GSI Helmholtzzentrum für Schwerionenforschung GmbH

Injection into Traps

Traps and methods

Frank Herfurth

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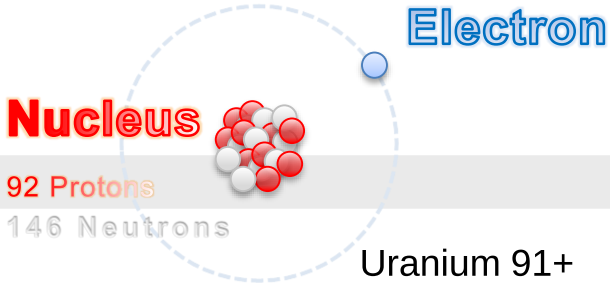
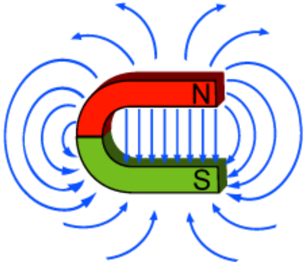
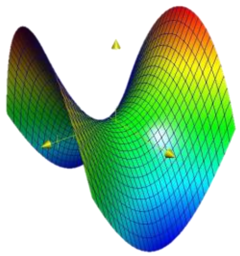
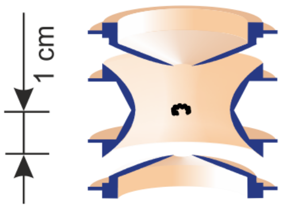


- Introduction with Application Examples
- Ion Traps
  - RF Traps (Paul Traps)
  - Penning Traps
- Injection and complications
  - dynamic (RF field, capture)
  - static (degrader, gas)
- Ion trap facility principles
  - Production
  - deceleration

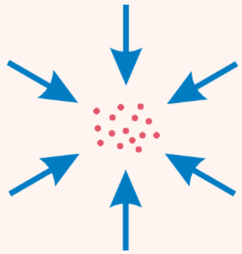






Basic ideas behind "traps"

Radial force

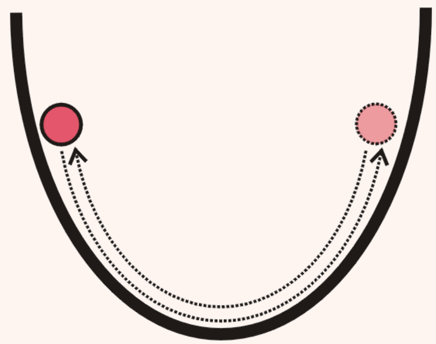


electric fields

magnetic fields

light fields

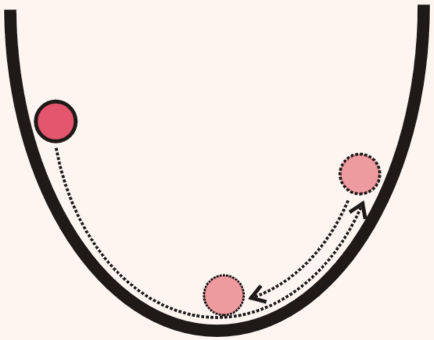
Harmonic potential



harmonic oscillation

independent eigenmodes

Cooling



damping of motional amplitudes

minimization of trap imperfections

"infinite" storage and observation time

Application (for exotic ions*)

- Ion(beam) manipulation
  - Cooling
  - “reactions” like mixing positrons and antiprotons
  - Separation by mass
  - Store until something happens – radioactive decay
- Measurements
  - Masses
  - Atomic properties (Fine Structure, Hyperfinestructure)
    - Radii of nuclei
    - Moments of nuclei
    - g-factor of electron(free&bound)/positron/proton/antiproton

**exotic means highly charged, short lived, antimatter*

Application (for exotic ions*)

- Ion(beam) manipulation
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  - **“reactions” like mixing positrons and antiprotons**
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- Measurements
  - **Masses**
  - Atomic properties (Fine Structure, Hyperfinestructure)
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    - Moments of nuclei
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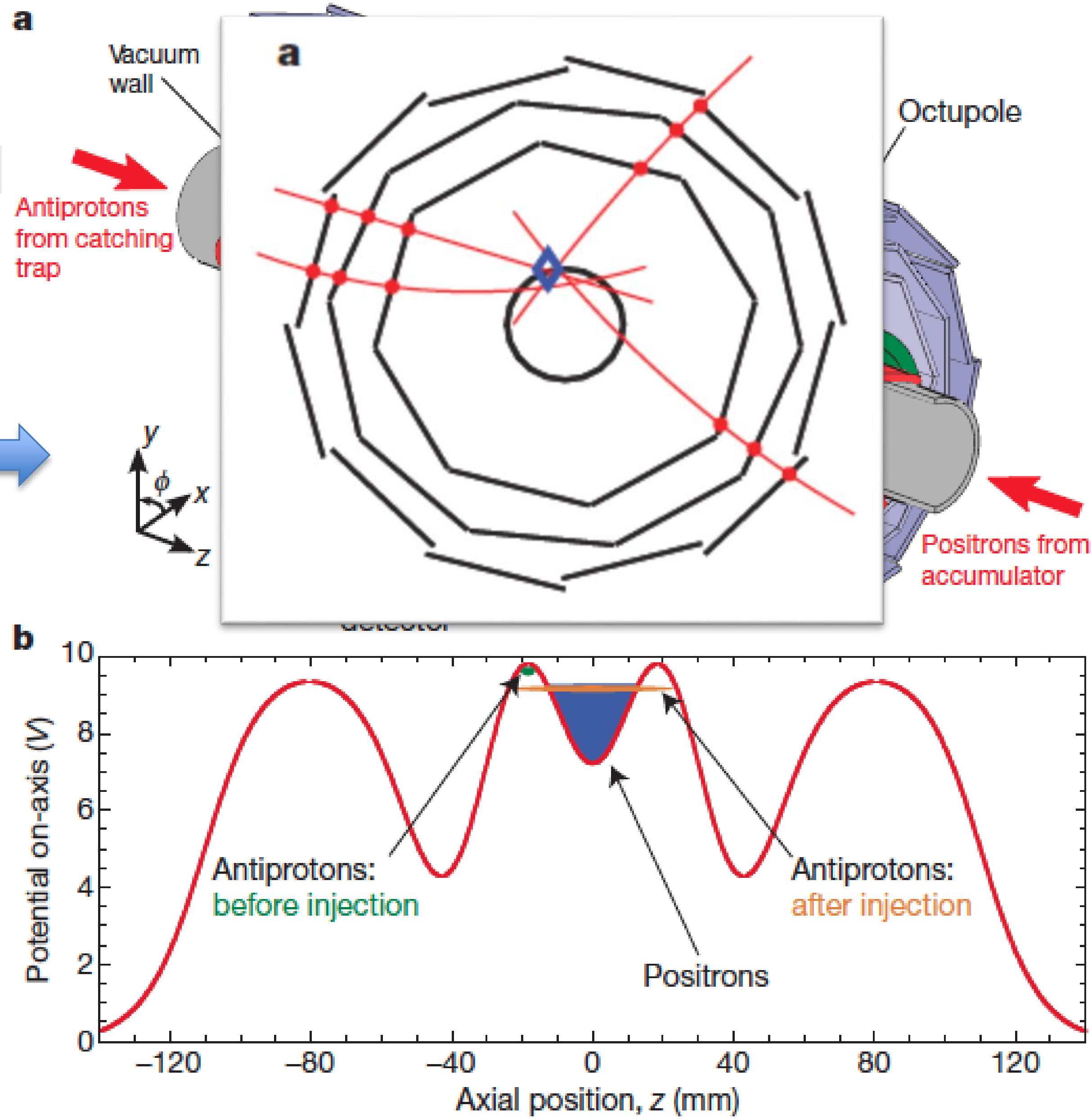
**exotic means highly charged, short lived, antimatter*

Mixing Antimatter

- ATHENA
- ASACUSA
- **ALPHA**
- ATRAP
- BASE

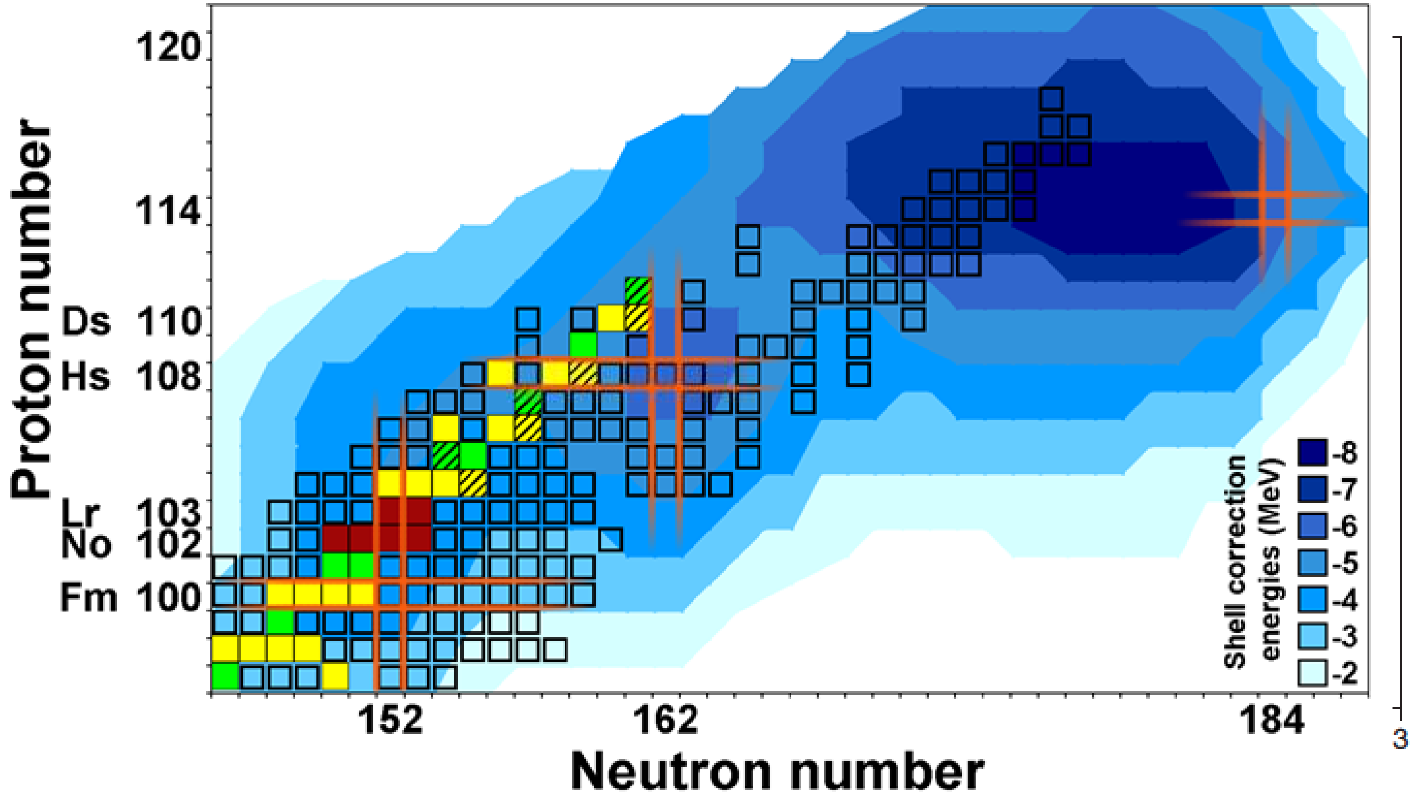
at the AD/CERN



Andresen et al., Nature 2010, doi:10.1038/nature09610

Masses of rare Nuclei

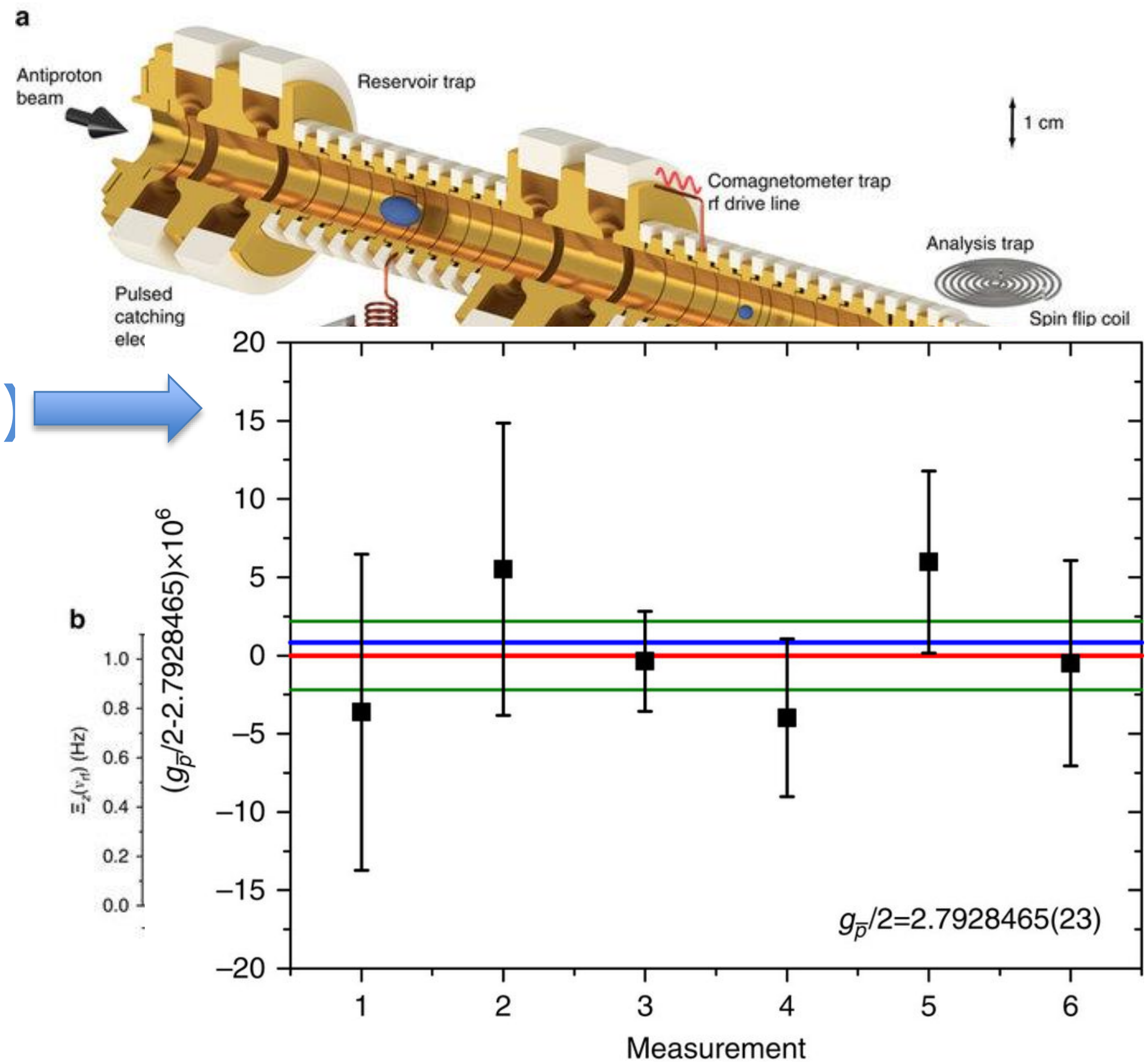
- ISOLTRAP (CERN)
- CPT (ANL)
- **SHIPTRAP (GSI)**
- JYFLTR...
- LEBIT (N...
- TITAN (T...
- TRIGAT...
- MLLTRA...
- MATS (F...
- …



Ramirez et al., Science, 2012; DOI: 10.1126/science.1225636

g-factor of Electron(free&bound)/Proton/Antiproton

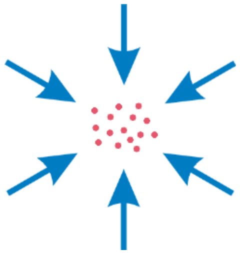
- Dehmelt
- Gabrielse et al.
- Mainz/MPI-K Heidelberg
- **BASE (AD/CERN)**
- ARTEMIS (GSI)
- …



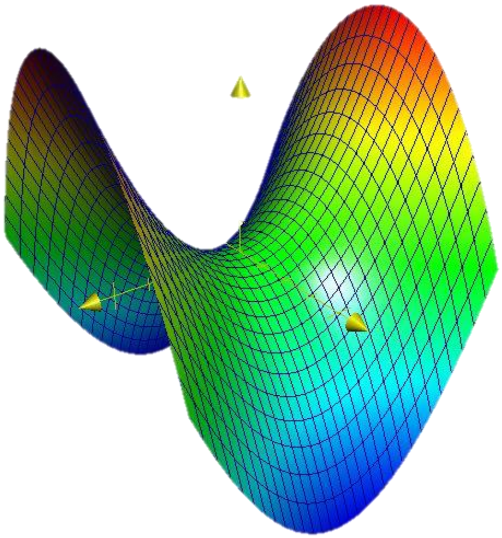
Nagahama et al., Nature Comm. 2017, doi:10.1038/ncomms14084

Ion traps – How not to

- Earnshaw's theorem (1842)
  - A collection of charges cannot be kept in equilibrium by electro**static** interaction alone.

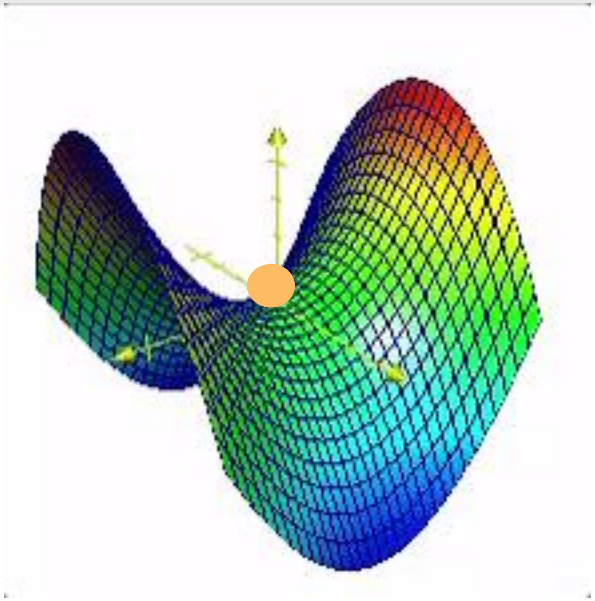


  - This is a consequence of Gauss's law, which doesn't allow field minima (or maxima) in 3D – only saddle points.

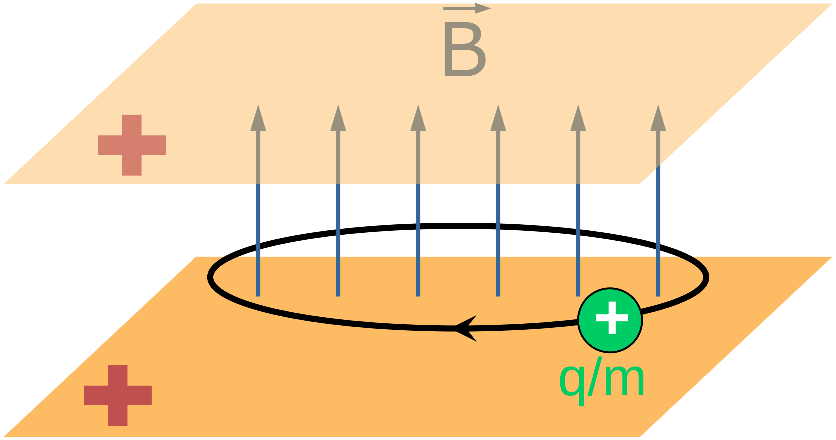


Ion traps – How to

- "many" different saddle points
  - RF Field trap = Paul trap

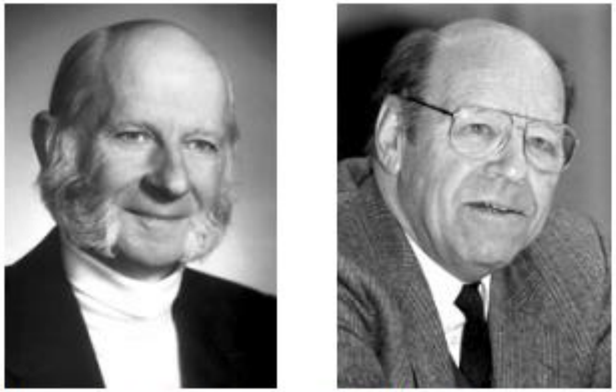


- electric and magnetic fields
  - Penning trap



(Early) History of Ion Trapping (not comprehensive!)

- 1923 Kingdon
- 1932 Cyclotron
- 1936 Penning
- 1949 Omegatron
- 1954 Pierce
- 1956 Paul trap (also Wuerker et al.)
- 1961 ICR drift cell
- 1965 Syrotron (first commercial ICR device)
- 1968 first g-factor measurement of free electron
- 1970 "Trapped Ion Analyzer Cell"
- 1973 First storage and detection of a single elec
- 1974 Invention of FT-ICR MS
- 1975 Suggestion of laser cooling (simultaneous
- 1976 g-factor of free electron by "continuous St
- 1977 Development of "ToF-effect" method for
- 1978 First optical observation of a singly trappe
- 1981 First commercial FT-ICR device
- 1989 Nobel prize for Dehmelt and Paul



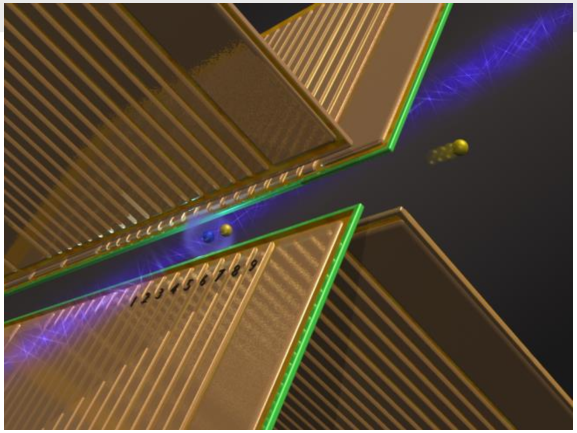
Hans G. Dehmelt   Wolfgang Paul

"for the development of the ion trap technique".

Principle of Ion Traps

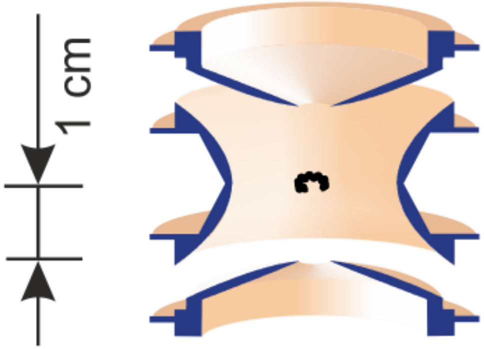
- RF electric field
  = Paul Trap
  - 3D
  - Linear

Wolfgang Paul‘s trap

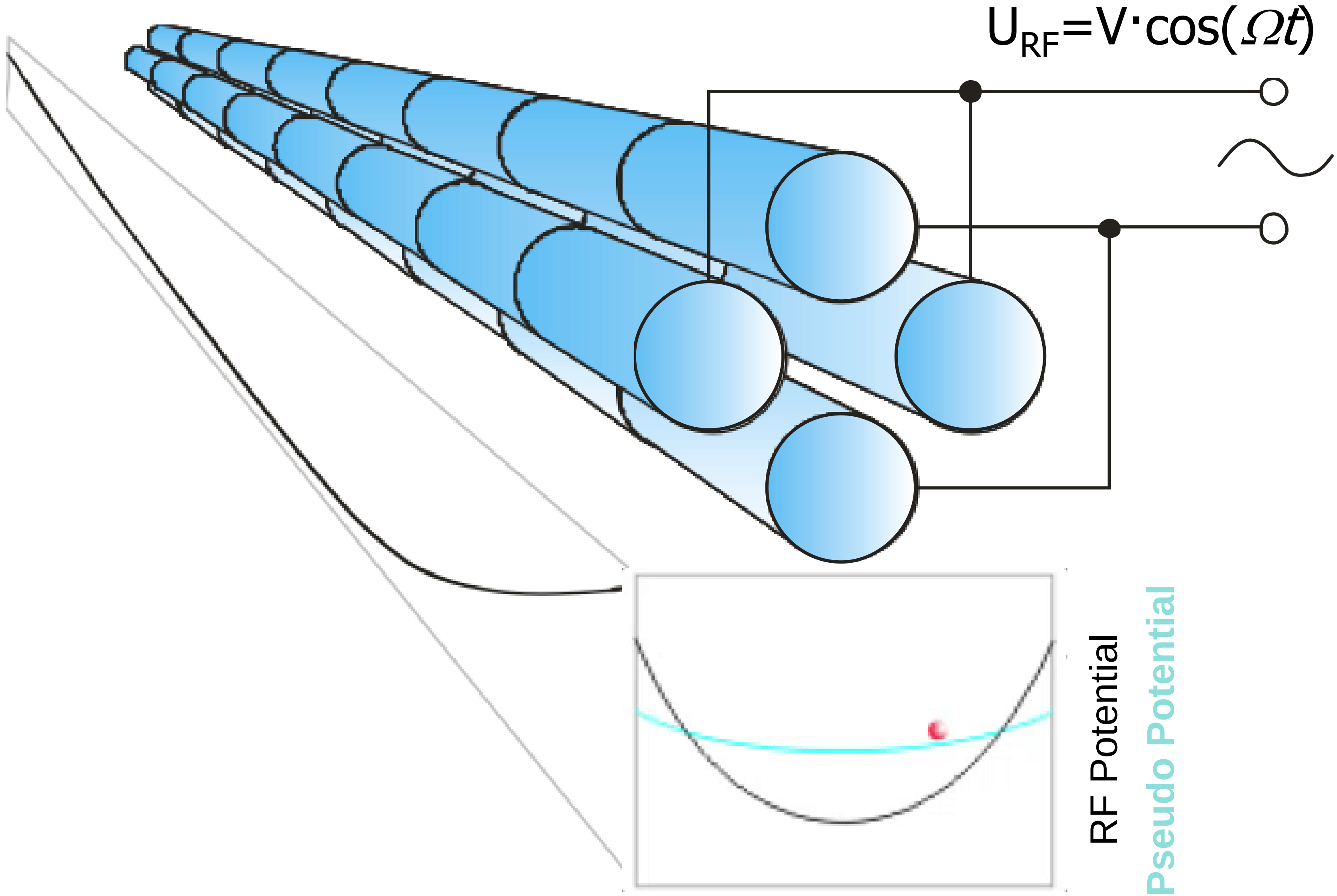


Paul-trap made of PCBs

- DC electric field + DC magnetic field = Penning Trap



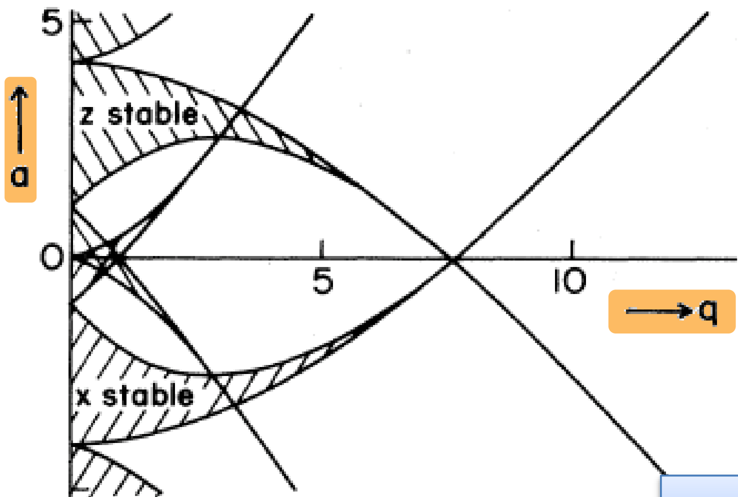
Principle of RF Traps (Paul Traps)



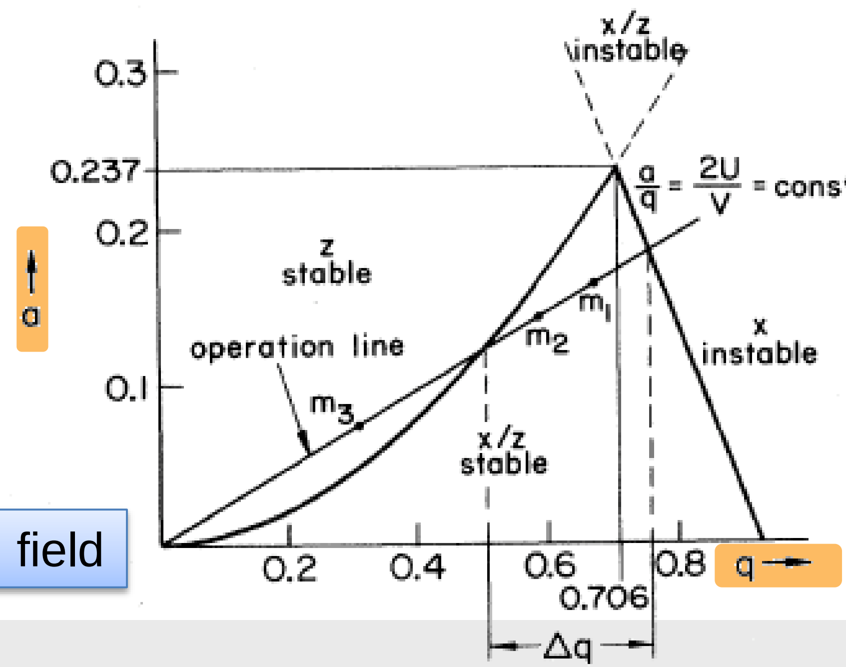
Ion Motion in RF Traps

- Motion described by Mathieu Equation
- Solutions well known, however, stability depends on
  - DC Voltage U
  - RF Voltage V
  - RF Frequency ω
  - q/m

$$a = \frac{4eU}{m r_0^2 \omega^2} \qquad q = \frac{2eV}{m r_0^2 \omega^2}$$



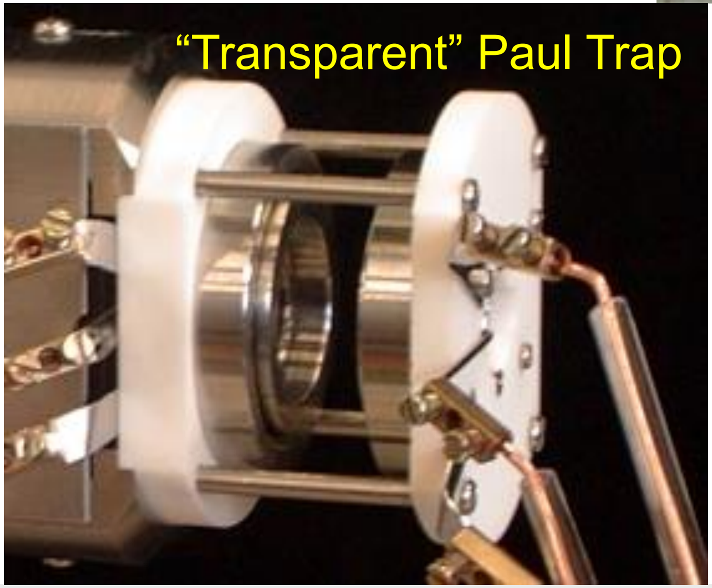
2D quad. field

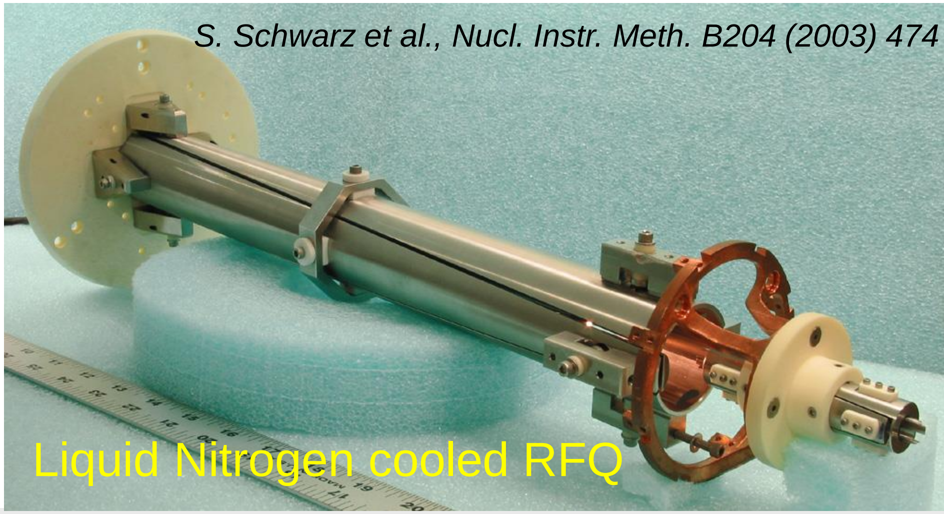


Figs. from W. Paul, RMP62 (1990) – Nobel Lecture

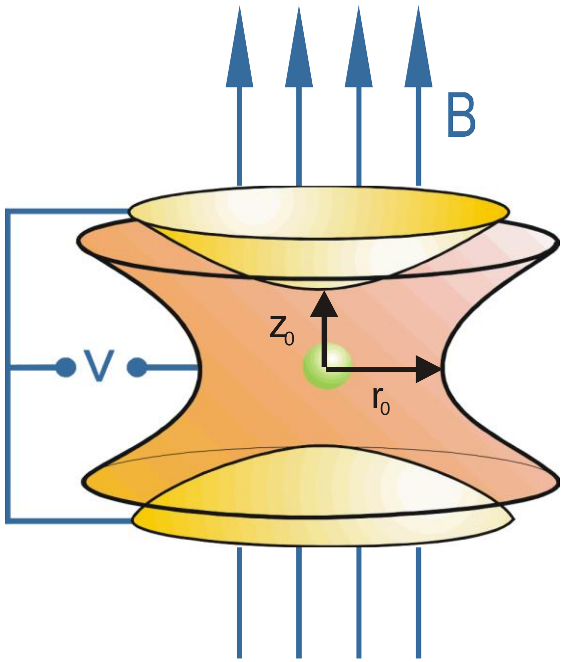
RF Traps

Wolfgang Paul's trap



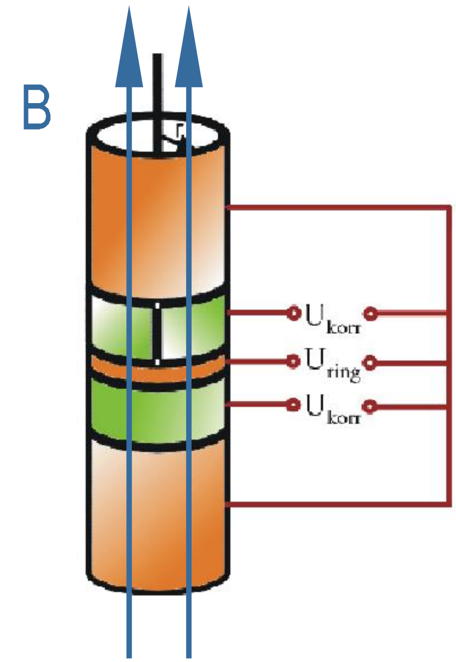


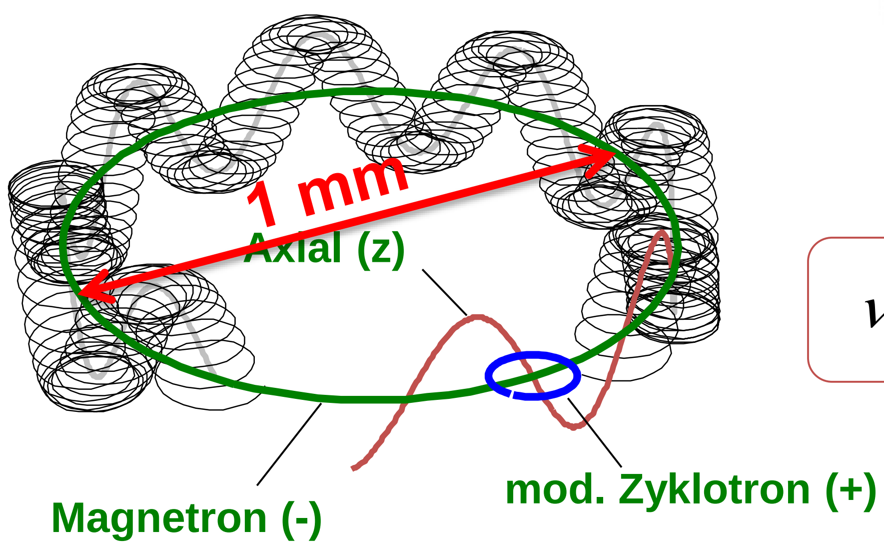
Penning Traps



cyclotron frequency:

$$\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

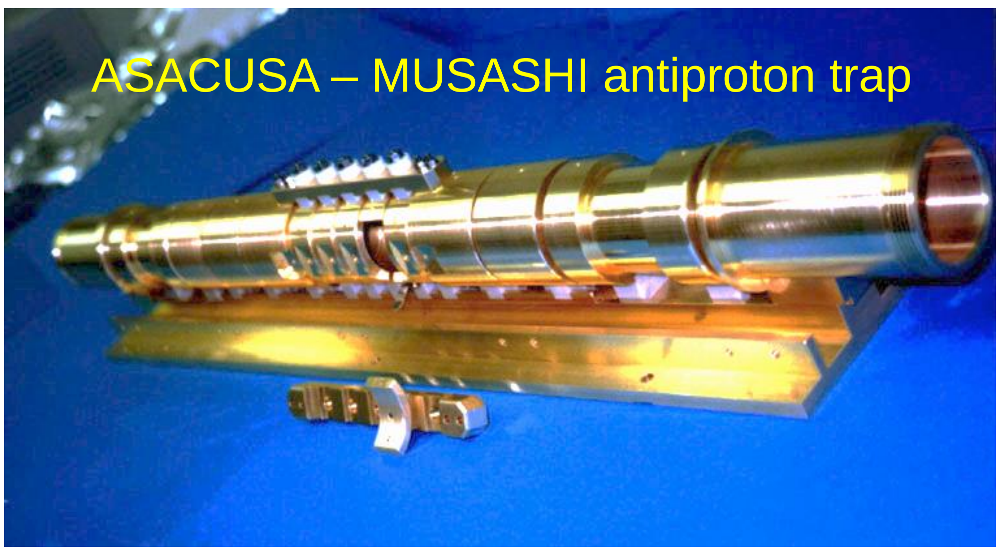




$$\nu_c = \nu_+ + \nu_-$$

Penning Traps

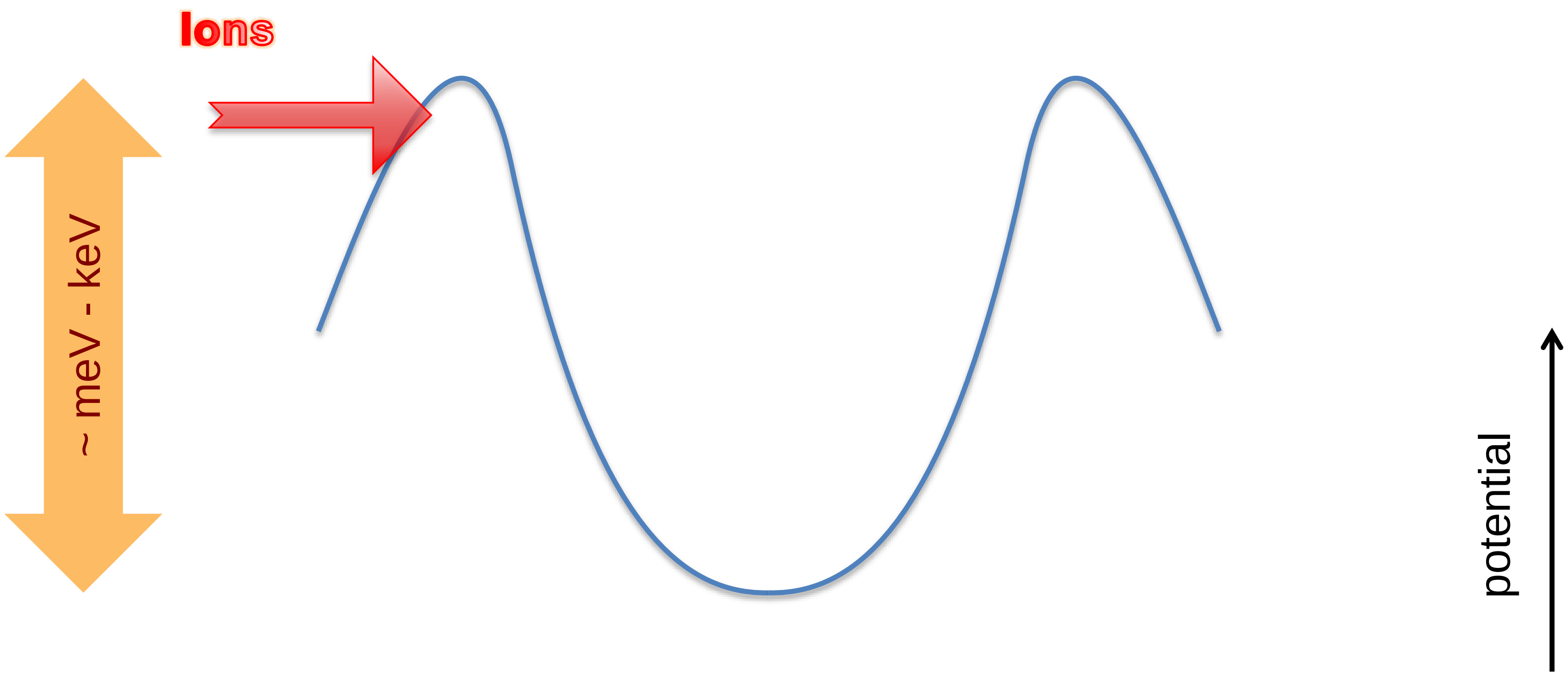
LEBIT/NSCL precision trap



N. Kuroda et al., https://doi.org/10.1103/PhysRevSTAB.15.024702

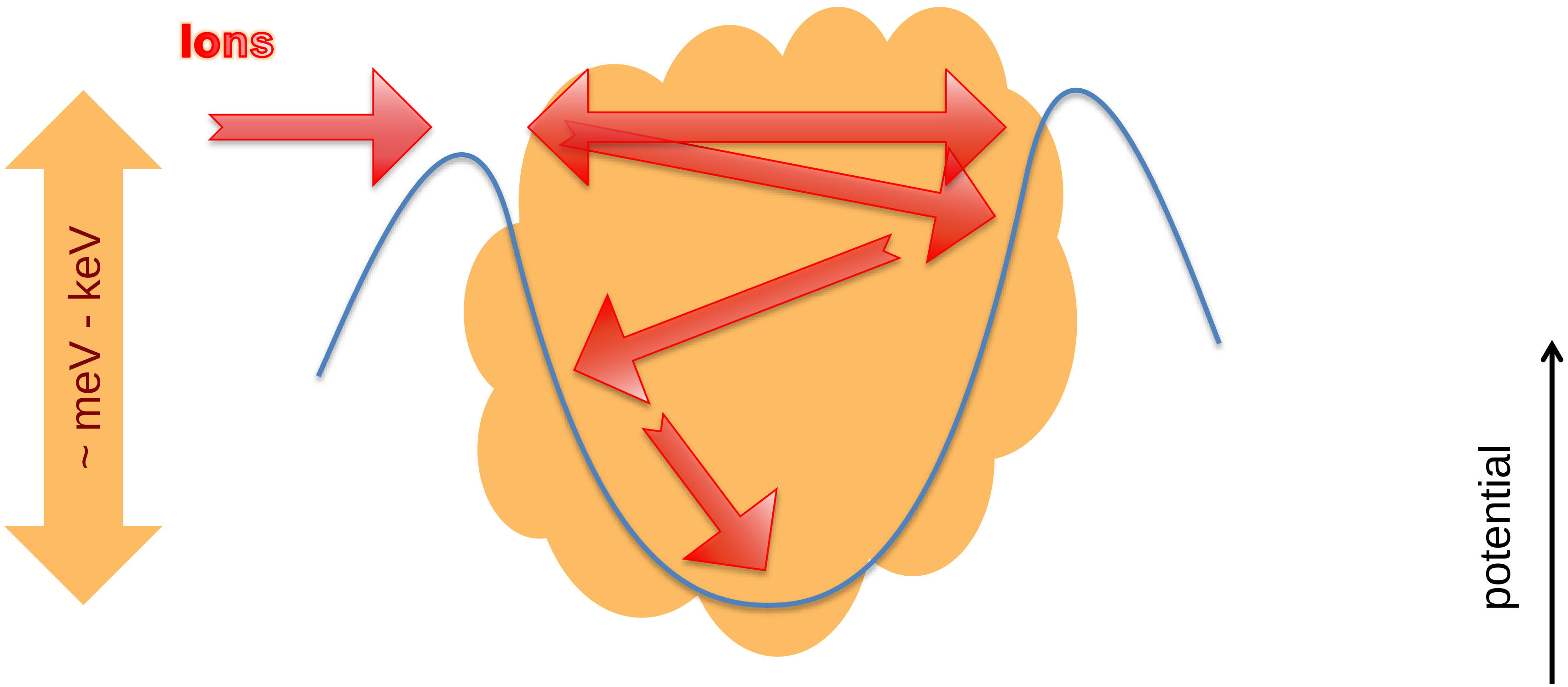
ISOLTRAP‘s cylindrical Penning Trap

Injection of Ions

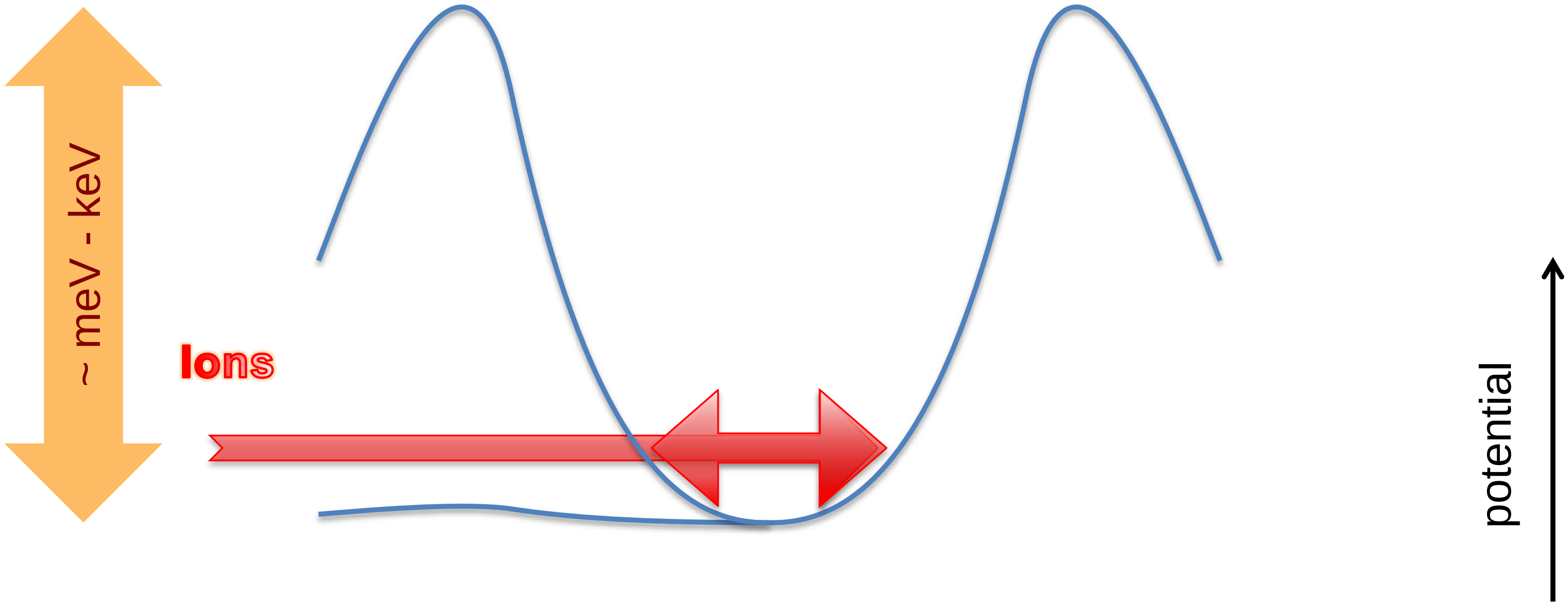


Injection of Ions – Continuously

Introduce energy loss (buffer gas, electrons, foil)

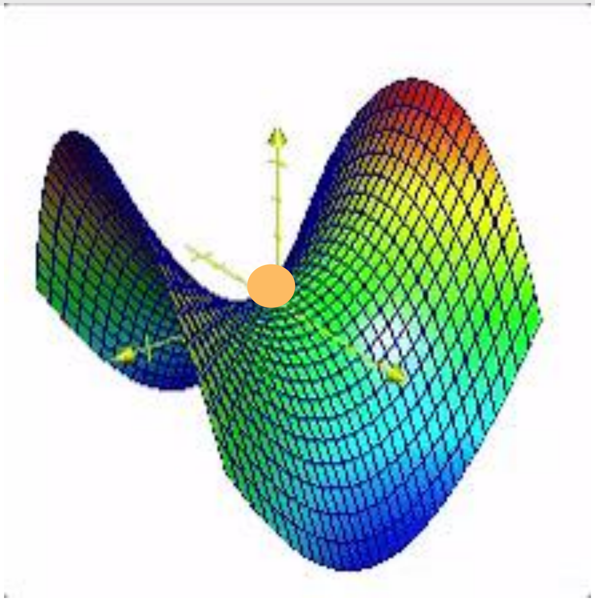


Injection of Ions – Dynamically

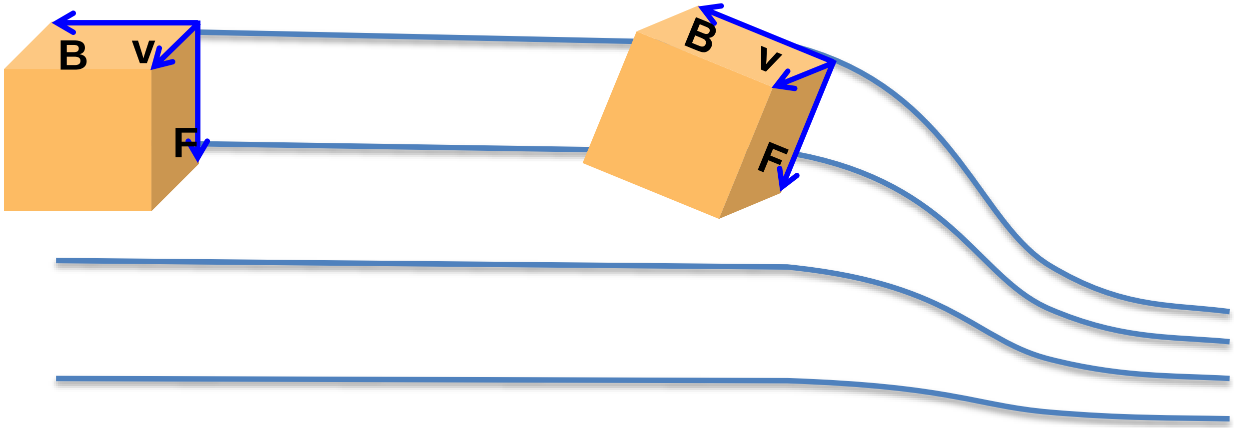


Two Complications for injection into Ion Traps

- RF field traps (Paul trap)
  - the field is not there all the time …



- Magnetic traps (Penning trap)
  - Need to get into strong (several Tesla) solenoid field – magnetic mirror effect !



Injection into RF field trap (Paul trap)

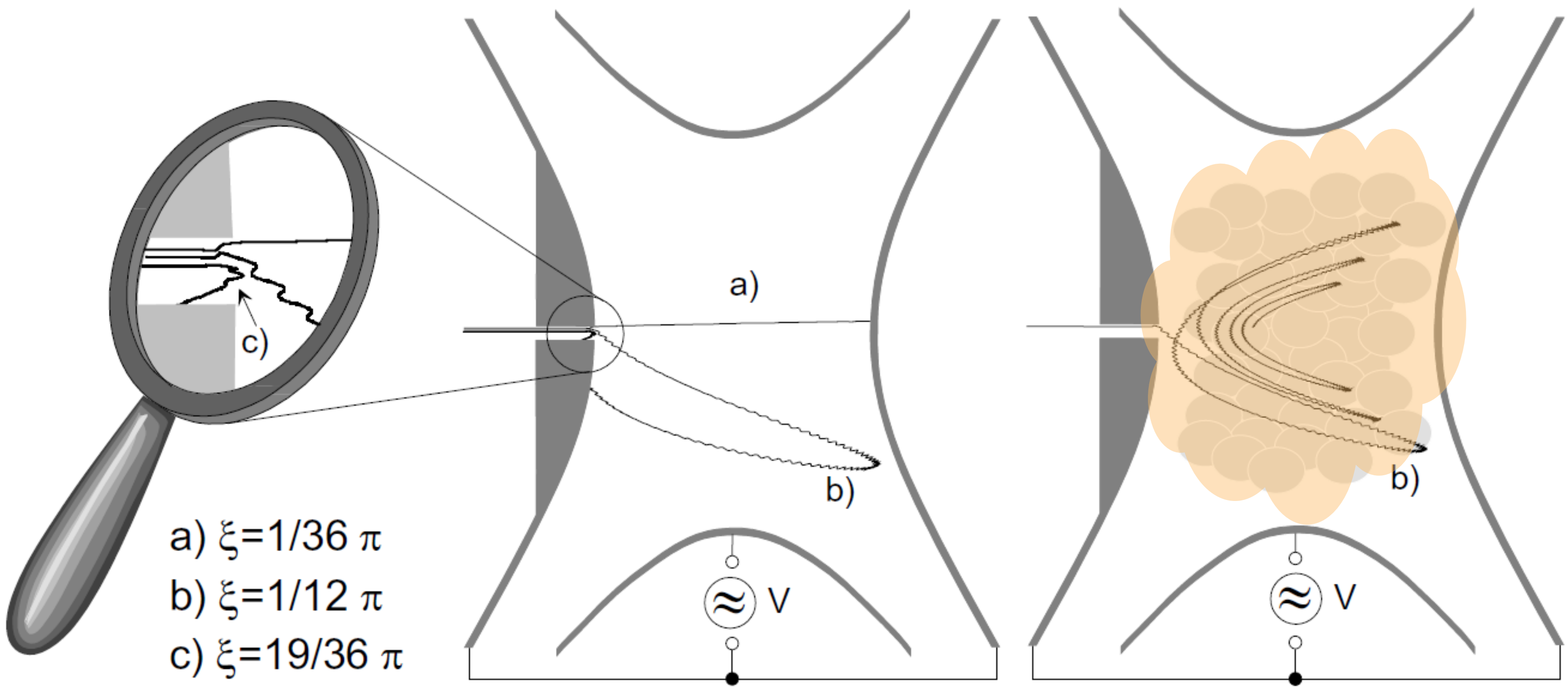
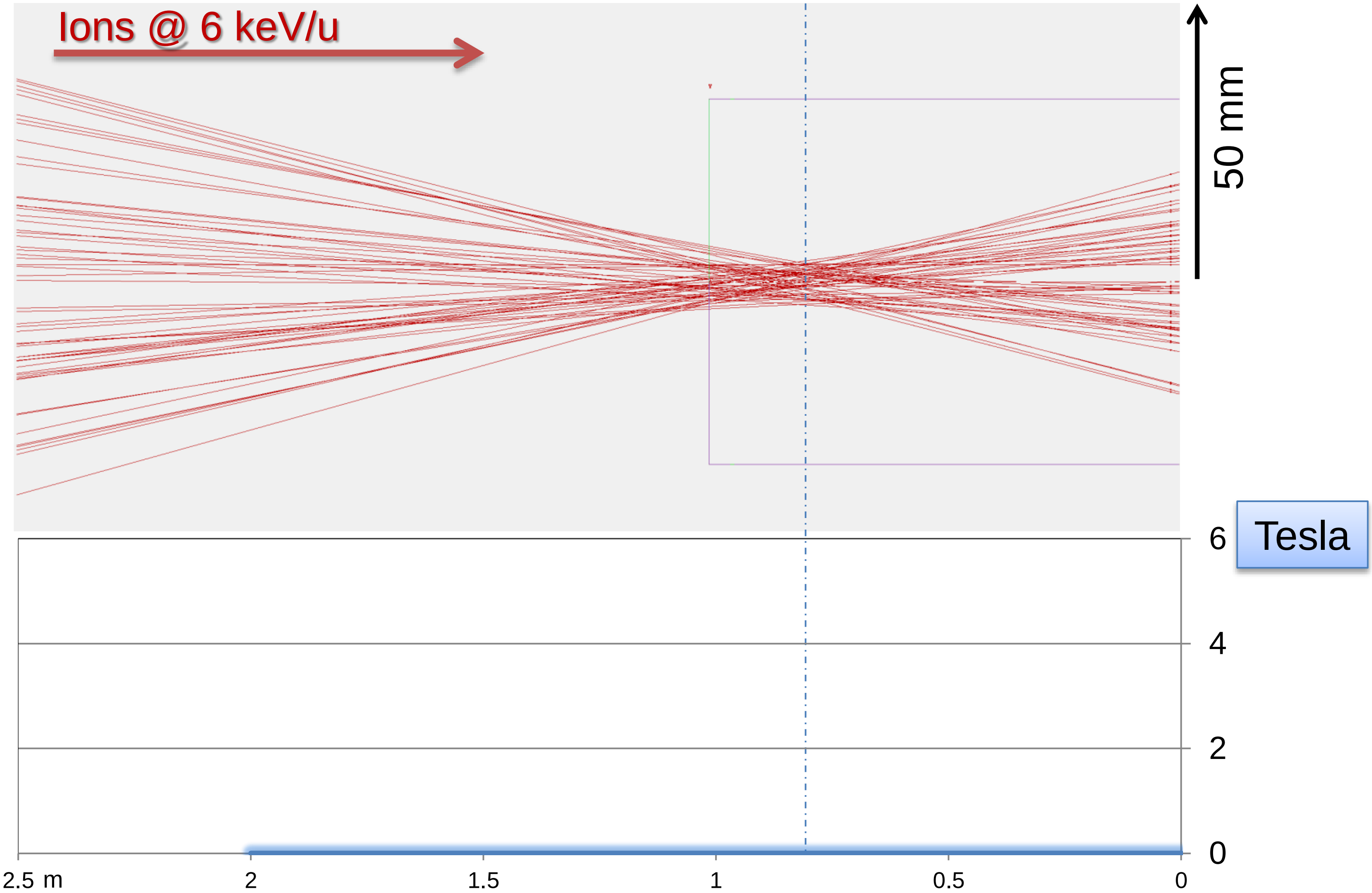


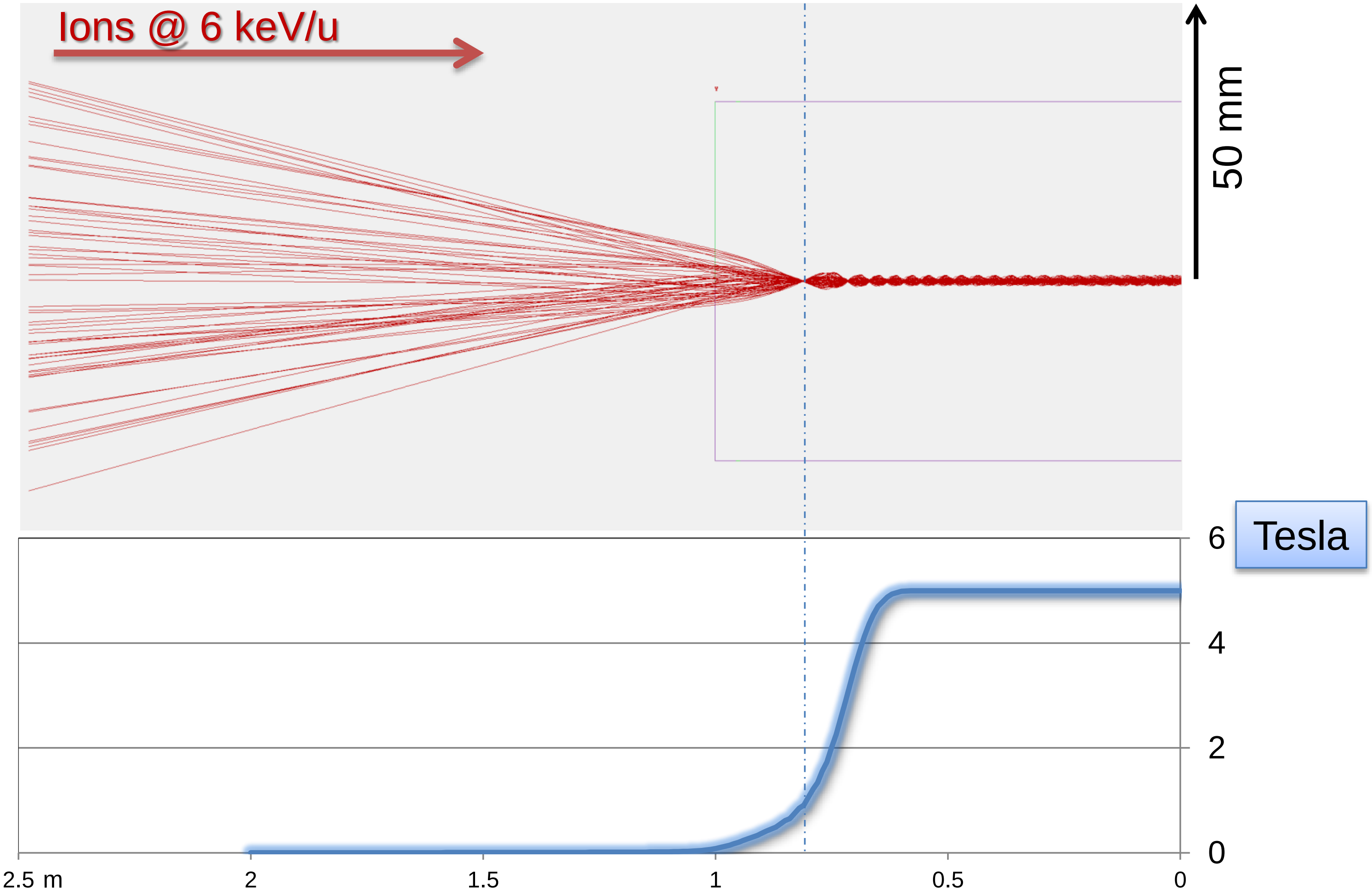
Fig. from Stefan Schwarz, PhD Thesis, Mainz 1998

add gas (0.01 mbar)

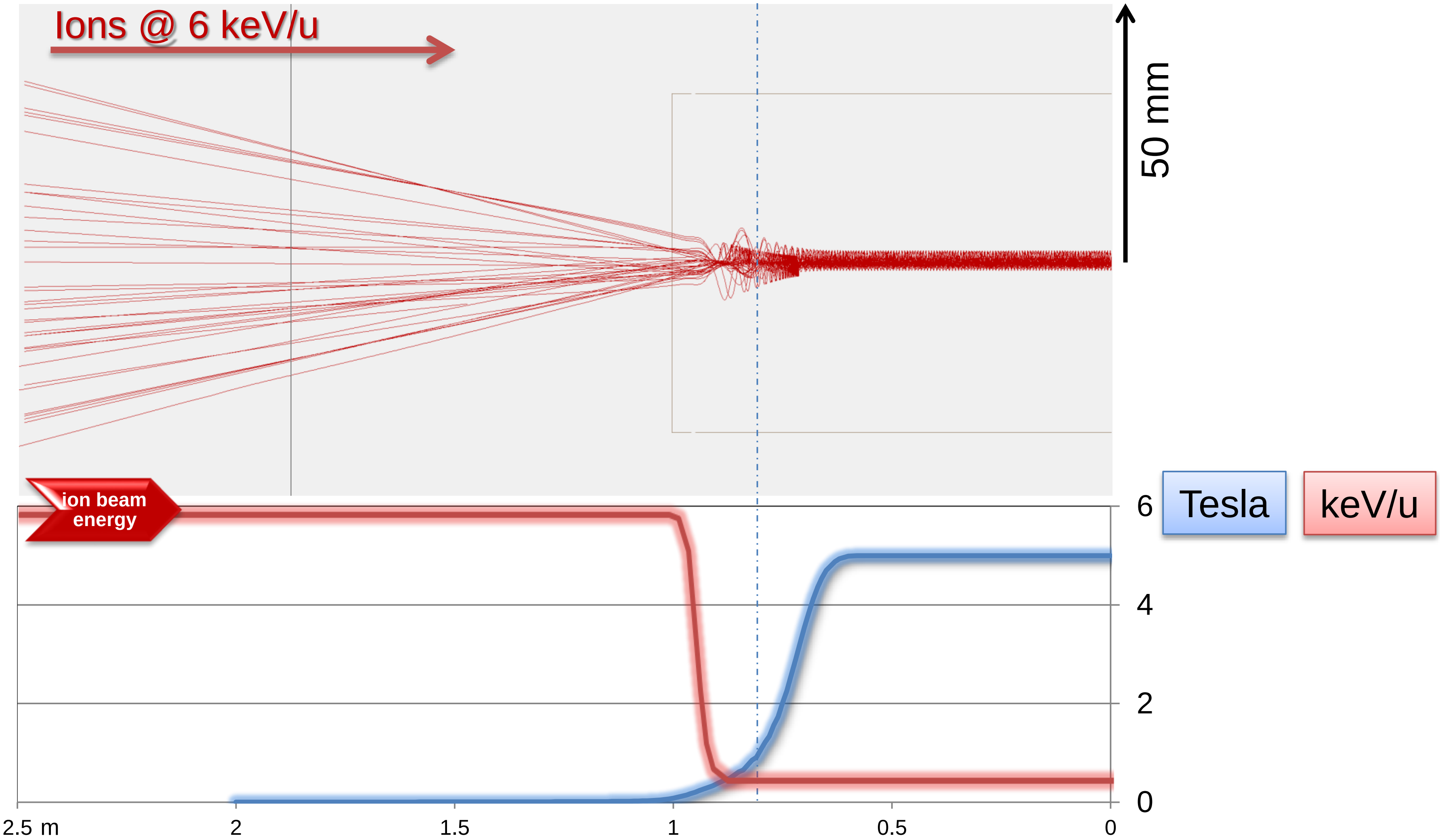
Injection into strong Magnetic Field



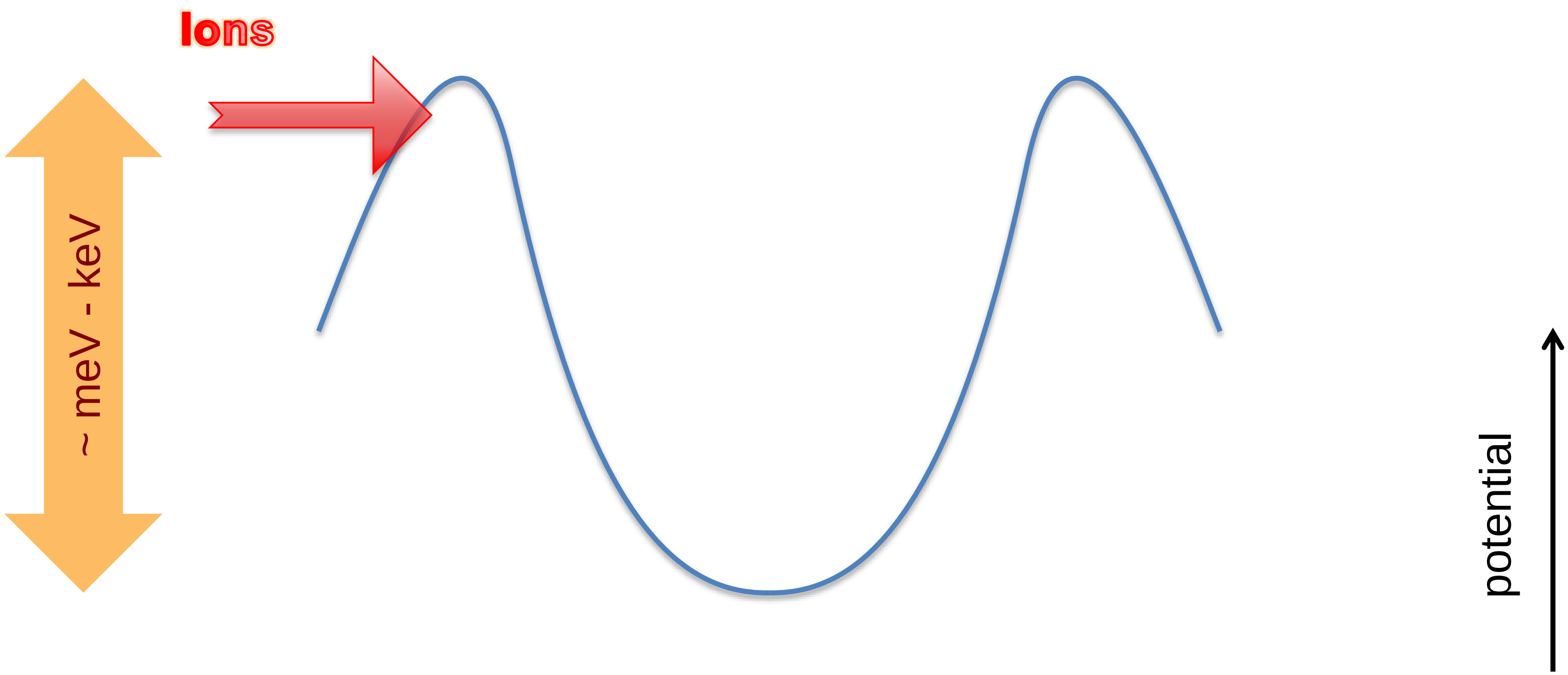
Injection into strong Magnetic Field



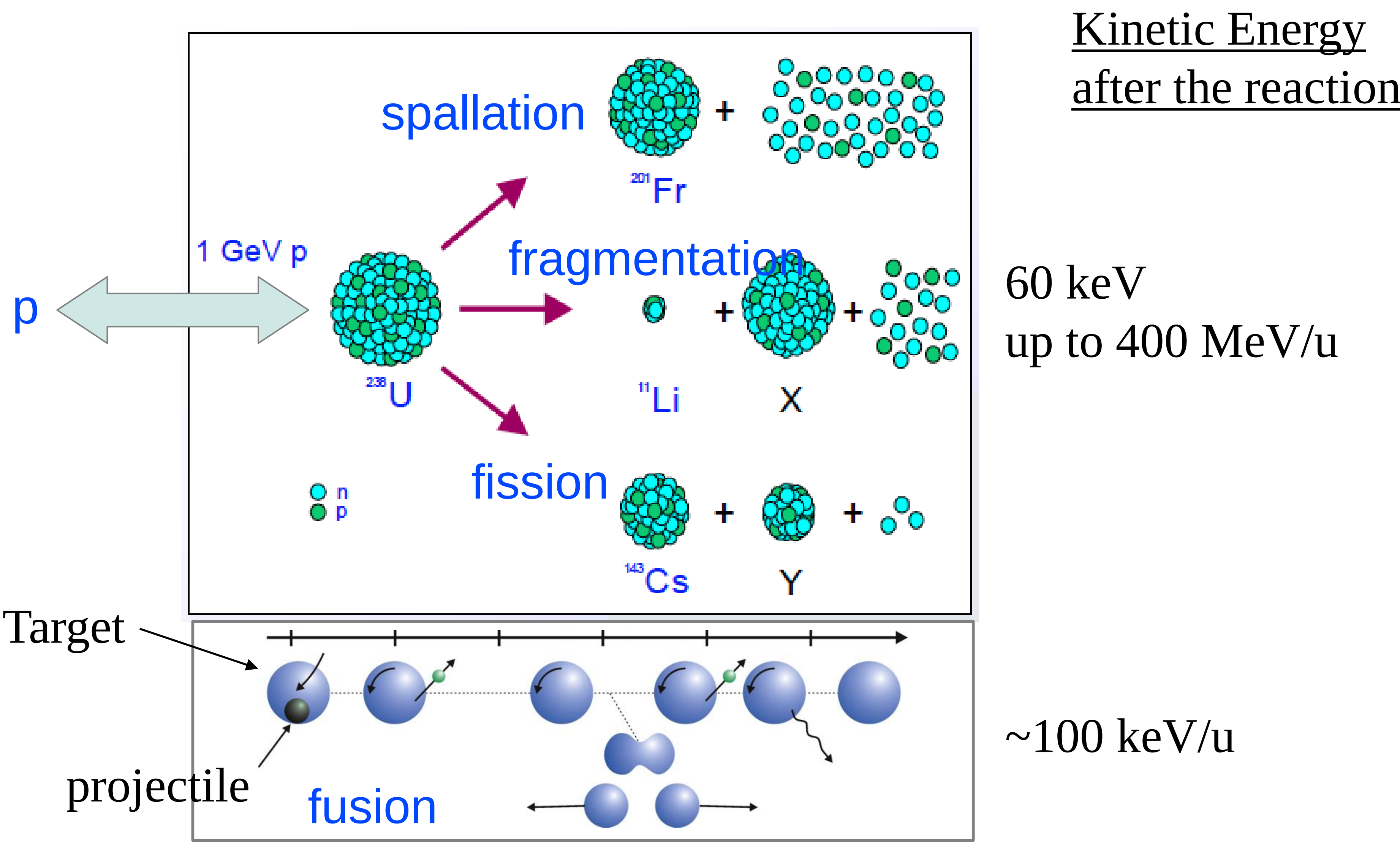
Injection into strong Magnetic Field



Injection of Ions – Requires Preparation

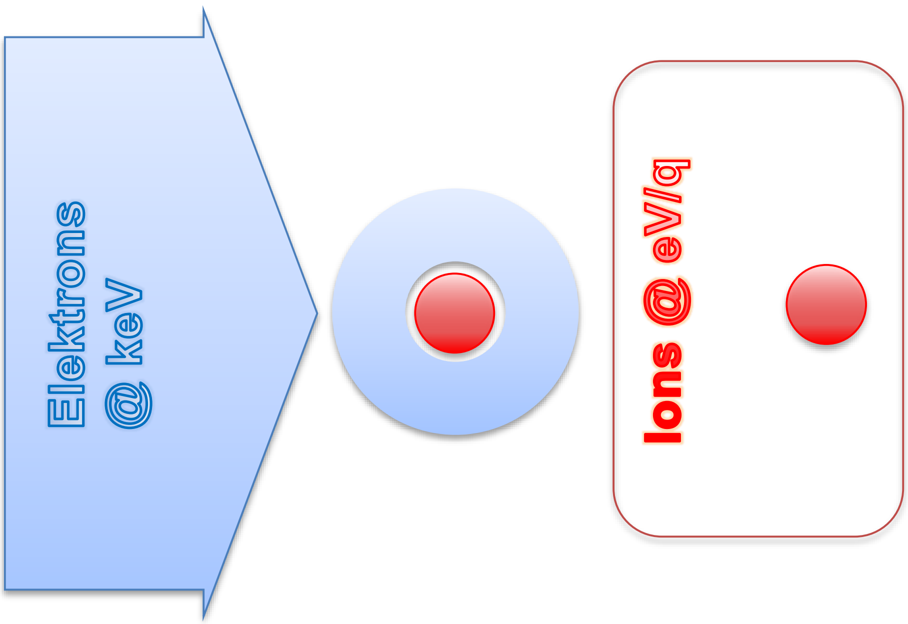


Production of short-lived Nuclei



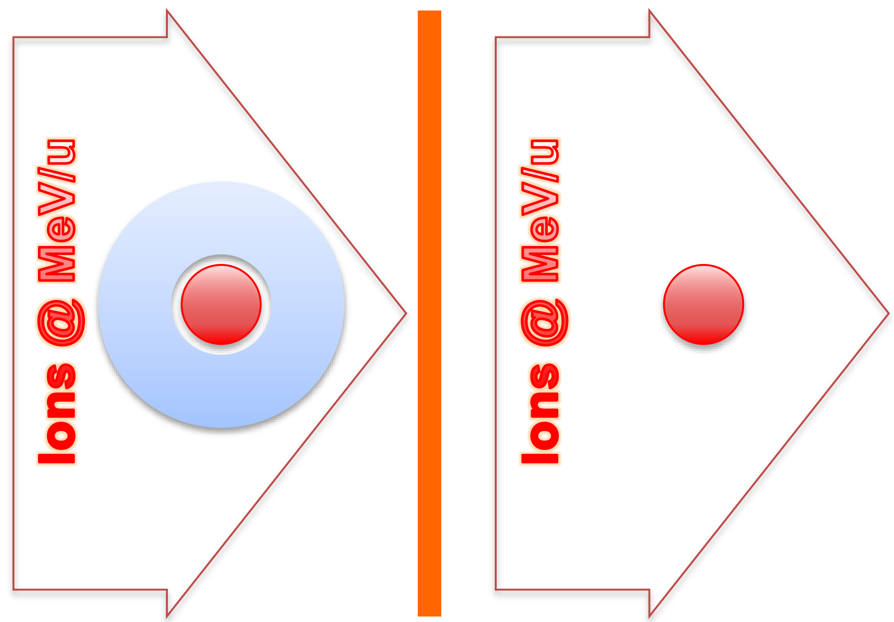
Production of heavy, highly charged Ions (HCI)

Bombard with Electrons



- rather small and “simple”
- temperature_{ion} ~ eV/q

Bombard Electrons



metall foil

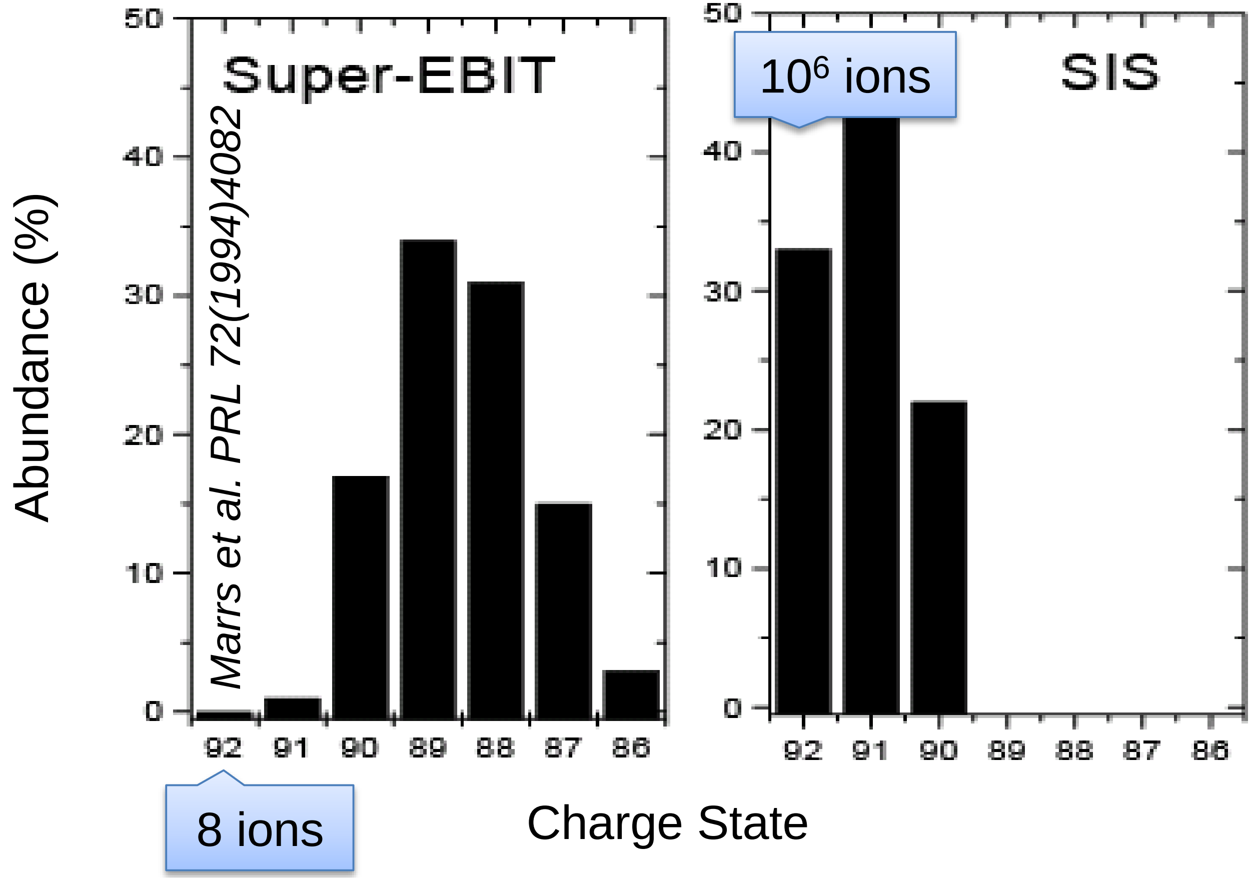
(full of electrons)

- fast and efficient
- works too for millions of uranium ions

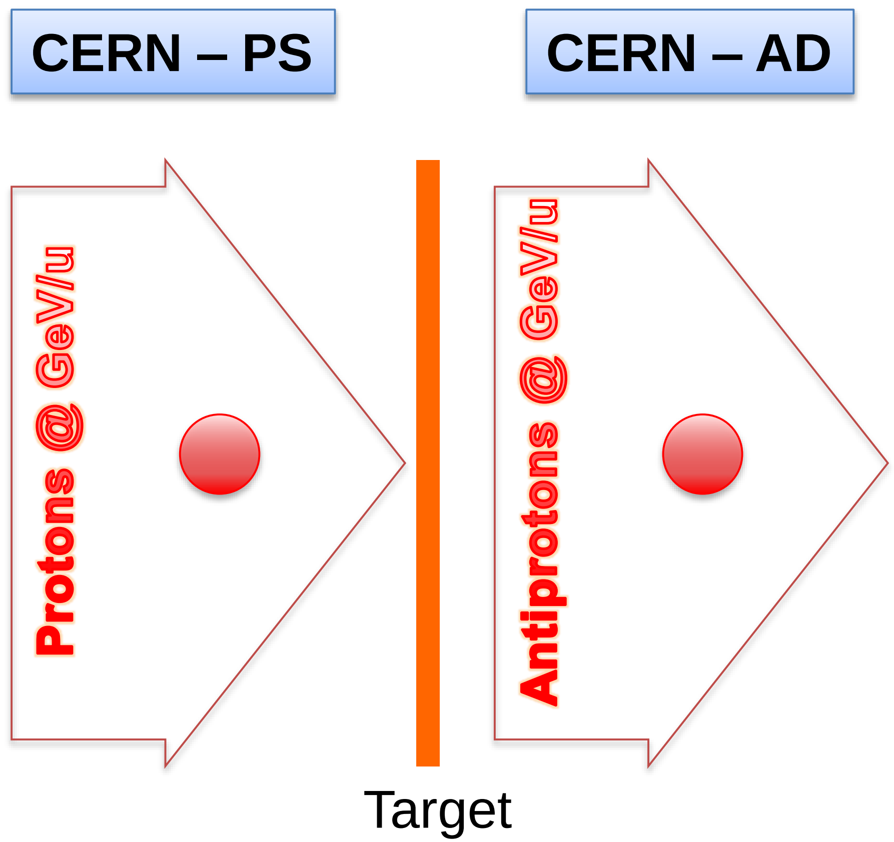
Production of HCI: Uranium

$E_{electron}$ = 198 keV

E_{U26+} = 360 MeV/u



Production of Antiproton



Why is it a problem?

Production energy >> trap potential

(We try to capture the results of an explosion in a card box)

Great variety of energies and species after production

(It's a mess)

Exotic ions are rare!

(Luckily just a few per measurement are often enough)

They are delicate.

(Some decay quickly and some “dislike” matter)

Want to have exotic Ions in a Trap!

Solutions:

Production energy >> trap potential

Decelerate/Stop in matter and/or electrically.

Great variety of energies and species after production

Cooling and Purification for instance using trap-specific properties.

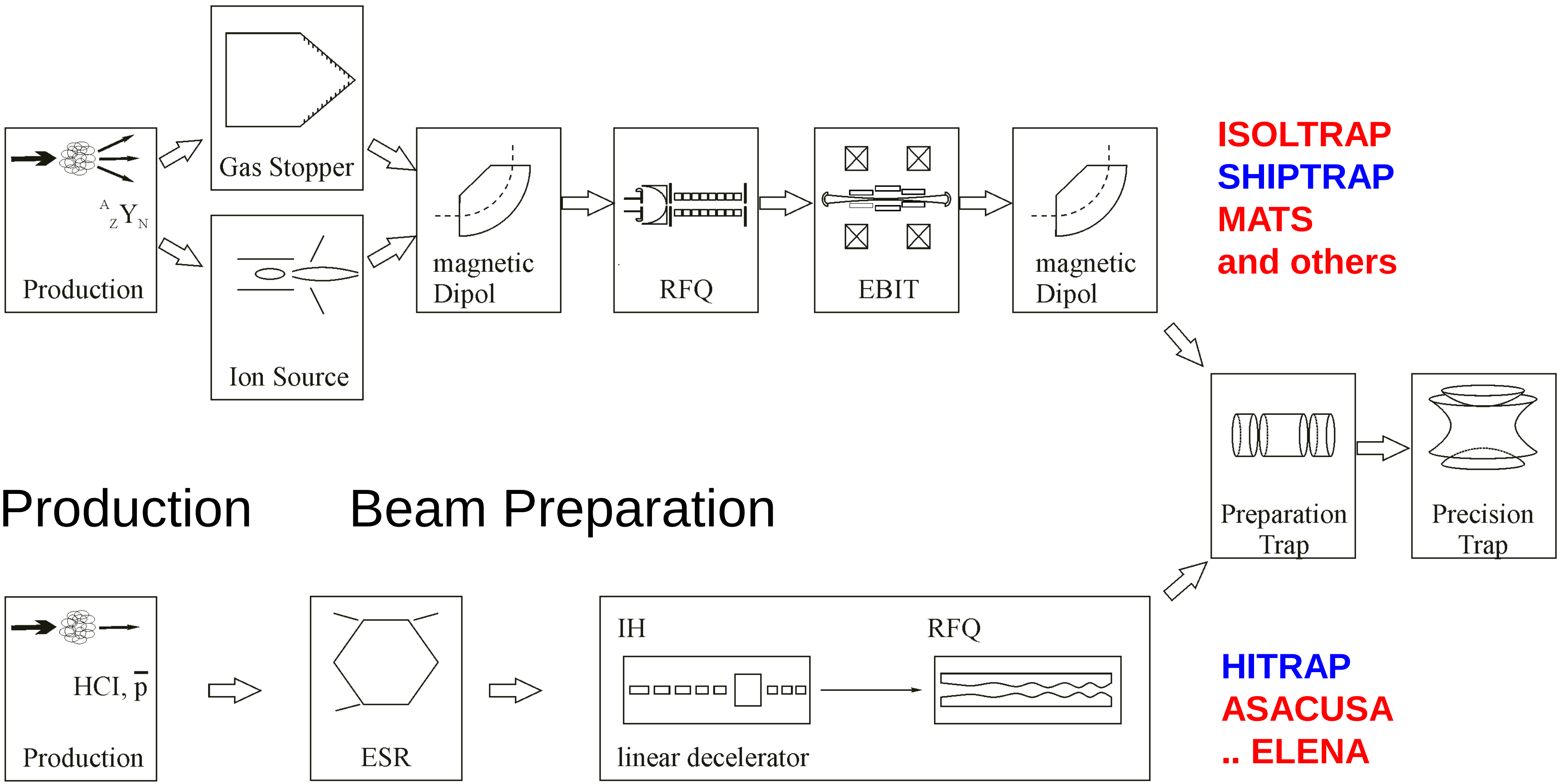
Exotic ions are rare!

Be efficient!

They are delicate.

Be fast and handle them carefully!

Trap Facilities for exotic Ions



Production

Beam Preparation

ISOLTRAP
SHIPTRAP
MATS
and others

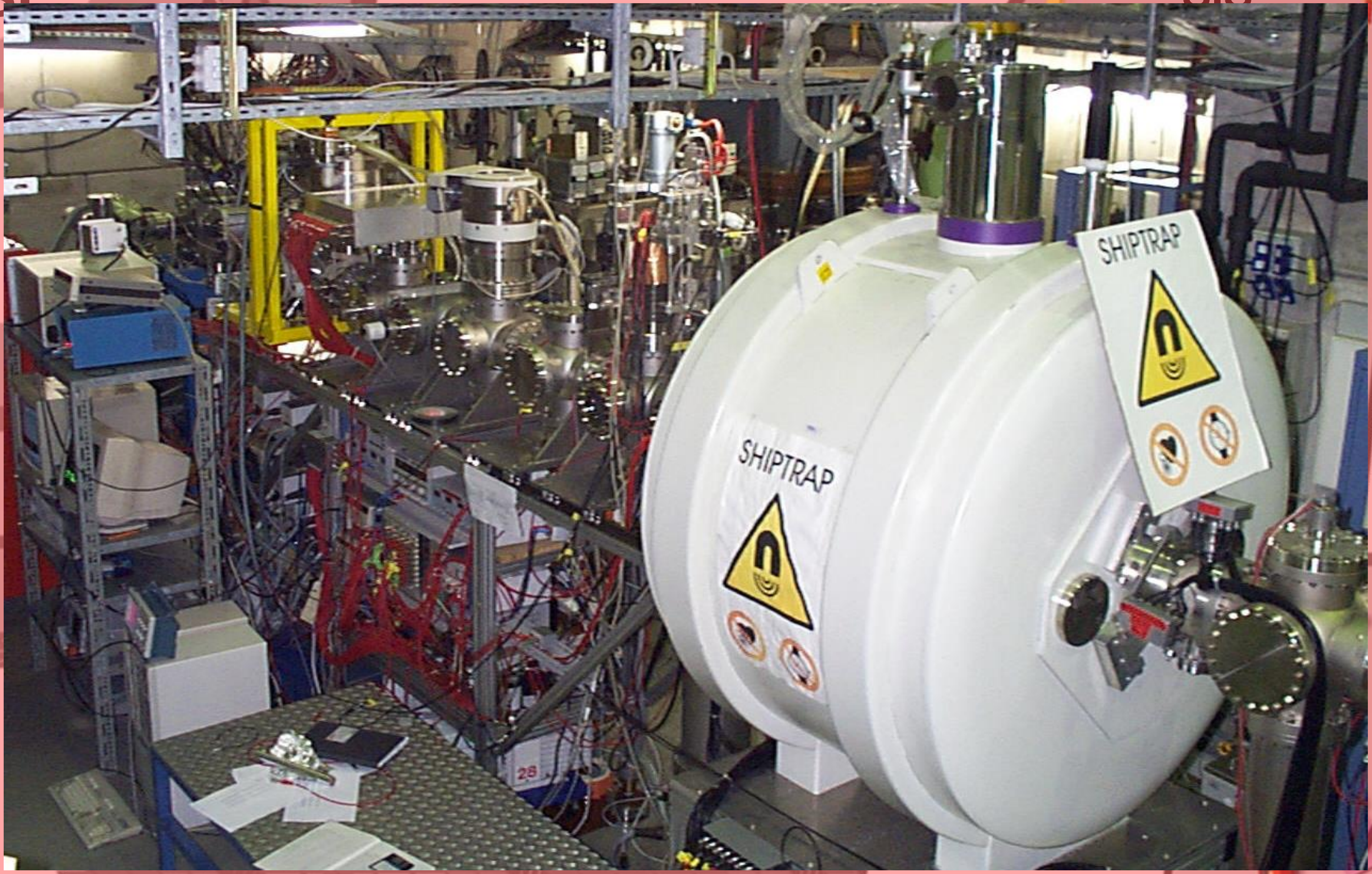
HITRAP
ASACUSA
.. ELENA

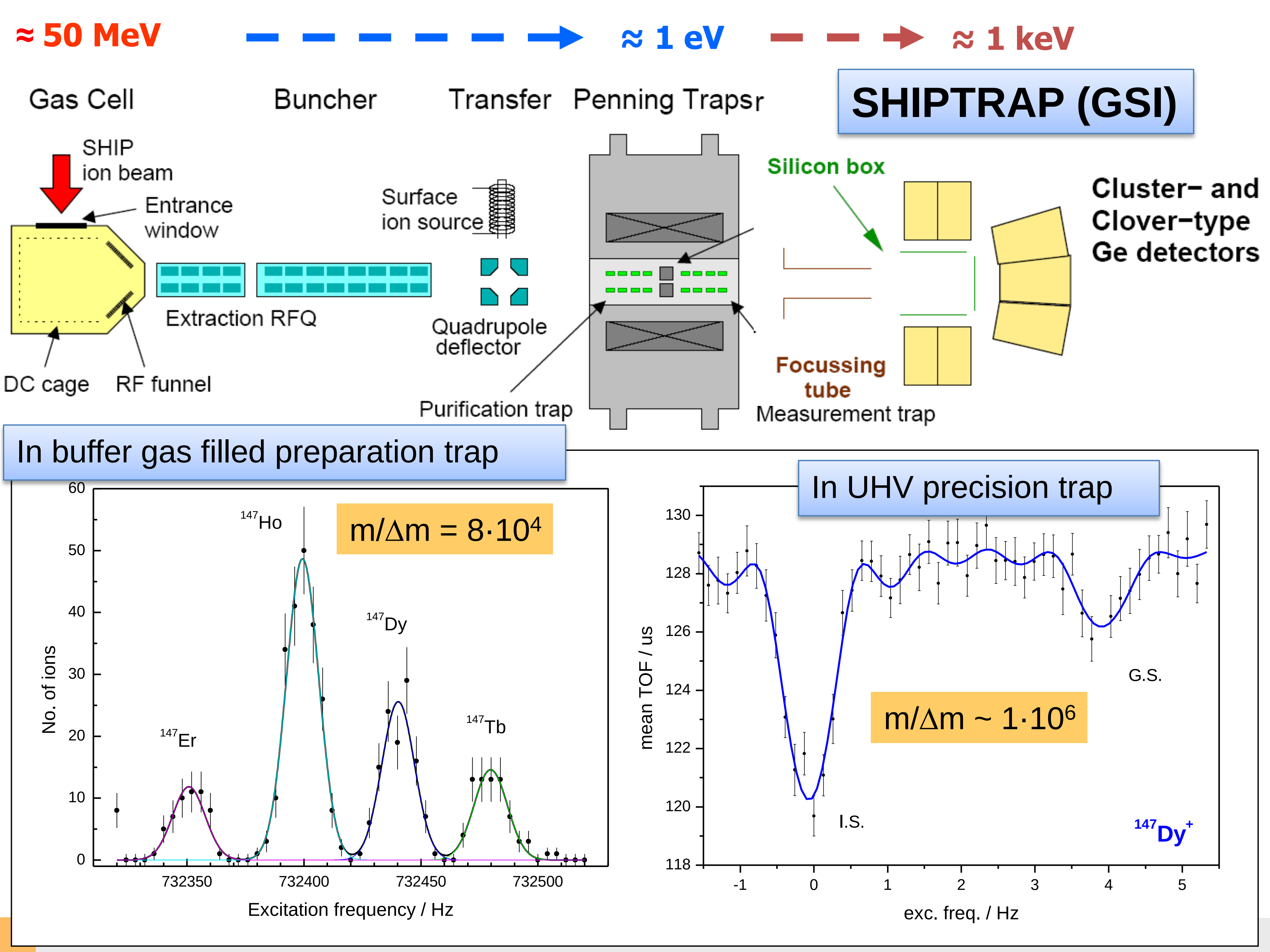
SHIPTRAP @

GSI

SIS

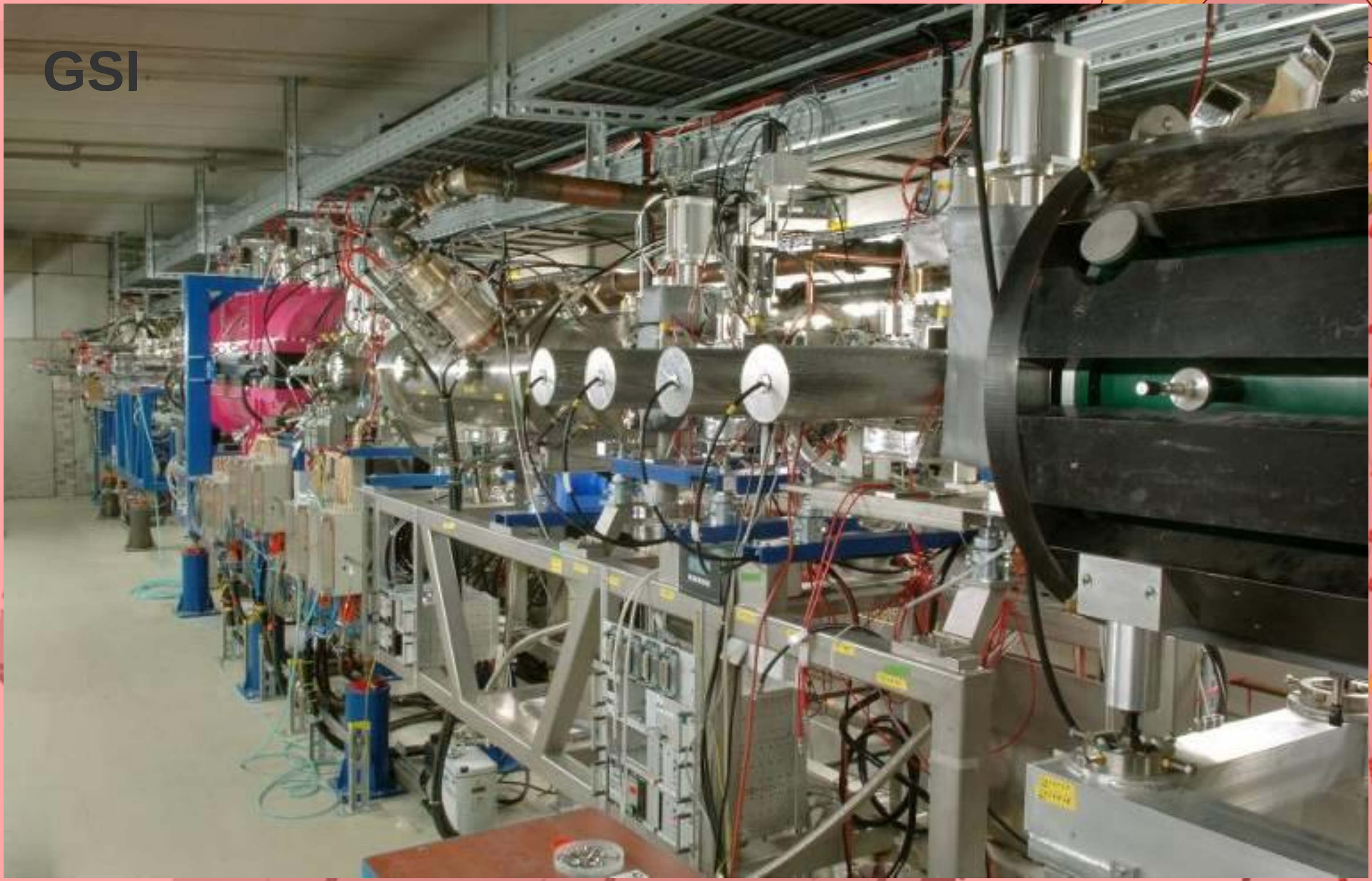
GeV/u




≈ 50 MeV
≈ 1 eV
≈ 1 keV
Gas Cell
Buncher
Transfer
Penning Trapsr
SHIPTRAP (GSI)
SHIP
ion beam
Entrance
window
Surface
ion source
Silicon box
Cluster– and
Clover–type
Ge detectors
Extraction RFQ
Quadrupole
deflector
DC cage
RF funnel
Focussing
tube
Purification trap
Measurement trap
In buffer gas filled preparation trap
In UHV precision trap
m/Δm = 8·10^4
147Ho
147Dy
147Er
147Tb
No. of ions
Excitation frequency / Hz
60
50
40
30
20
10
0
732350
732400
732450
732500
mean TOF / us
130
128
126
124
122
120
118
-1
0
1
2
3
4
5
exc. freq. / Hz
G.S.
I.S.
m/Δm ~ 1·10^6
147Dy+

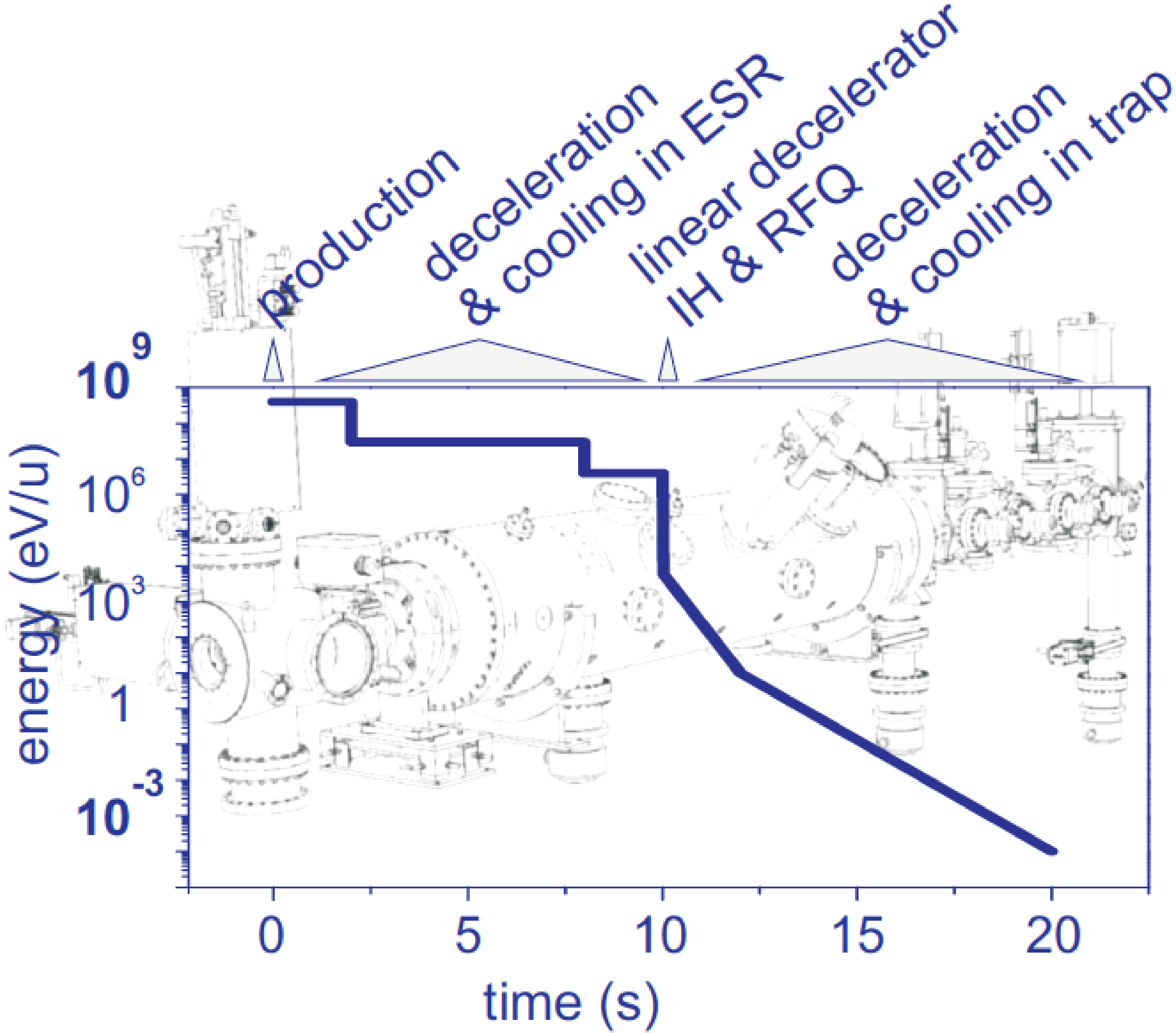
HITRAP @

GSI



GeV/u

Experimens with slow, heavy, highly charged ions - HITRAP

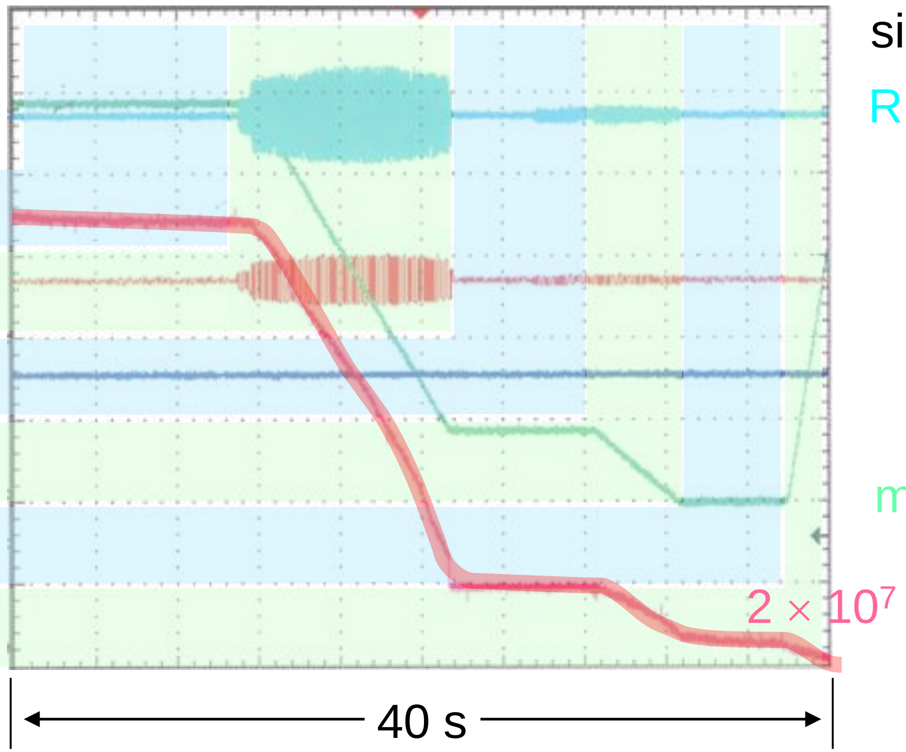


ESR – From 400 to 4 MeV/u

ESR – Experimental Storage Ring at GSI with stochastic and electron cooling

Ni^{28+} 400 → 30 → 4 MeV/u

time (s)	**ESR cycle during recent experiment**
5..20	injection, **stoch. cooling**
3..10	deceleration 400 – 30 MeV/u
2..6	e^- cooling, rebunching
2..5	deceleration 30 – 4 MeV/u
2..5	e^- cooling, ejection
3	reset magnets



signal:

RF amplitude

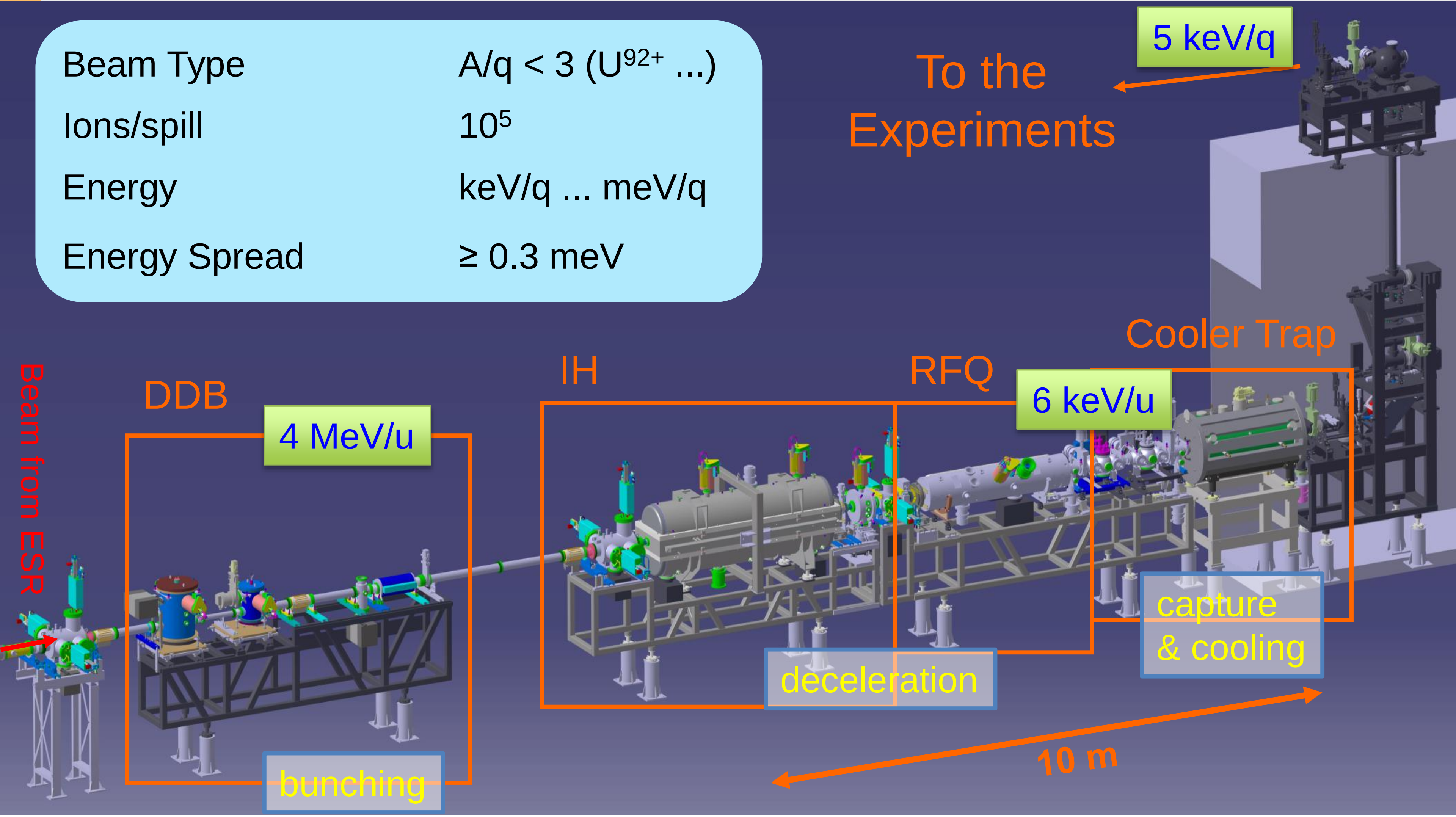
magn.dipole field

ion current

1100 μA → 180 μA → 25 μA

HITRAP – a linear Decelerator and Trap

Beam Type	A/q < 3 (U^{92+} ...)
Ions/spill	10^5
Energy	keV/q ... meV/q
Energy Spread	≥ 0.3 meV



HITRAP – a linear Decelerator and Trap

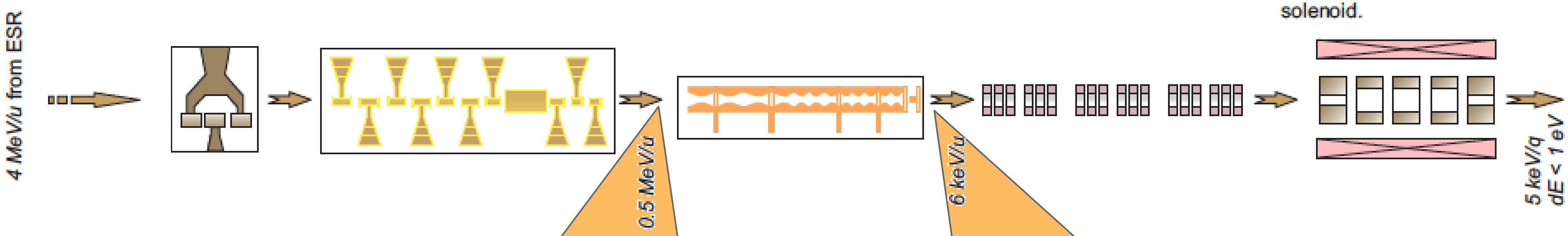
Double Drift Buncher running at 108.408 and 216.816 MHz

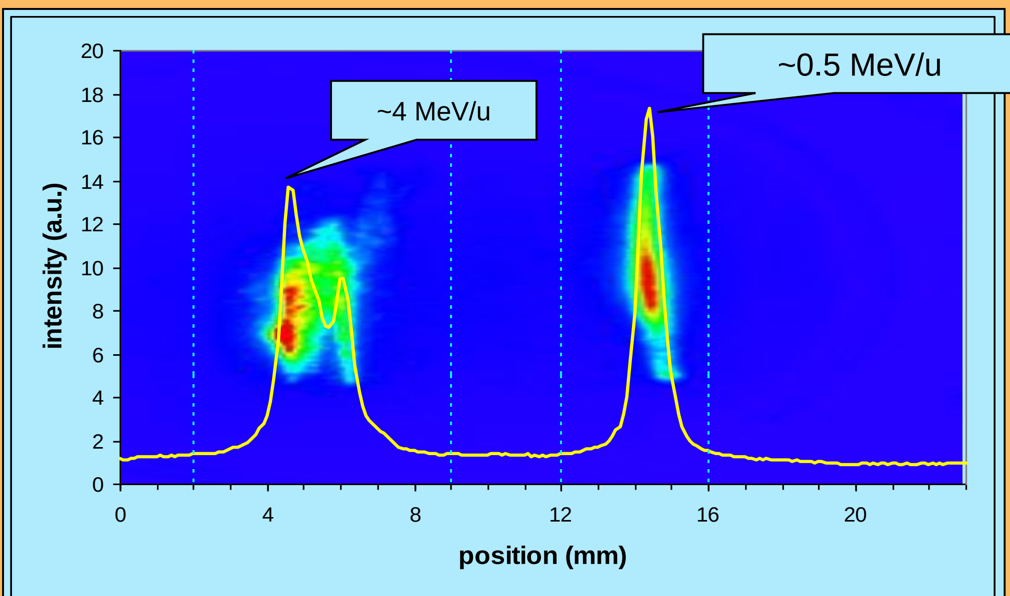
Interdigital H-type linac (*IH*) with integrated magnetic quadrupole triplet and steerer

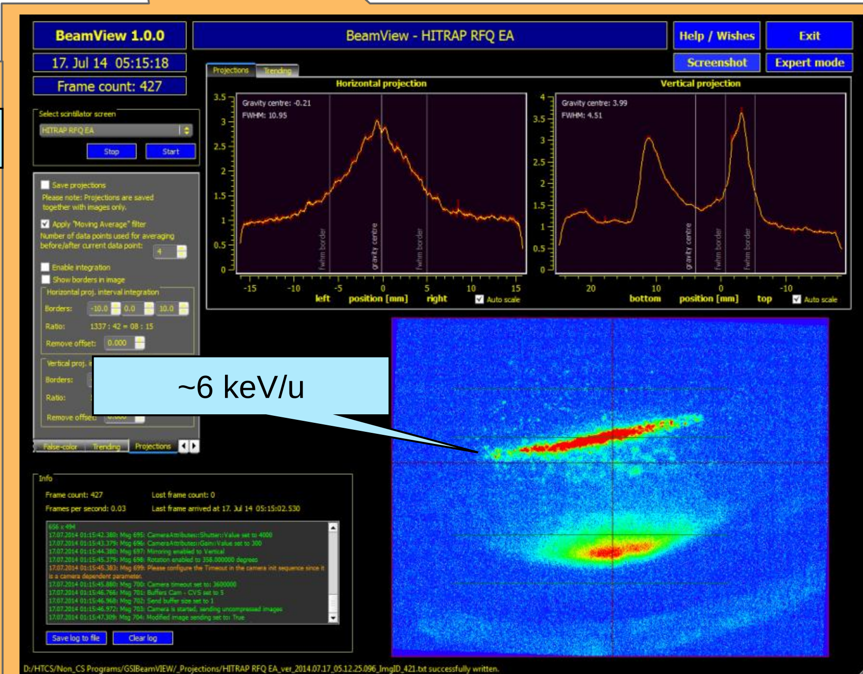
Four-rod radiofrequency quadrupole linac (*RFQ*) with integrated debuncher

Low energy beam transport line (*LEBT*) based on electrostatic *einzel lenses* and with integrated differential pumping barriers

Cooler Penning trap (TRAP) in the 400 mm long homogeneous field of a 6 Tesla superconducting solenoid.







Experiments with exotic Ions in Traps – require Injection of ions into Trap

Exotic Ions
- radioactive = short lived
- (heavy) highly charged ions (HCI)
- antimatter

This Seminar

Experiments in Traps
- precision spectroscopy
- (heavy) highly charged ions (HCI)
- Antimatter
- watching them decay