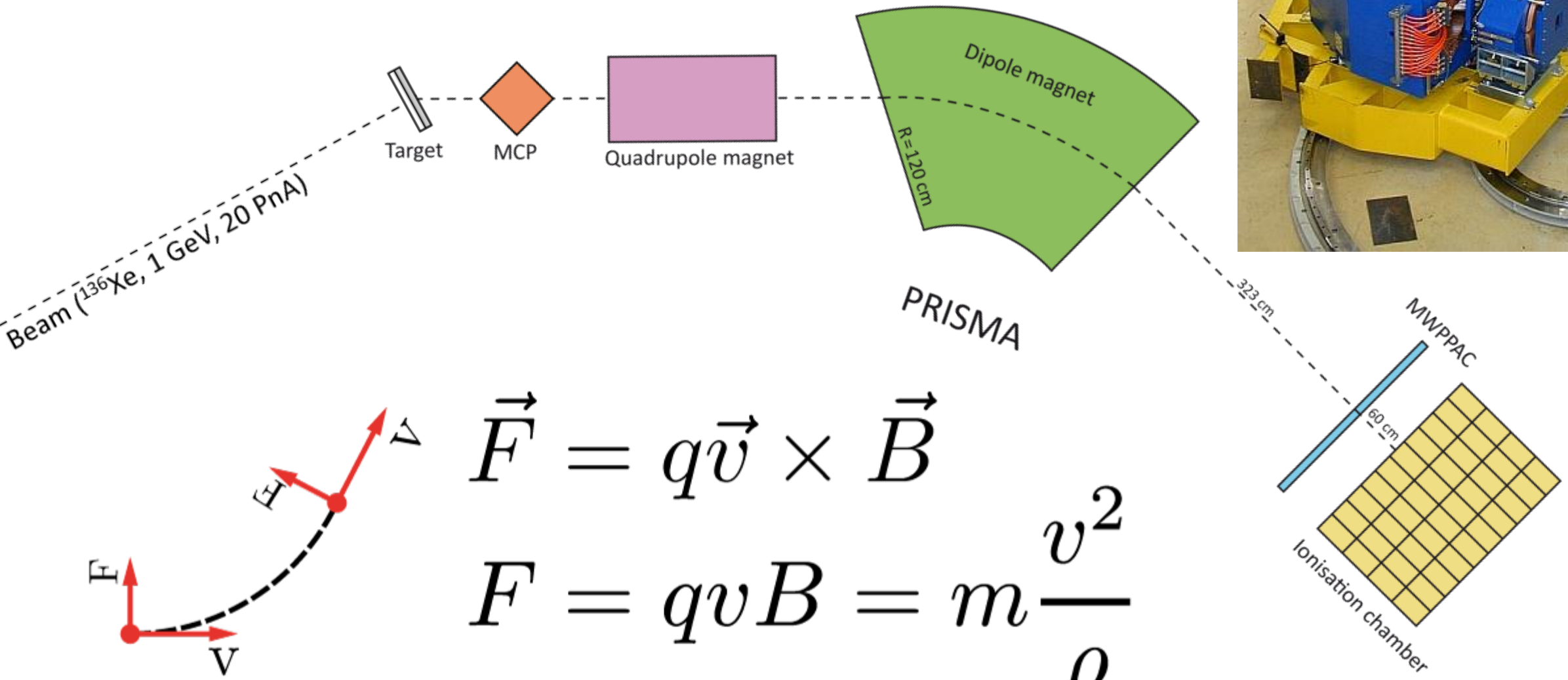
PRISMA - Quadrupol







PRISMA - Dipol



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

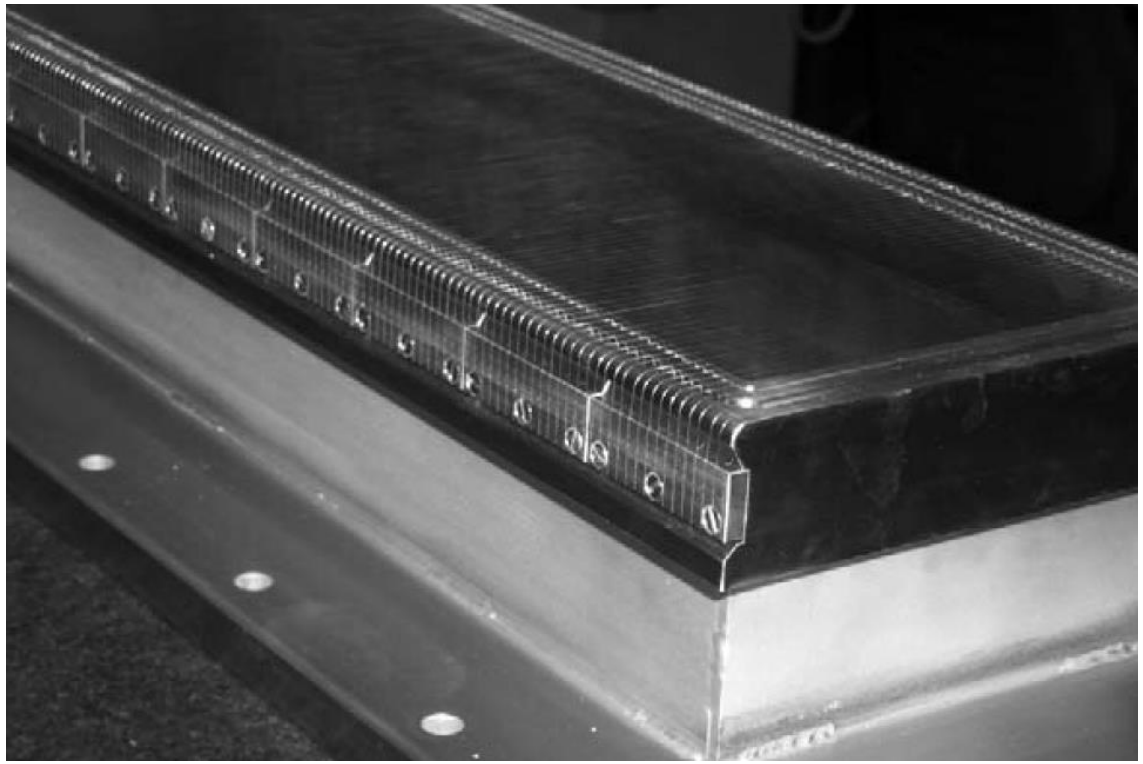
$$F = qvB = m\frac{v^2}{\rho}$$

PRISMA - MWPPAC
Multi Wire Parallel Plate Avalanche Counter

- Active area 1 m x 13 cm
- Structure with 3 electrodes:
  - centrale cathode (3300 gold coated tungsten wire, 20 µm, 300 µm distance, 500 – 600 V)
  - X-plane (10 sections with 100 wires, 1mm pitch)
  - Y-plane (130 wires, 1 m length, 1 mm pitch)

- Counting gas C_4H_{10} (Butan) at ~ 7mbar

PRISMA - MWPPAC
Multi Wire Parallel Plate Avalanche Counter

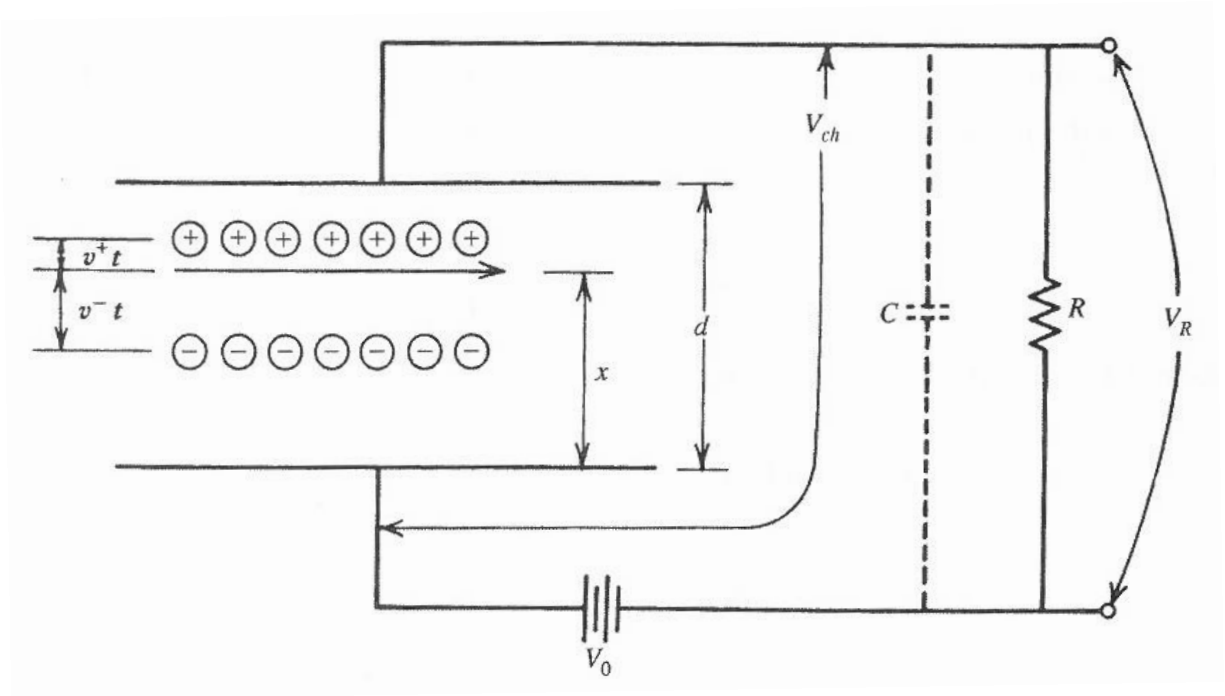


- Gas ionisation
- Electrons and ions are collected at anode and cathode
- High field strength close to wire
- Avalanche effect cause high signal amplitude

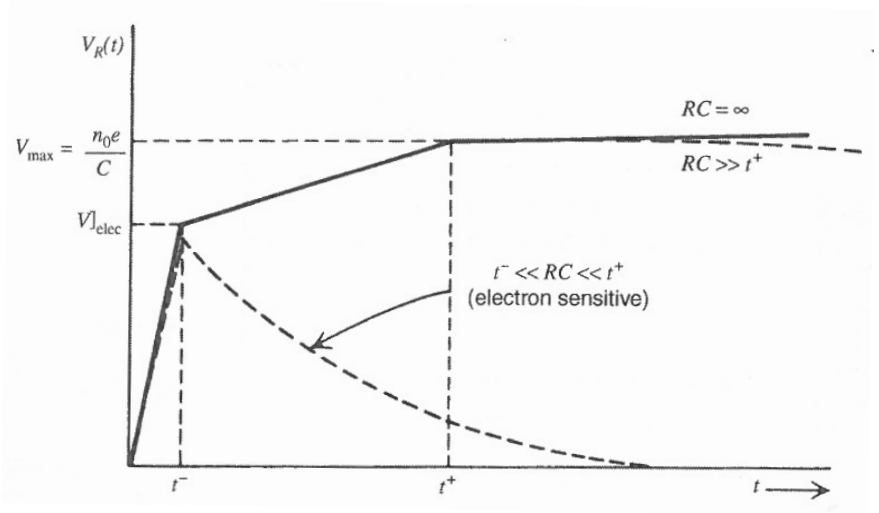
- Position resolution (1 mm X, 2 mm Y)
- Timing resolution (300 ps)

PRISMA – ionization chamber (IC)

Ionisation chamber in pulse mode

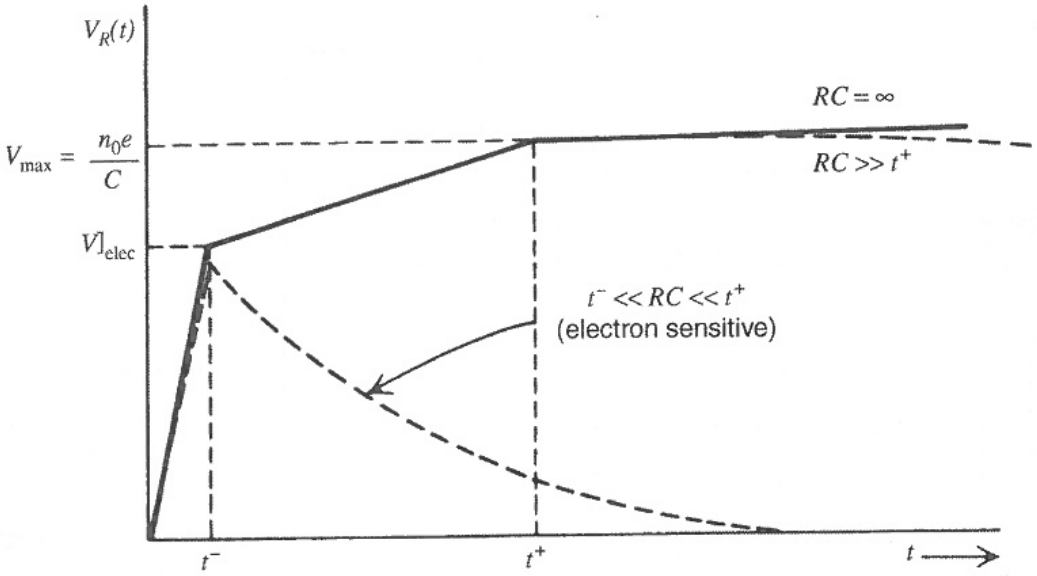


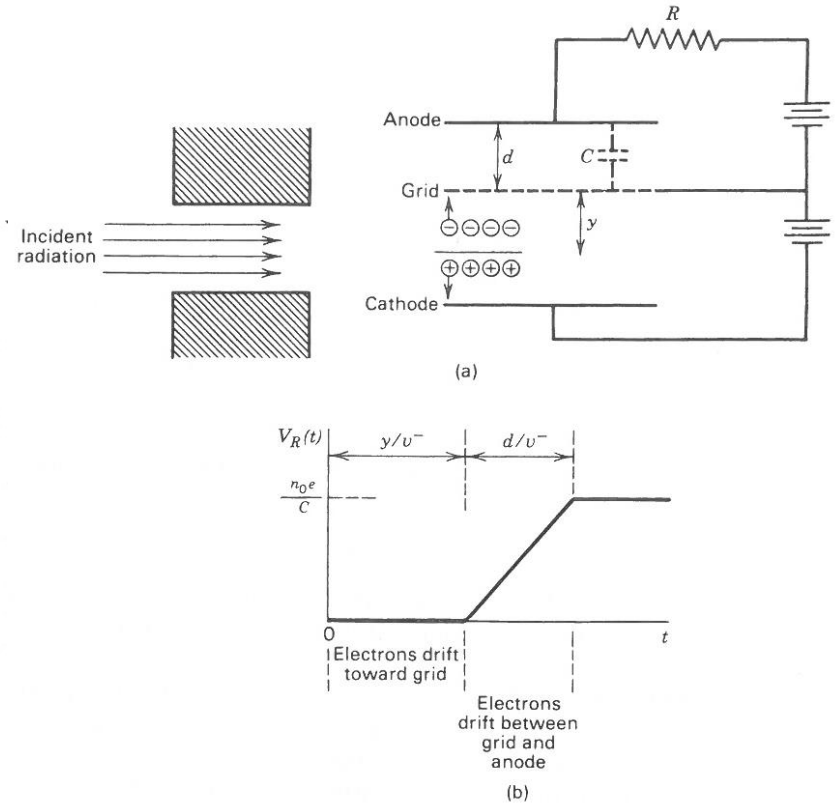
$$V_r = \frac{n_o e}{dC}(v^+ + v^-)t$$



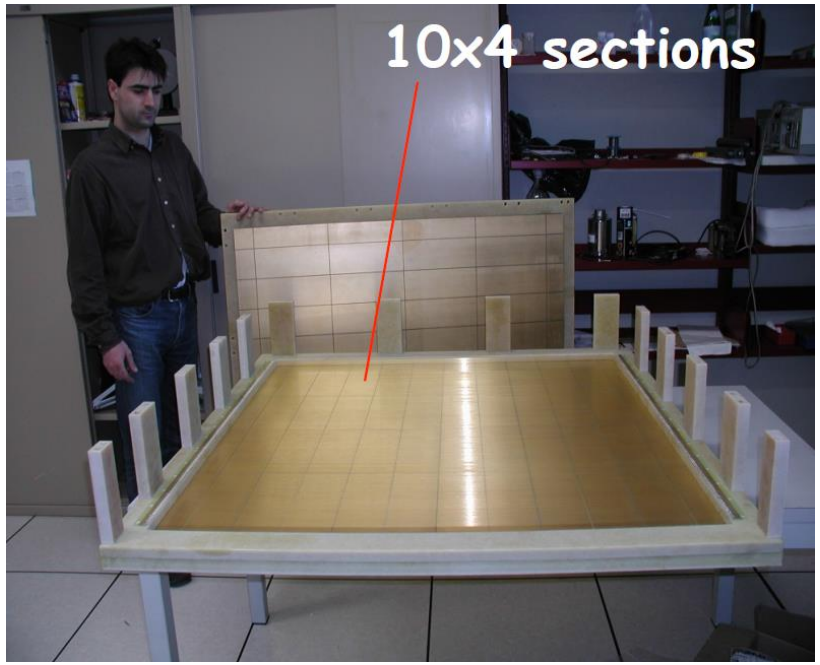
PRISMA – IC

Ionisation chamber in pulse mode Frisch grid





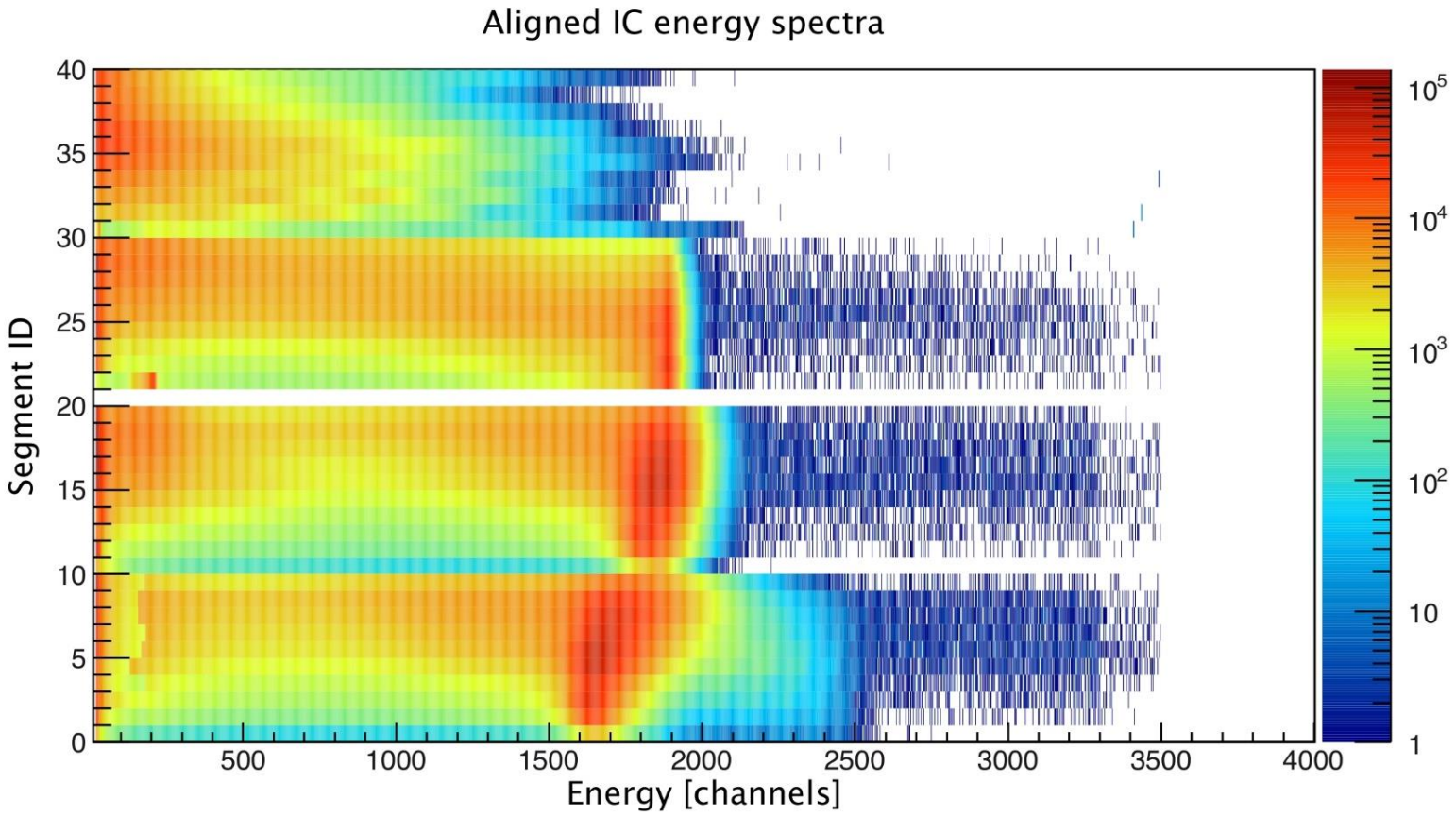
PRISMA – IC



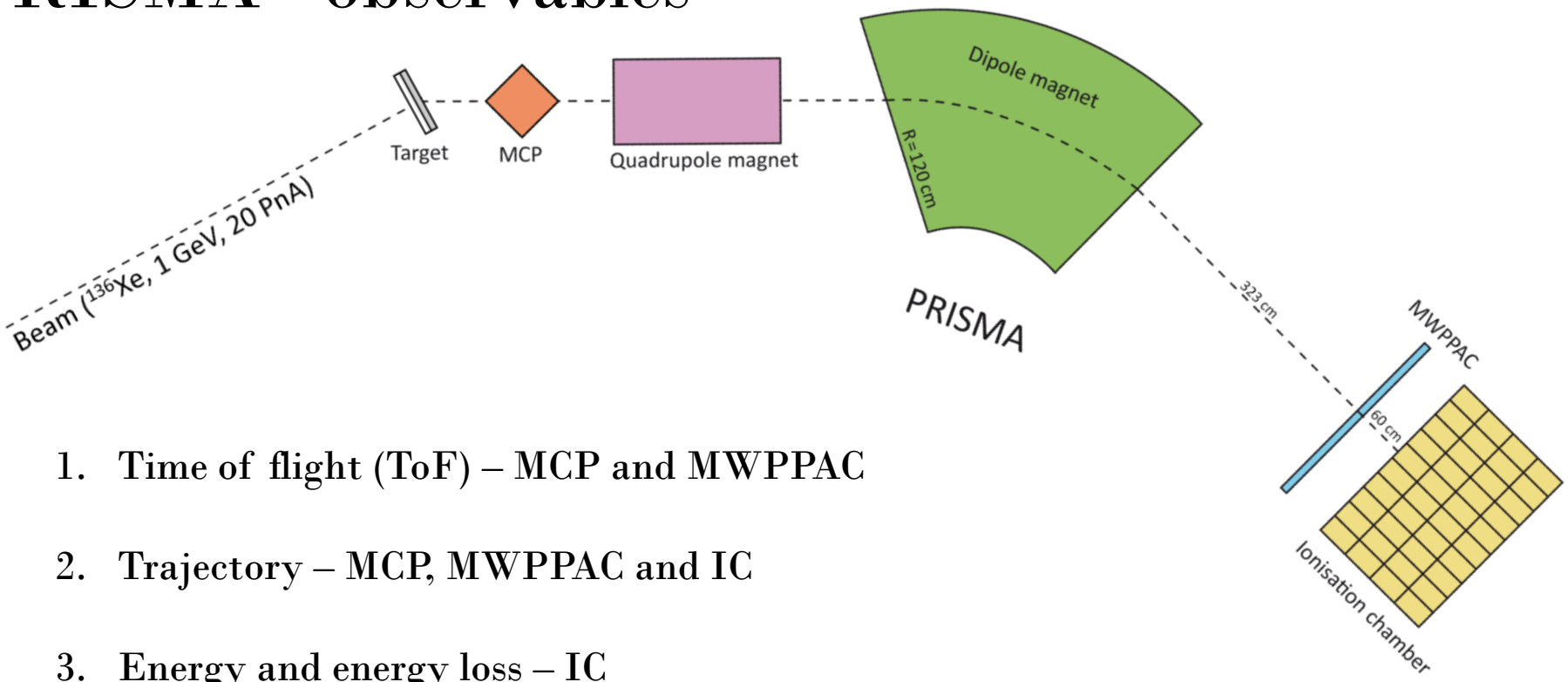
- 10 x 4 sections /anode and cathode(10x25 cm^2)
- Frisch grid (1000 wire, 100 µm diameter, 1 mm pitch, 1 m length)
- Counting gas CH_4 / CF_4 at 20-100 mbar
- Energy resolution of individual sections

- Particles are completely stopped
- Gas pressure is adapted to different energies and charges of beam like particle

PRISMA – IC

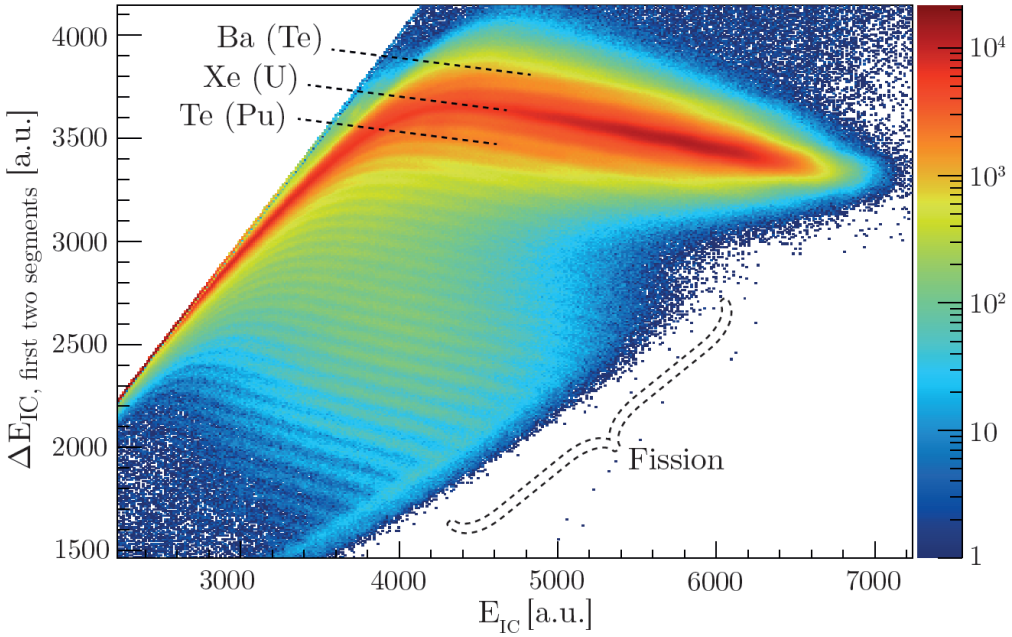

Aligned IC energy spectra
Segment ID
Energy [channels]
0
5
10
15
20
25
30
35
40
500
1000
1500
2000
2500
3000
3500
4000
1
10
10^2
10^3
10^4
10^5

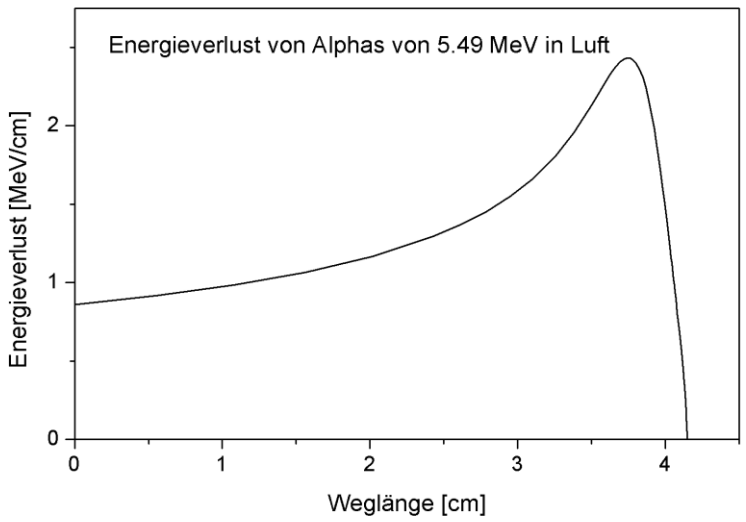
PRISMA - observables



1. Time of flight (ToF) – MCP and MWPPAC
2. Trajectory – MCP, MWPPAC and IC
3. Energy and energy loss – IC

Elemental identification – E / ΔE

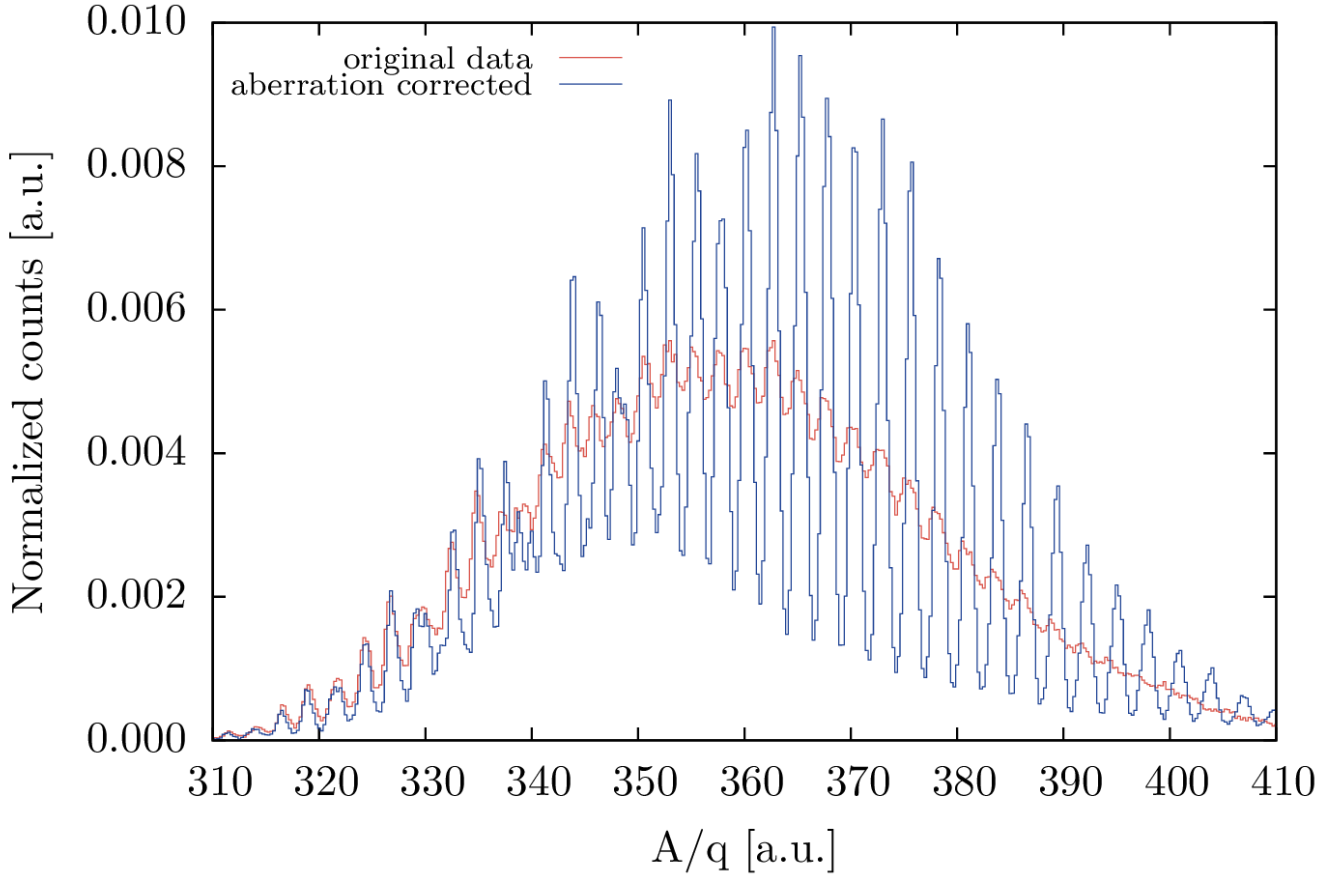




Bethe-Bloch Formel

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho_a \frac{Z_a}{A_a} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{\max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

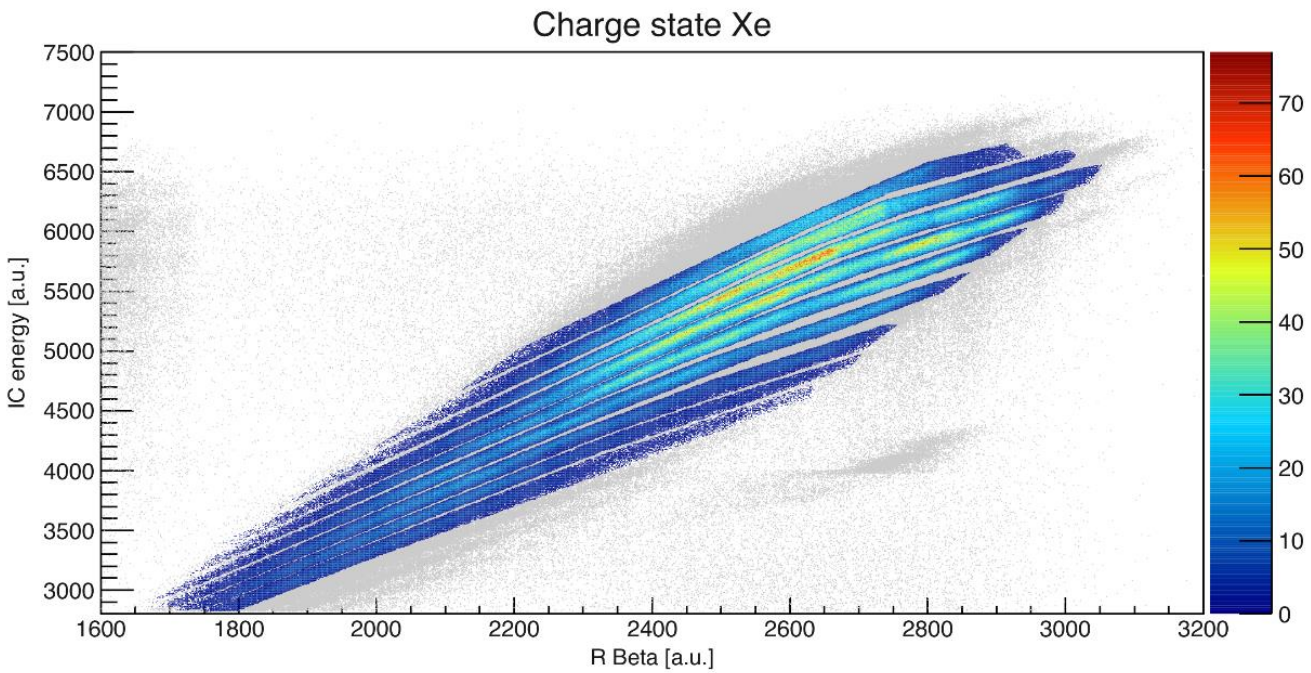
A over Q – mass charge ratio



$$A/q = B \times \rho \frac{t}{l}$$

A – mass number
q – charge state
B – magnetic field strength
ρ – bending radius
t – time of flight
l – flight distance

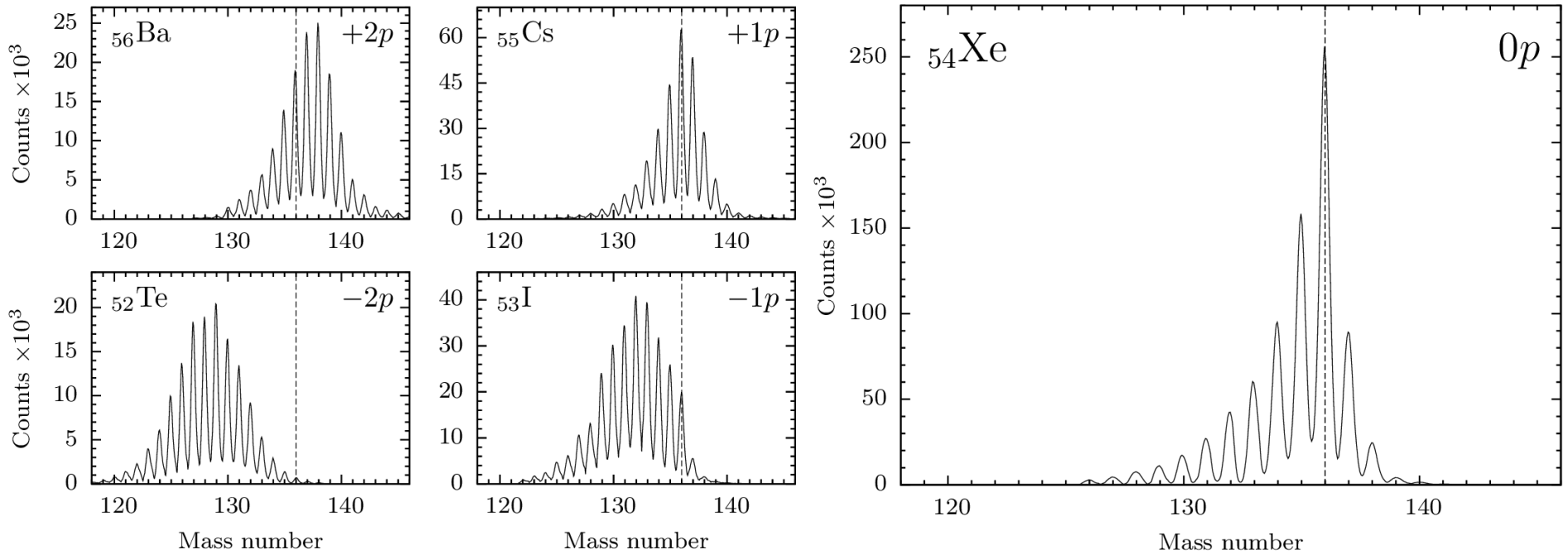
Charge state – charge of single ions



$$E/_{\rho\beta} \sim q$$

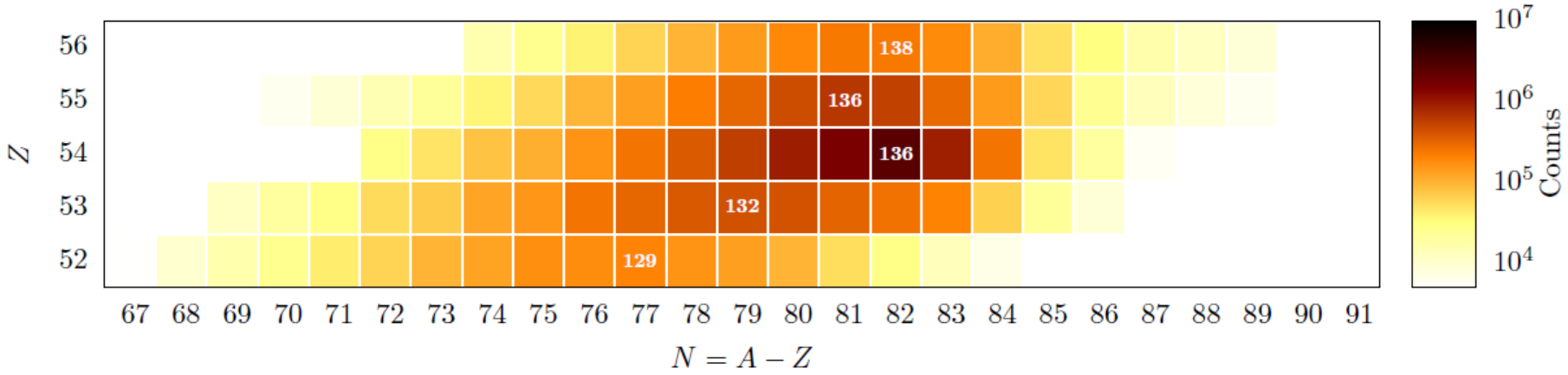
E – Energy
q – electr. charge state
ρ – bending radius
β – v/c velocity

Mass after multiplication



$$A/_q \times q = A$$

Final result



- mass and chemical element of reaction products
- angular distribution of reaction products
- velocity of reaction products

AGATA

- Advanced Gamma Tracking Array

  Bazzacco, Nucl. Phys. A 746 (2004) 248-254
  Akkoyun, Nucl. Instrum. Meth. A 668 (2012) 26

- 8 Triple cryostats / 24 capsules

  Wiens, Nucl. Instrum. Meth. A 618 (2010) 99

- Full digital electronics

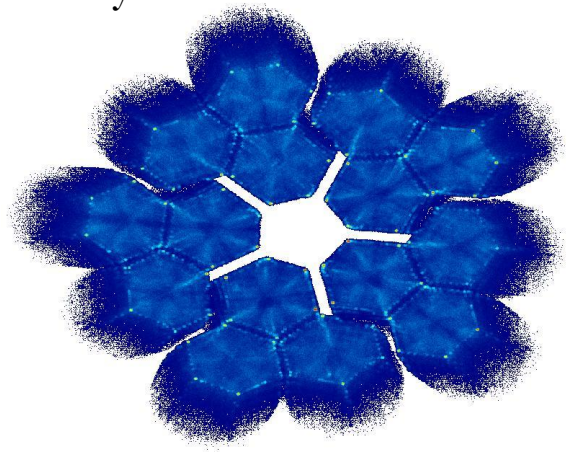
- Online PSA and Tracking

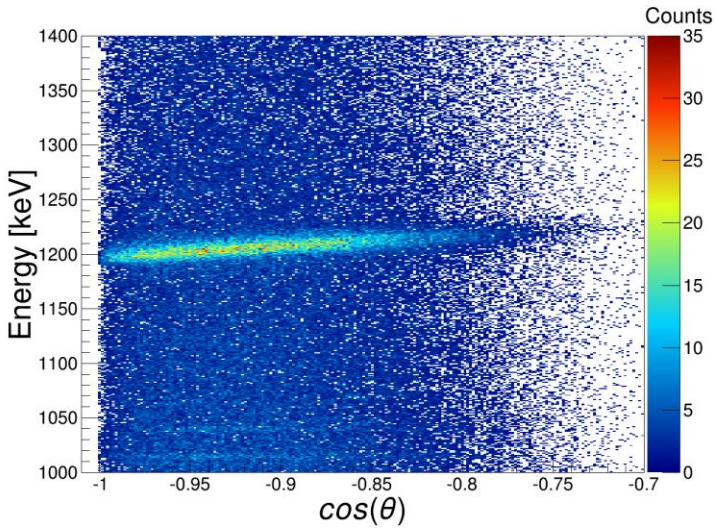
- High resolution position sensitive γ ray spectroscopy

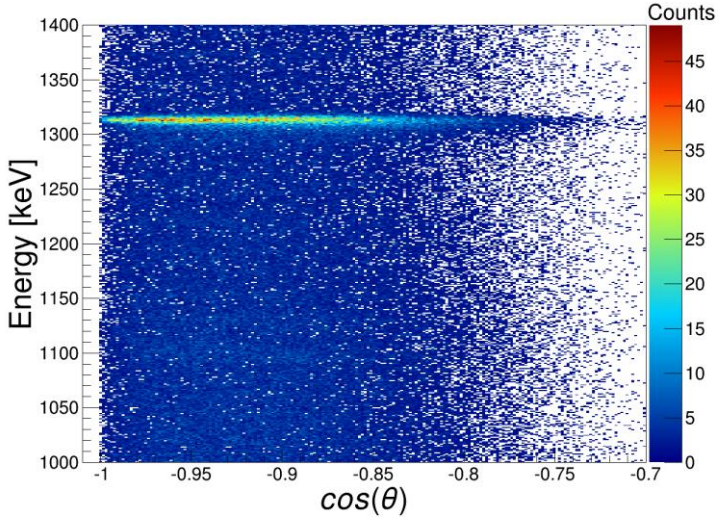
- High count rate capabilities

Gamma Ray Spectra

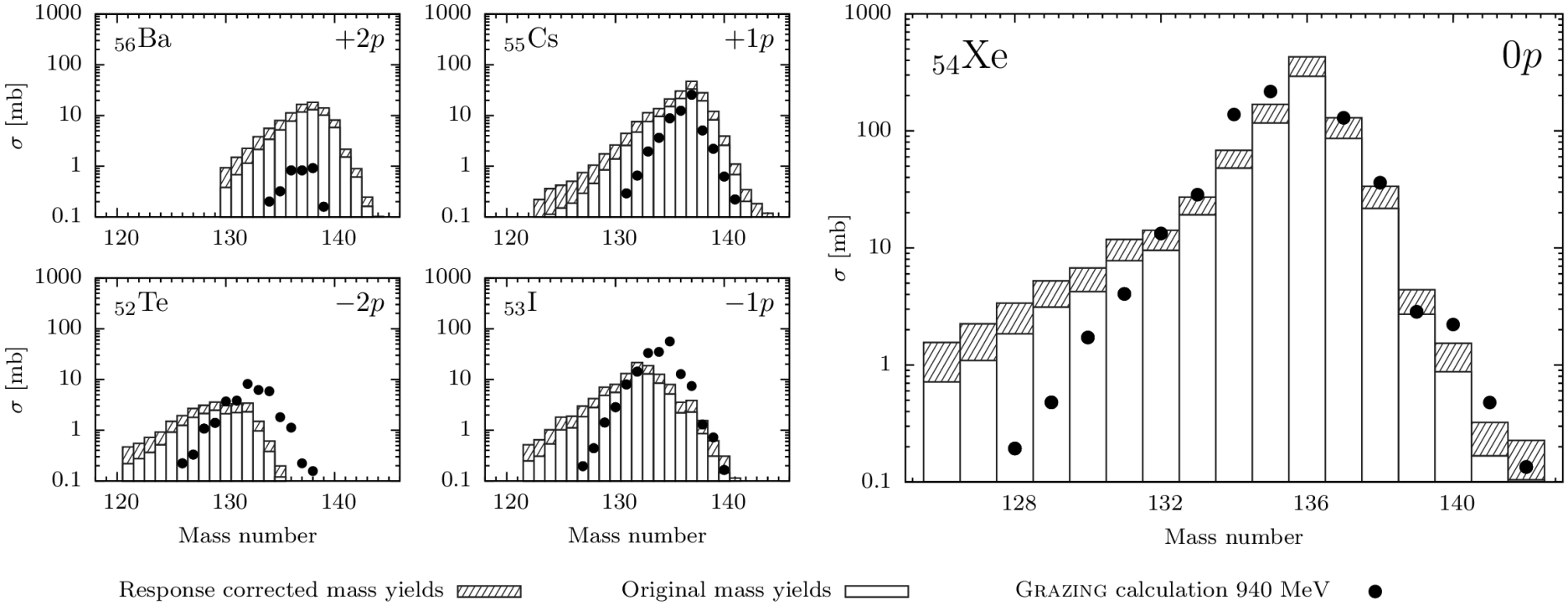
- Doppler correction needed (β ~ 9%)
- Ejectile velocity given by PRISMA
- Recoil velocity calculated
- Gamma direction by AGATA



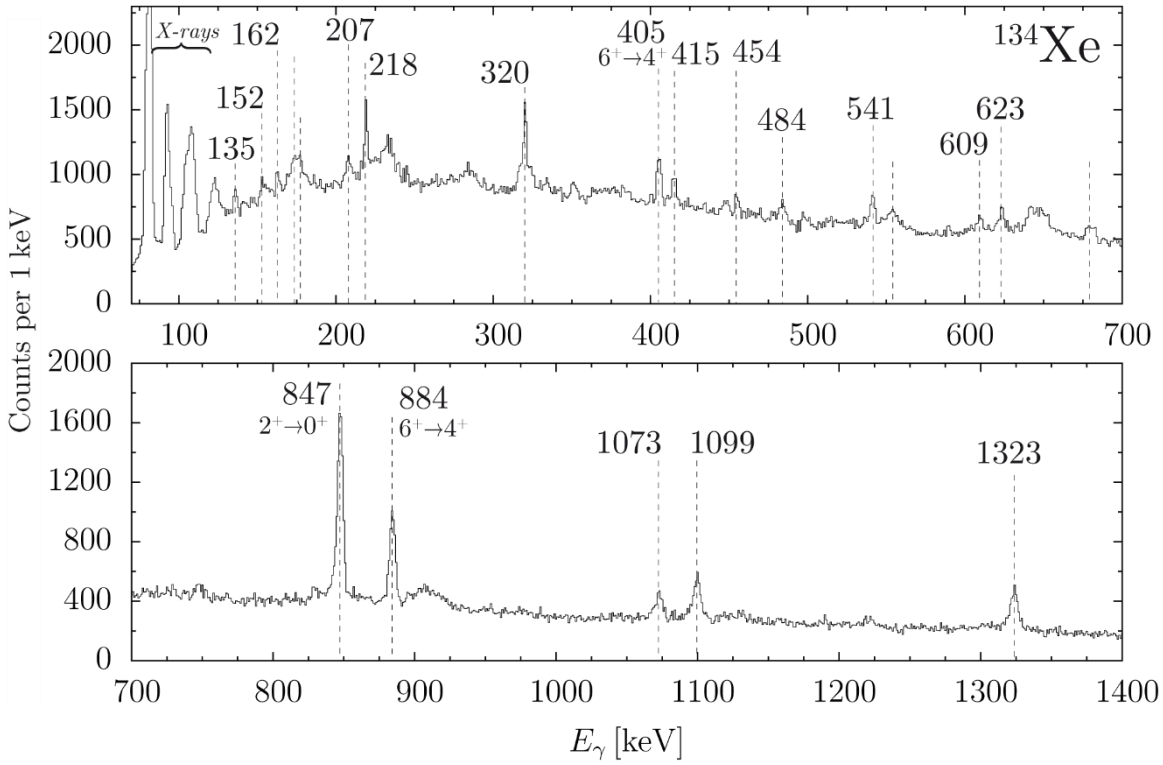




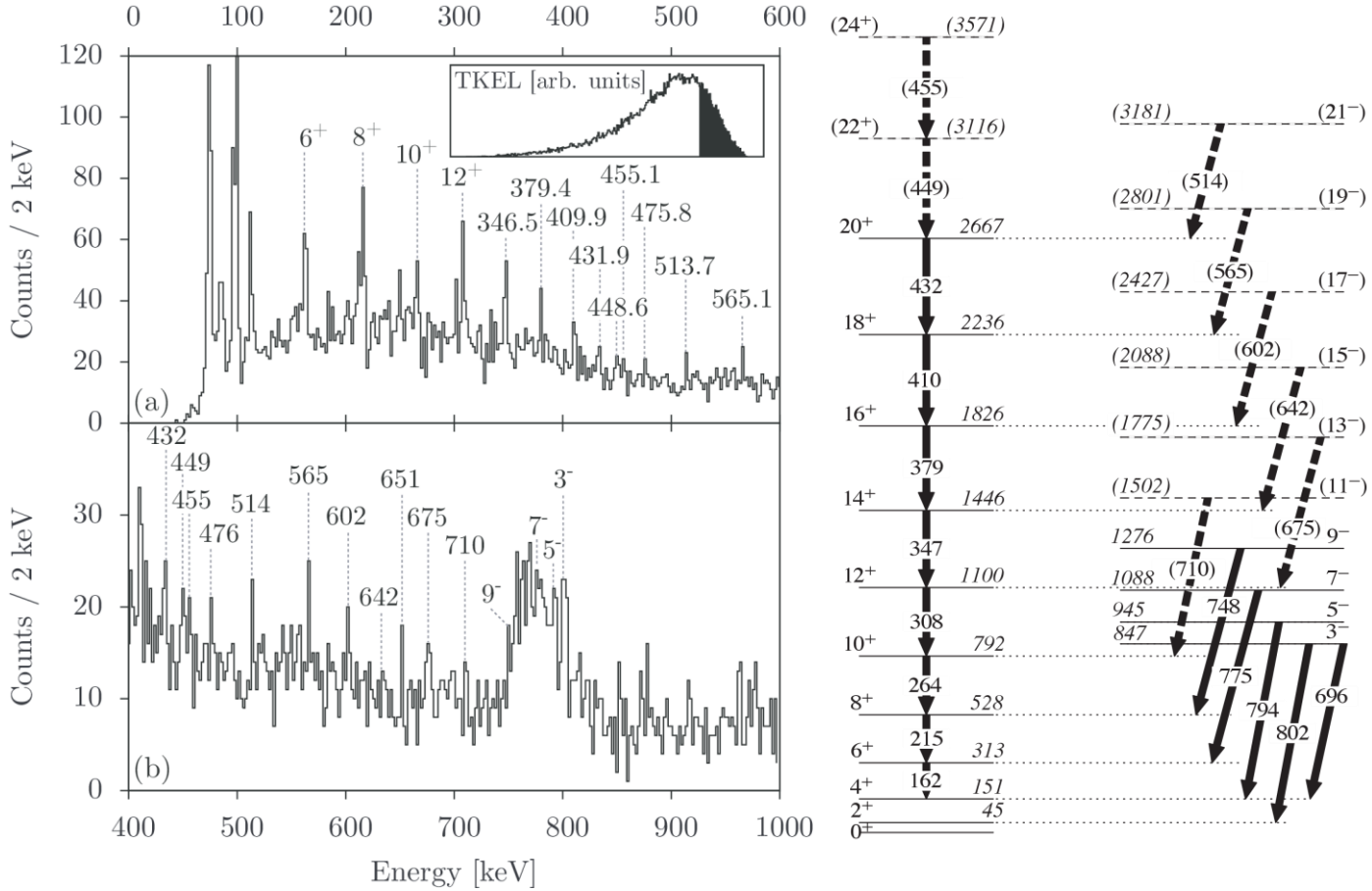
Final result comparison with reaction theory



Spectrum of ^{134}Xe



Spectrum of ^{240}U



Results

Reaction studies

- reaction mechanism of MNT
- cross sections and comparison with theory

PHYSICAL REVIEW C™

Light and heavy transfer products in 136Xe + 238U multinucleon transfer reactions
A. Vogt *et al.* **PRC 92, 024619 (2015)**

Spectroscopy of heavy reaction product

- Rotational bands and octupole vibration in ^{240}U

PHYSICAL REVIEW C™

Spectroscopy of ^{240}U after multinucleon transfer reactions
B. Birkenbach *et al.* **PRC 92, 044319 (2015)**

Results

Spectroscopy of light reaction product

- Nuclear structure on top of the 10^+ and 7^- isomers in ^{134}Xe

PHYSICAL REVIEW C™

High-spin structure of ^{134}Xe
A. Vogt *et al.* **PRC 93, 054325 (2016)**

- High-spin states in ^{137}Ba and ^{135}Xe
- p-n correlations near the N = 82 shell closure

PHYSICAL REVIEW C™

Isomers and high-spin structures in the N=81 isotones ^{135}Xe and ^{137}Ba
A. Vogt *et al.* **PRC 96, 024316 (2017)**

- High-spin states and a new spin-trap isomer in ^{133}Xe
- High-spin spectroscopy of ^{132}Xe

PHYSICAL REVIEW C™

High-spin structures in ^{132}Xe and ^{133}Xe and evidence for isomers along the N=79 isotones
A. Vogt *et al.* **PRC 96, 024321 (2017)**

Results

Spectroscopy of light reaction product

- Backbending in ^{131}Xe in the favoured neg.-parity band
- Description within the shell-model

PHYSICAL REVIEW C™

High-spin structure in the transitional nucleus ^{131}Xe: Competitive neutron and proton alignment in the vicinity of the N = 82 shell closure
L. Kaya *et al*. **Phys. Rev. C 98, 014309 (2018)**

- High-spin states and new 23/2$^+$ spin-trap isomers in ^{133}Xe and ^{135}Ba

PHYSICAL REVIEW C™

Millisecond 23/2+ isomers in the N=79 isotones ^{133}Xe and ^{135}Ba
L. Kaya *et al*. **Phys. Rev. C 98, 054312 (2018)**

- High-spin states in ^{136}Ba and ^{137}Ba
- p-n correlations near the N = 82 shell closure

PHYSICAL REVIEW C™

Identification of high-spin proton configurations in ^{136}Ba and ^{137}Ba
L. Kaya *et al.* **Phys. Rev. C 99, 014301 (2019)**