Secondary Beams

Helmut Weick, GSI Helmholtzzentrum

CERN Accelerator School on beam injection, extraction and transfer
Erice, 17th March 2017

- **Which Secondary Particles?**
- **Motivation (Why and Where ?)**
- **Production Reactions**
- **Influence on Emittance**
- **Limits by Targets**
- **Separation**
- **Diagnostics**

Which Secondary Particle?

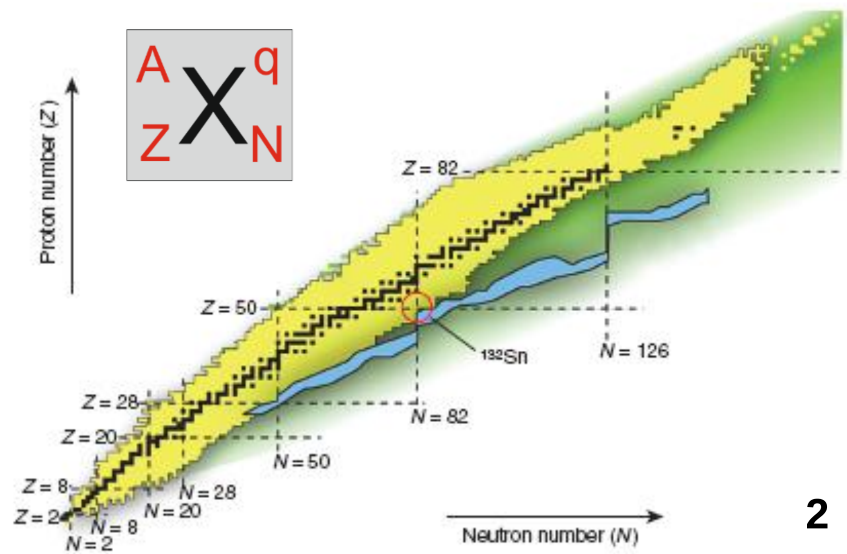
1.) It should have charge !

2.) Lifetime: γ = Lorentz factor

- ★ positron e^+ (stable) — $m_e = 0.511$ MeV/c^2
- ★ muon $\mu^{+/-}$ $\tau = 2.2\ \mu s \; * \gamma$ — $m_\mu = 105.7$ MeV/c^2
- ★ pion $\pi^{+/-}$ $\tau = 26$ ns $* \gamma$ — $m_\pi = 139.6$ MeV/c^2
- ★ antiproton $\bar{p}$ (pbar, stable) — $m_p = 938.3$ MeV/c^2
- ★ RIBs = rare isotope beams
  - ~ 2200 with $\tau > 1$ ms,
  - ~ 1100 with $\tau > 1$ min,
  - some $\tau = 10^n$ years

  $m = 3 \,..\, 260$ amu

  $= 3 \,..\, 260 \times 938.5$ MeV/c^2



Where ?

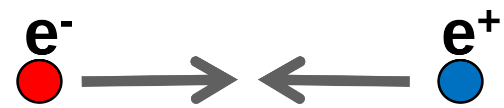
stopped, running, under construction, plans

positrons: BINP (VEPP-2, VEPP-4, VEPP2000), DESY (DORIS, PETRA), Cornell (CESR), CERN (LEP), SLAC (SPEAR, PEP II), KEKB => Super-KEKB, BEPC => BEPC-II, LN Frascati (ADA, ADONE, DAΦNE), ILC, CLIC (all e^+e^- colliders)

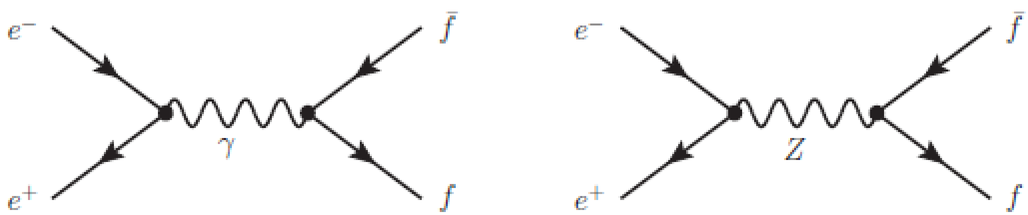
Why ?

Example for e^+e^- collider

Goal: set free energy in a collider after annihilation,
For symmetric collisions we release all energy.
$E = 2 \times 511\ keV/c^2 + 2 \times$ kinetic energy

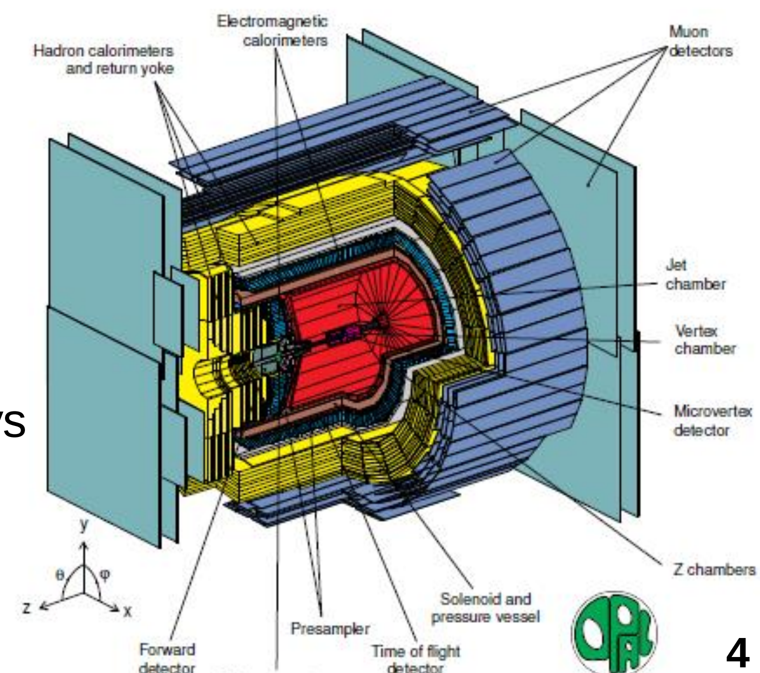


Z^0-Boson, $m = 91.2\ GeV/c^2$ measured exactly in LEP
with energy 45.5 GeV for e^+ and e^- to reach $91.2\ GeV/c^2$,
Using antiparticles makes cross section
much larger and reaction possible at all.



f = other Fermions (70% hadrons) with further decays
observed decay products, 17×10^6 collision events

➔ **exact mass of Z^0 and W^+, W^-**

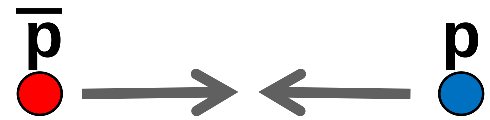


OPAL detector (1 of 4 det. in LEP)

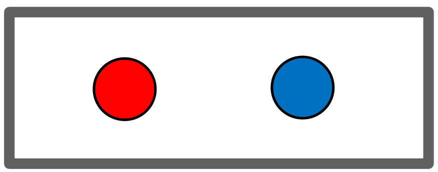
Why ?

Examples for $\bar{p}$+p collider

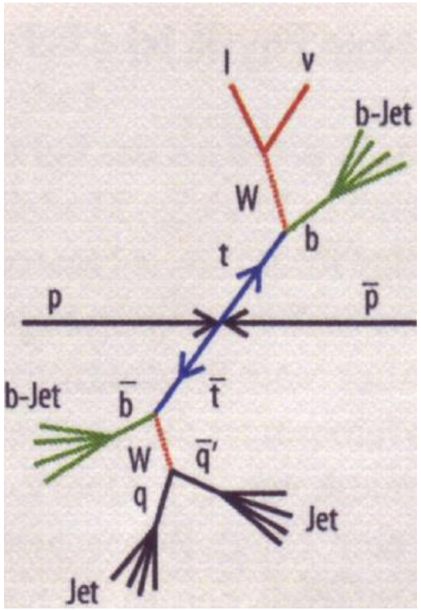
Goal: set free energy in a collider after annihilation,
E = 2 x 938 MeV/c^2 + 2 x kinetic energy



Z^0-Boson m = 91.2 GeV/c^2 first observed directly in SPS converted into a p+$\bar{p}$ collider   (Nobel price 1984, C. Rubbia , S. van der Meer)
Store p + $\bar{p}$ in same ring circulating in opposite directions at E > 44.7 GeV.



Same trick used in Tevatron of Fermilab for discovery of top quark (1995), m_{top} = 173.1 GeV/c^2 .



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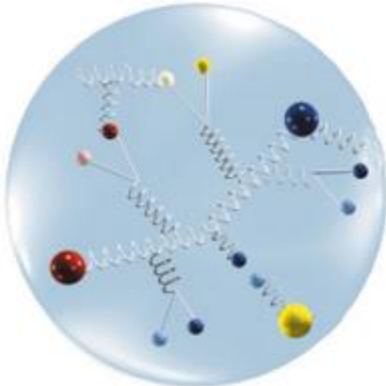
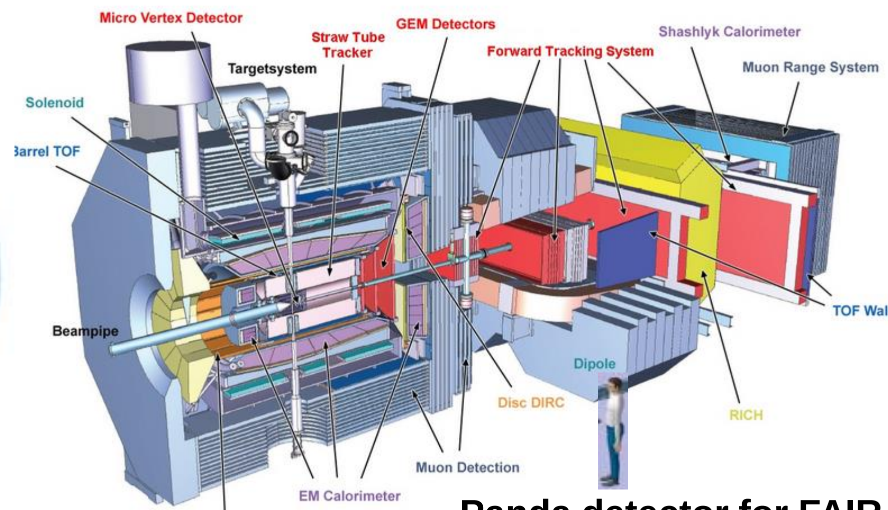
$\bar{p}$ (pbar): CERN PS -> AA -> SPS collider, AC->AA->LEAR, AD -> ELENA
Fermilab Main Ring -> pbar ring -> Tevatron as collider
FAIR SIS-100 -> CR -> HESR -> Cryring

More Experiments with $\bar{p}$

Nucleon Structure (quarks and gluons)

After p+$\bar{p}$ collision new forms of hadronic matter: glueballs (only gluons), or hybrids with quarks.



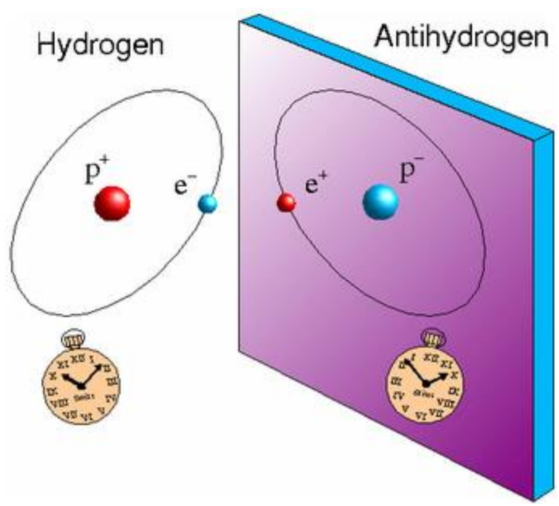


Panda detector for FAIR hydrogen jet target

Does antimatter really behave symmetric to normal matter (CPT theorem) ?

Put $\bar{p}$ in a trap, combine with e^+, (ATRAP, ASACUSA, BASE @ CERN)

Do spectroscopy of anti atom.
Compare mass and magnetic moment of p and $\bar{p}$.



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muons:
Fermilab pbar ring => muon Delivery Ring -> g-2 ring
plans for muon collider

Where ?

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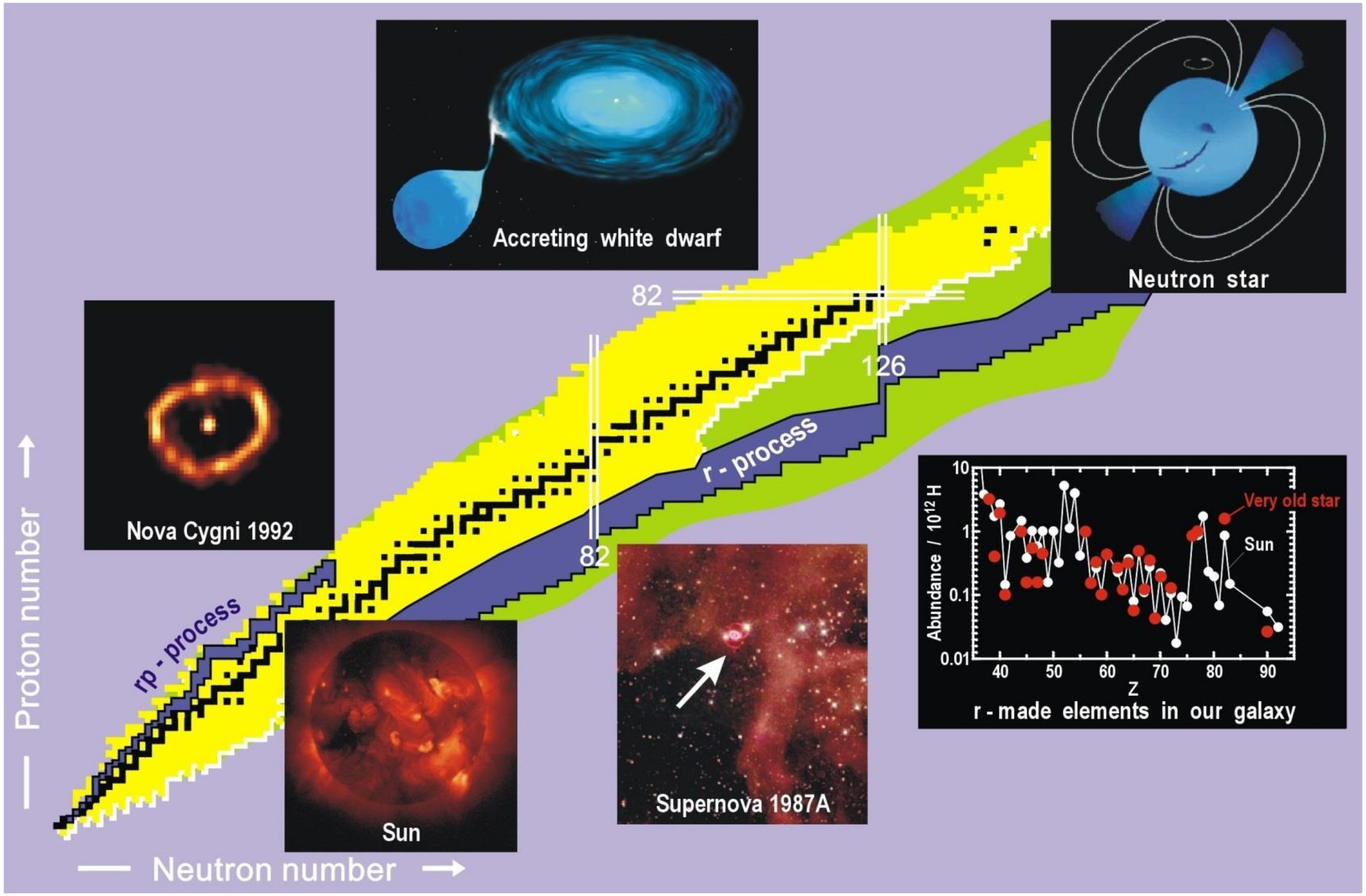
RIBs in flight:
GSI Darmstadt (SIS18 -> FRS -> ESR)
IMP Lanzhou (CSRm -> CSRe)
RIKEN (SRC -> BigRIPS -> Rare RI Ring)
FAIR (SIS100 -> Super-FRS -> CR -> HESR)
HIAF (China) BRing -> SRing

RIBs ISOL:
Many ISOL facilities worldwide, none coupled to a ring, yet.
CERN plan for ISOLDE -> TSR (from MPI Heidelberg)
idea of β beams (ν_e production by β-decay in long ring)

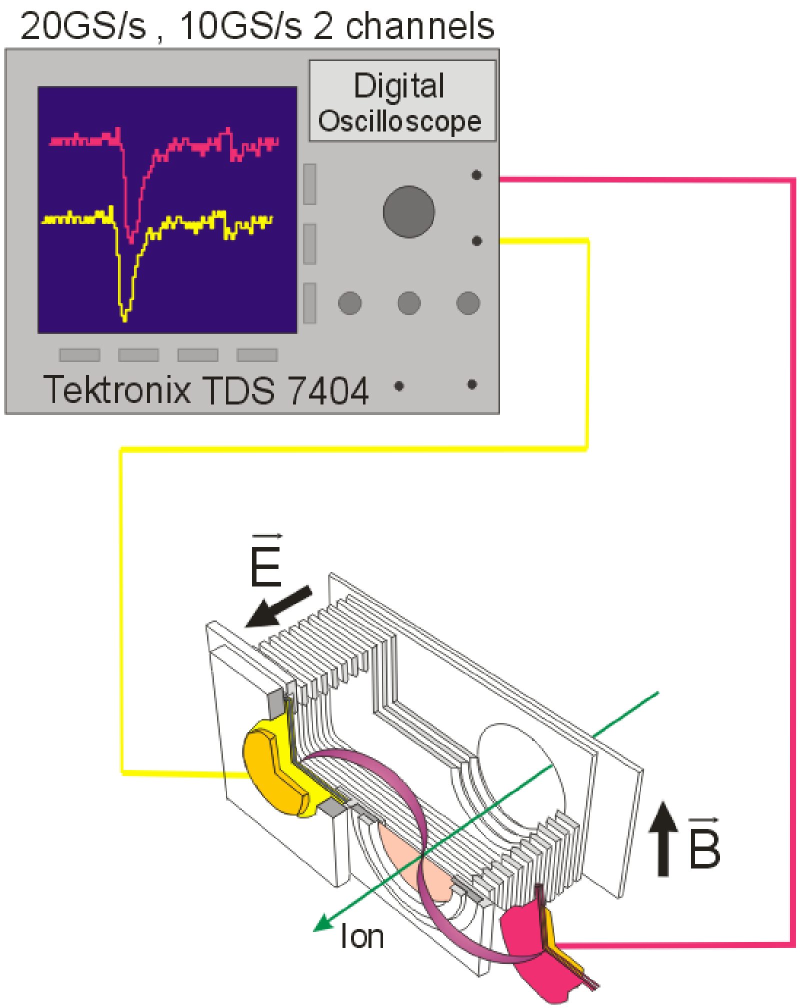
Why ?

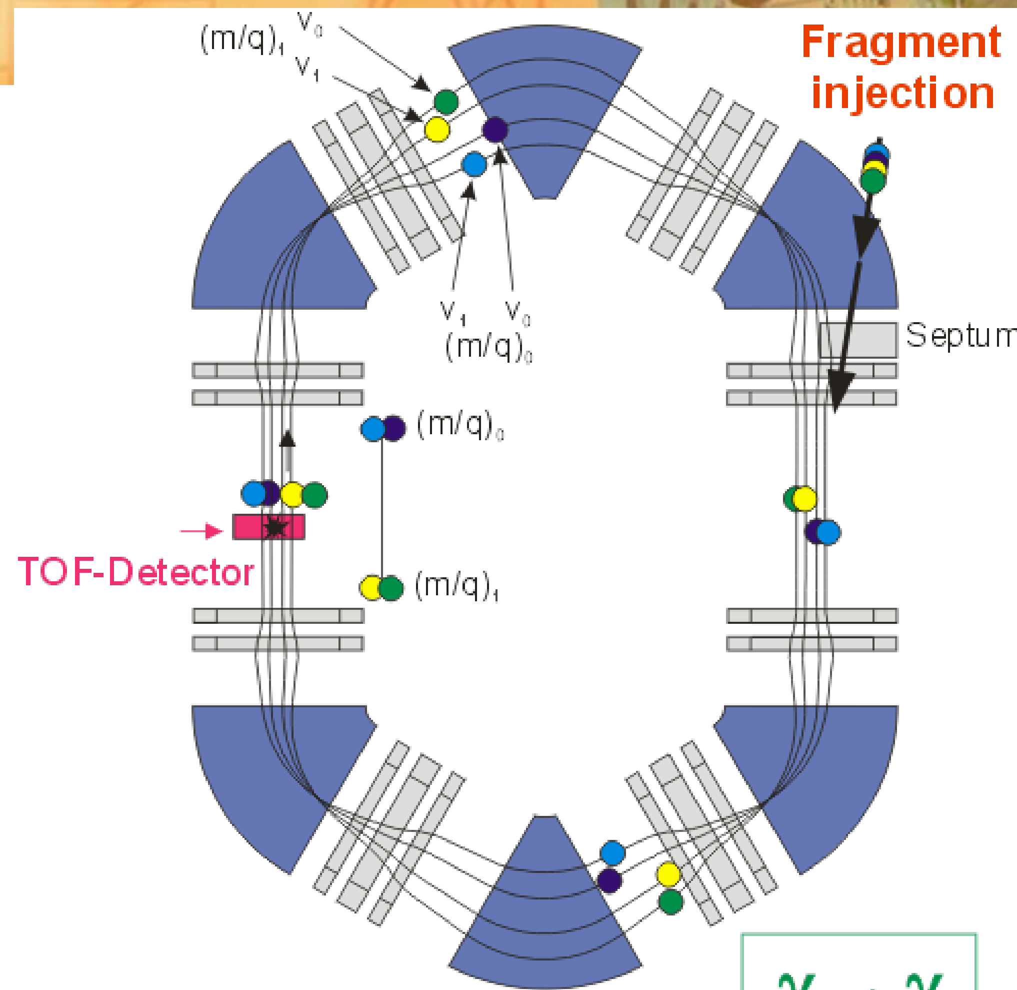
Nucleosynthesis of heavier elements

Should happen in Super-Nova explosions or merging stars, mechanism unclear, must proceed via rare isotopes and successive capture of neutrons/protons and decays. Path depends on binding energy for added nucleons and lifetimes.



Isochronous Mass Spectrometry in the ESR

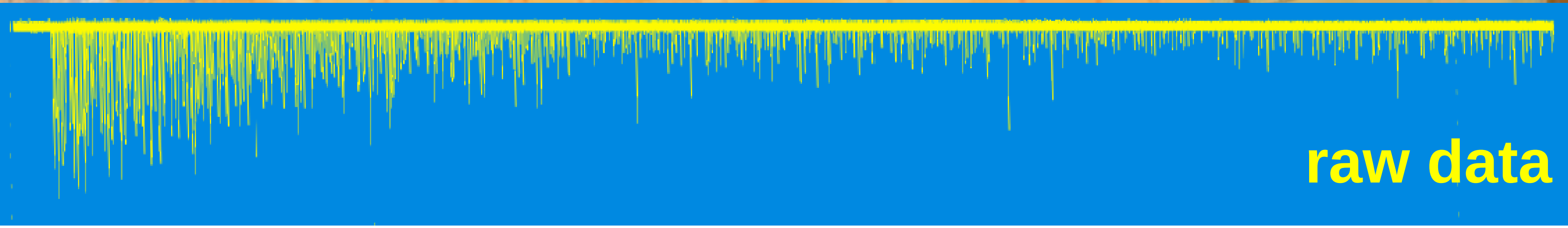




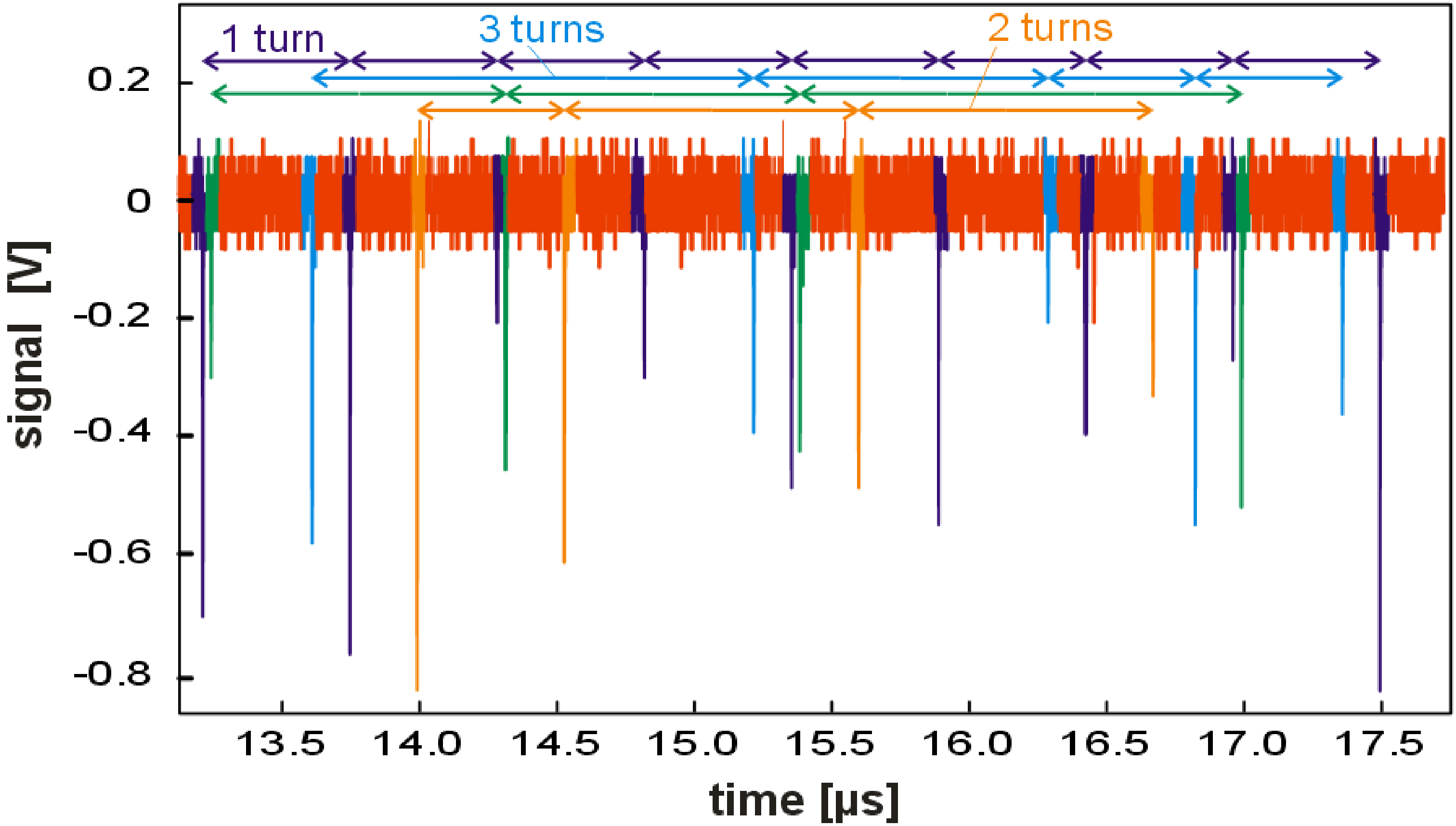
$\gamma_t \rightarrow \gamma$

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1 - \frac{\gamma^2}{\gamma_t^2}\right)$$

Sorting of Ions

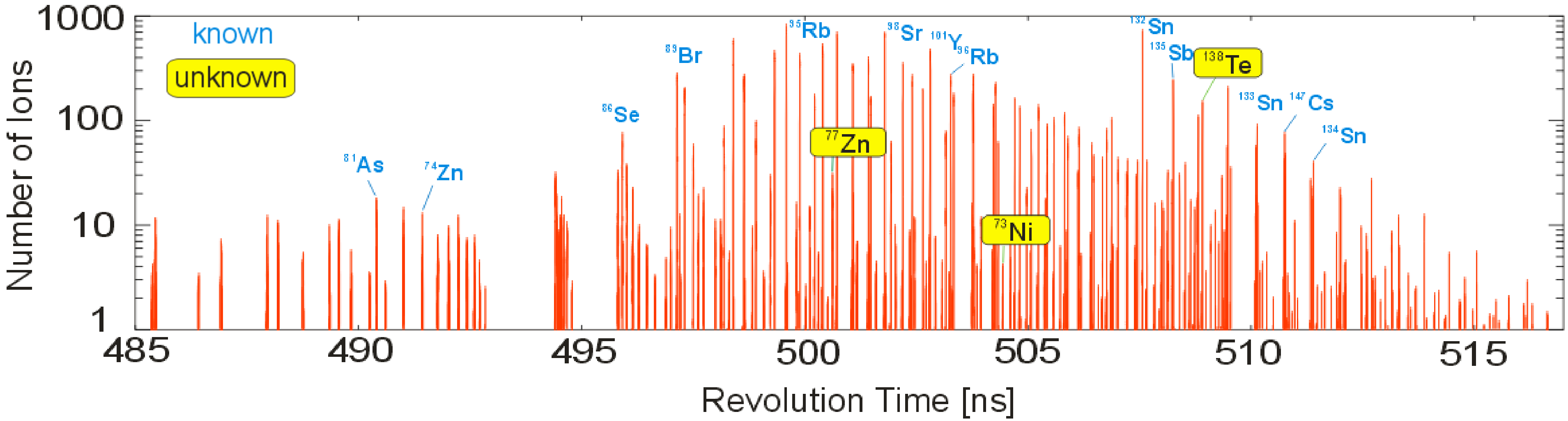


Look for repeating peaks



Time-of-flight Spectrum

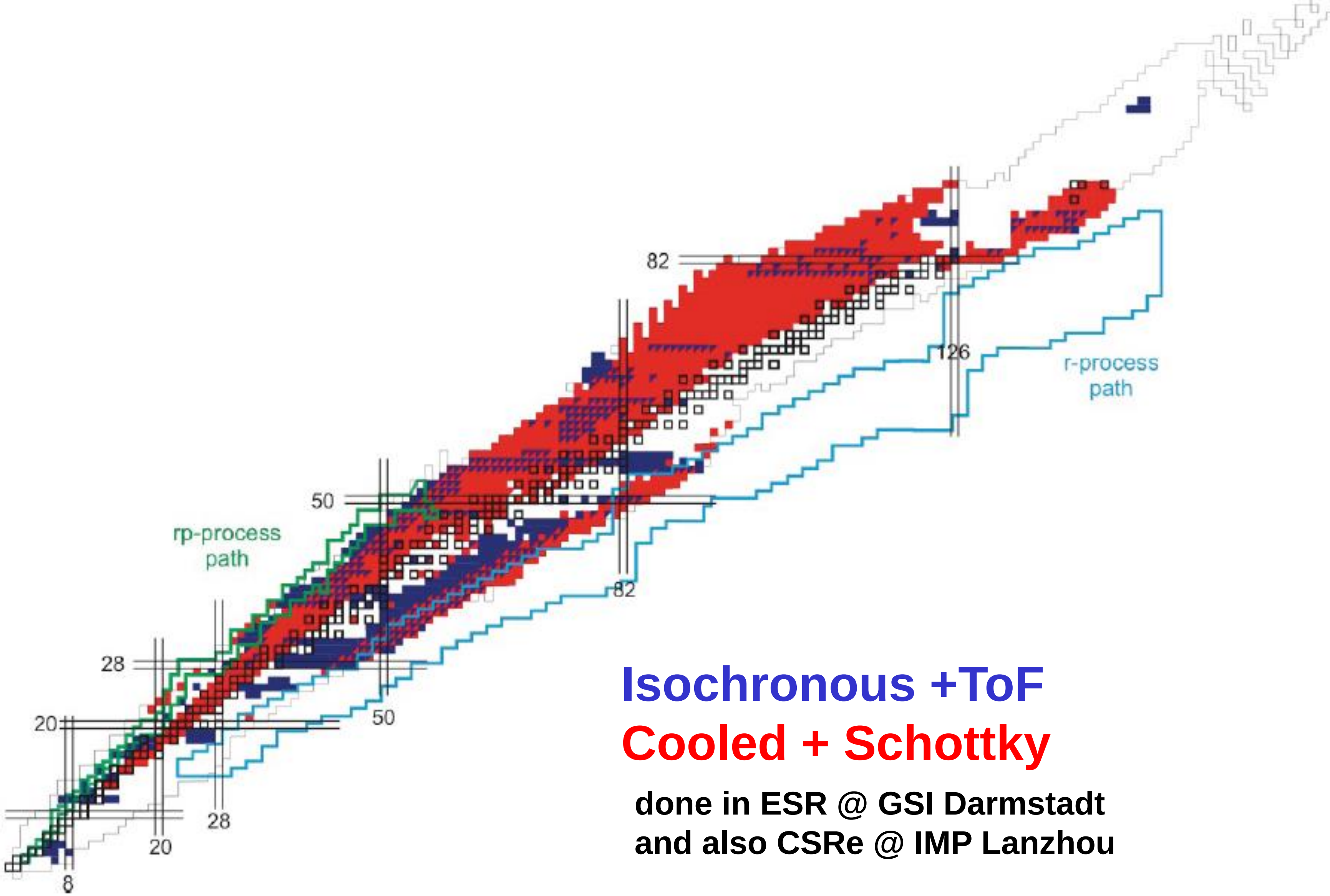
Fragments from fission of ^{238}U



Identification by m/q ratio.

Baohua Sun, thesis Univ. Giessen 2005.

Masses Measured with Storage Rings



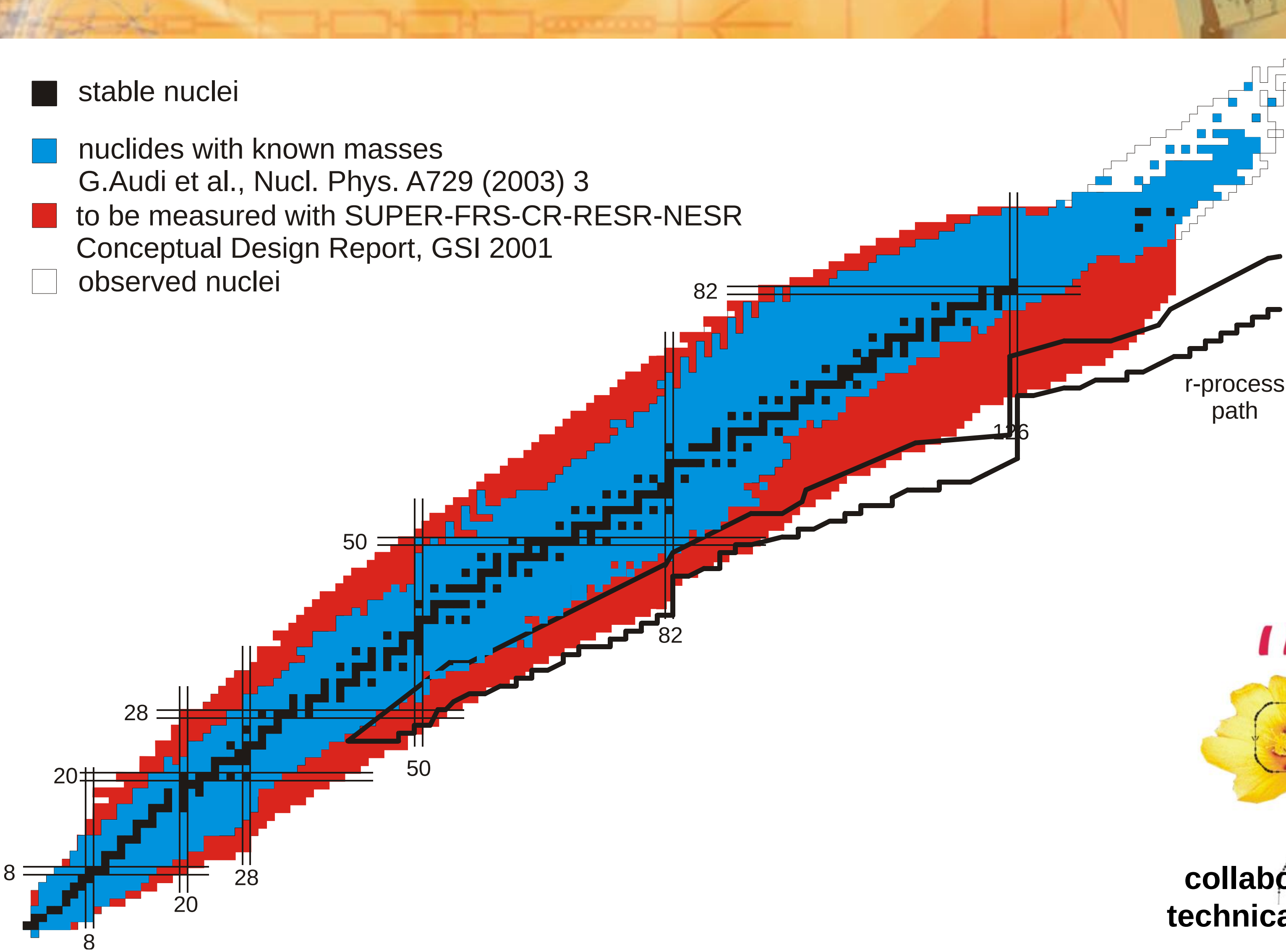
Isochronous +ToF

Cooled + Schottky

done in ESR @ GSI Darmstadt
and also CSRe @ IMP Lanzhou

thesis Daria Shubina, Univ. Heidelberg 2012

Future Possibilities

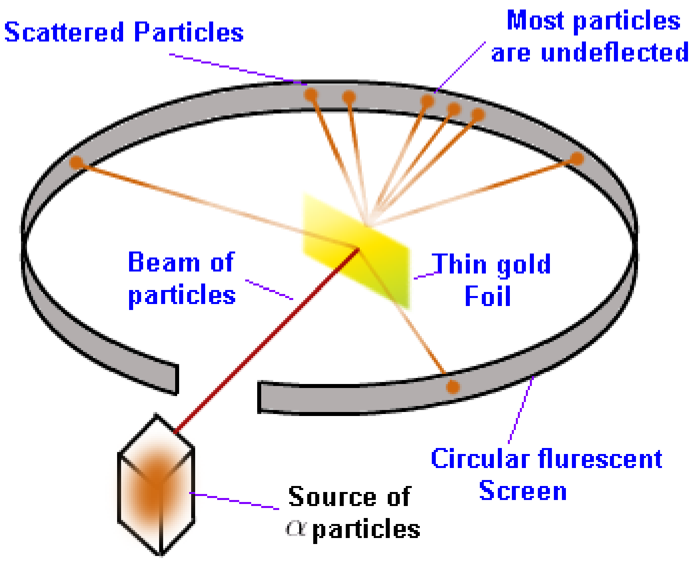


collaboration for FAIR technical proposal 2005

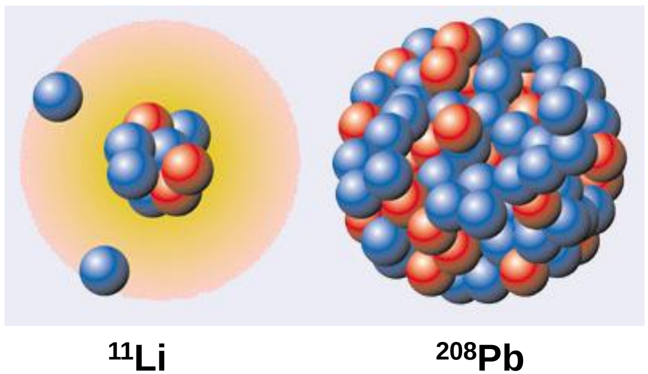
Why ?

Reactions with Rare Isotopes

Proton scattering is a technique to learn about matter distribution.
Like once Rutherford with α particles on gold foil,
with ~ 1 GeV proton beam on target made of material of interest.



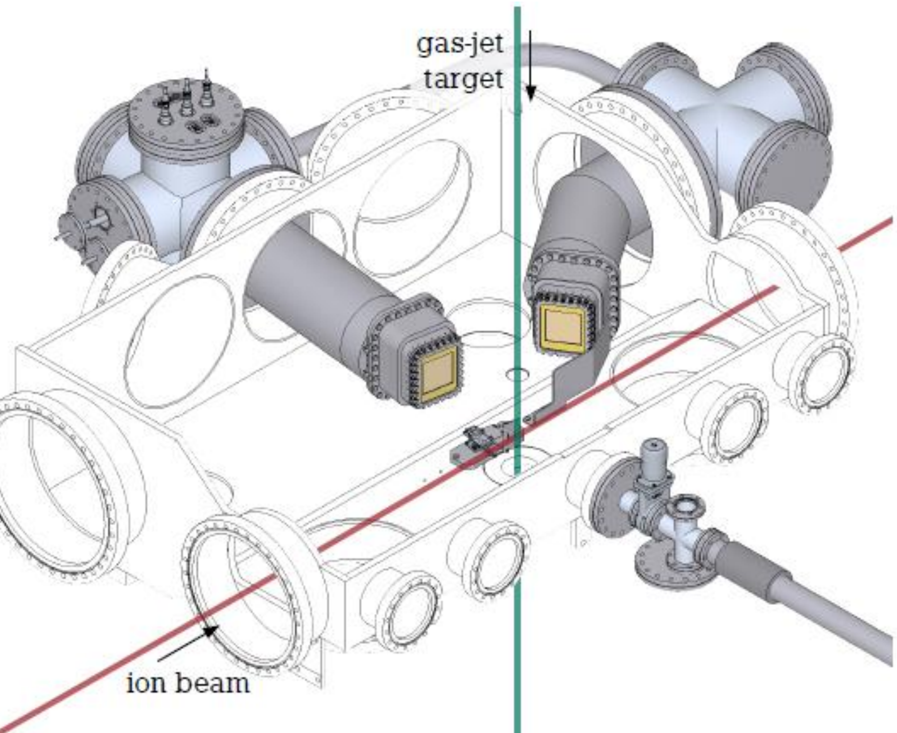
Extremes of matter distribution inside nuclei



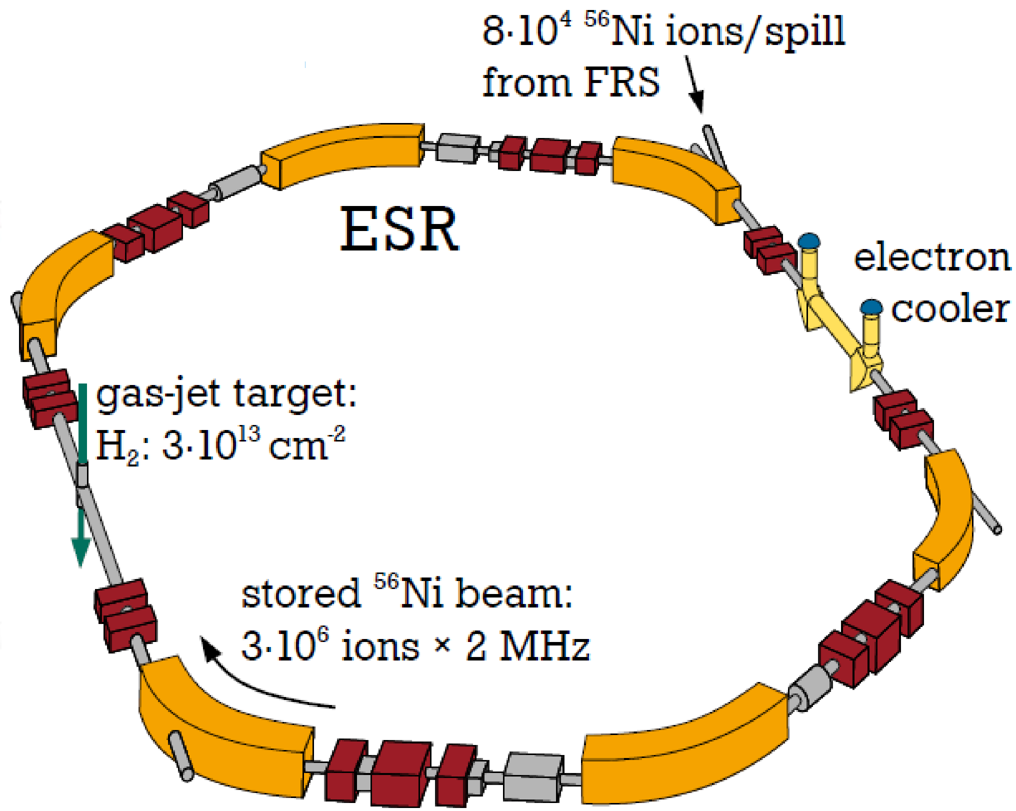
Shape of nucleus follows from shape of scattering distribution.

Not possible for short lived radioactive nuclides.
➔ Reverse role of target and beam, shoot RIB on hydrogen target.
A very clean way and sensitive way is inside a storage ring.

Scattering of RIB on Hydrogen Target



measure position and energy with Si detectors



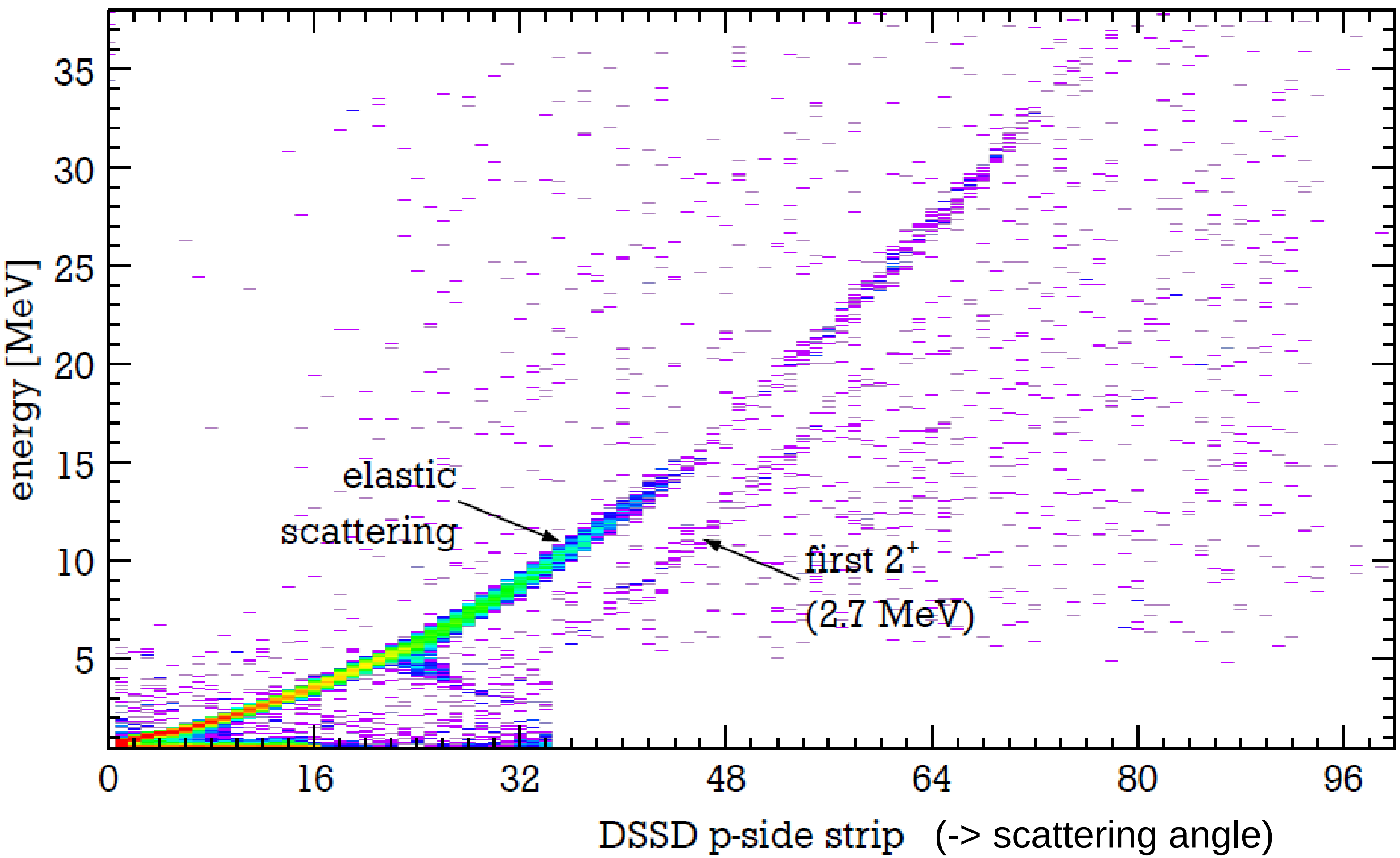
Picture: Phys. Scr. T156 (2013) 014016

luminosity: $2\cdot10^{26}\ \frac{\text{particles}}{\text{s cm}^2}$

⇨ **RMS radius of ^{56}Ni**

M. von Schmid, EXL, Physica Scripta T116 (2015) 014005.

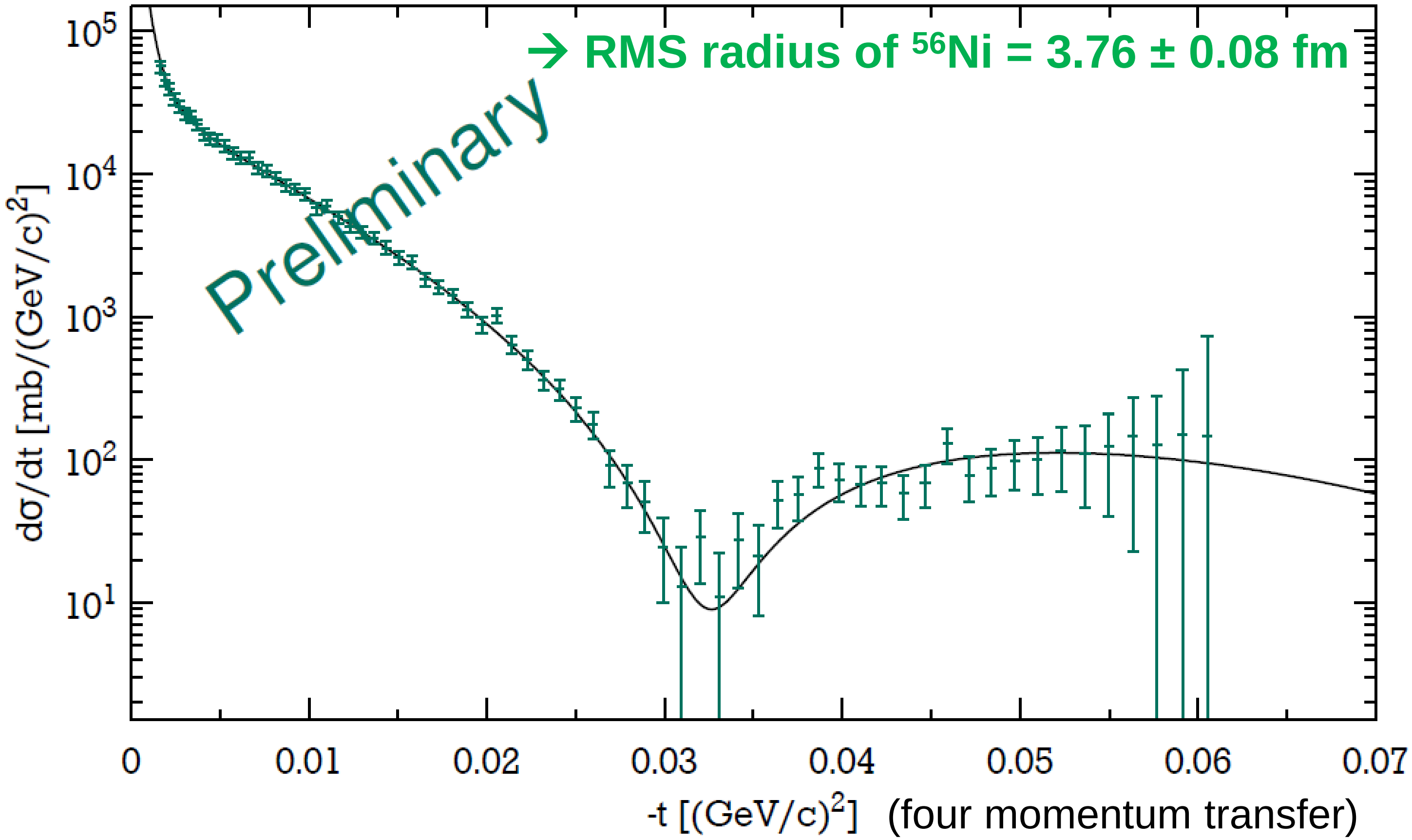
$^{56}Ni(p,p)$ scattering distribution



EXL collaboration, thesis Mirko von Schmid

$^{56}Ni(p,p)$ scattering distribution

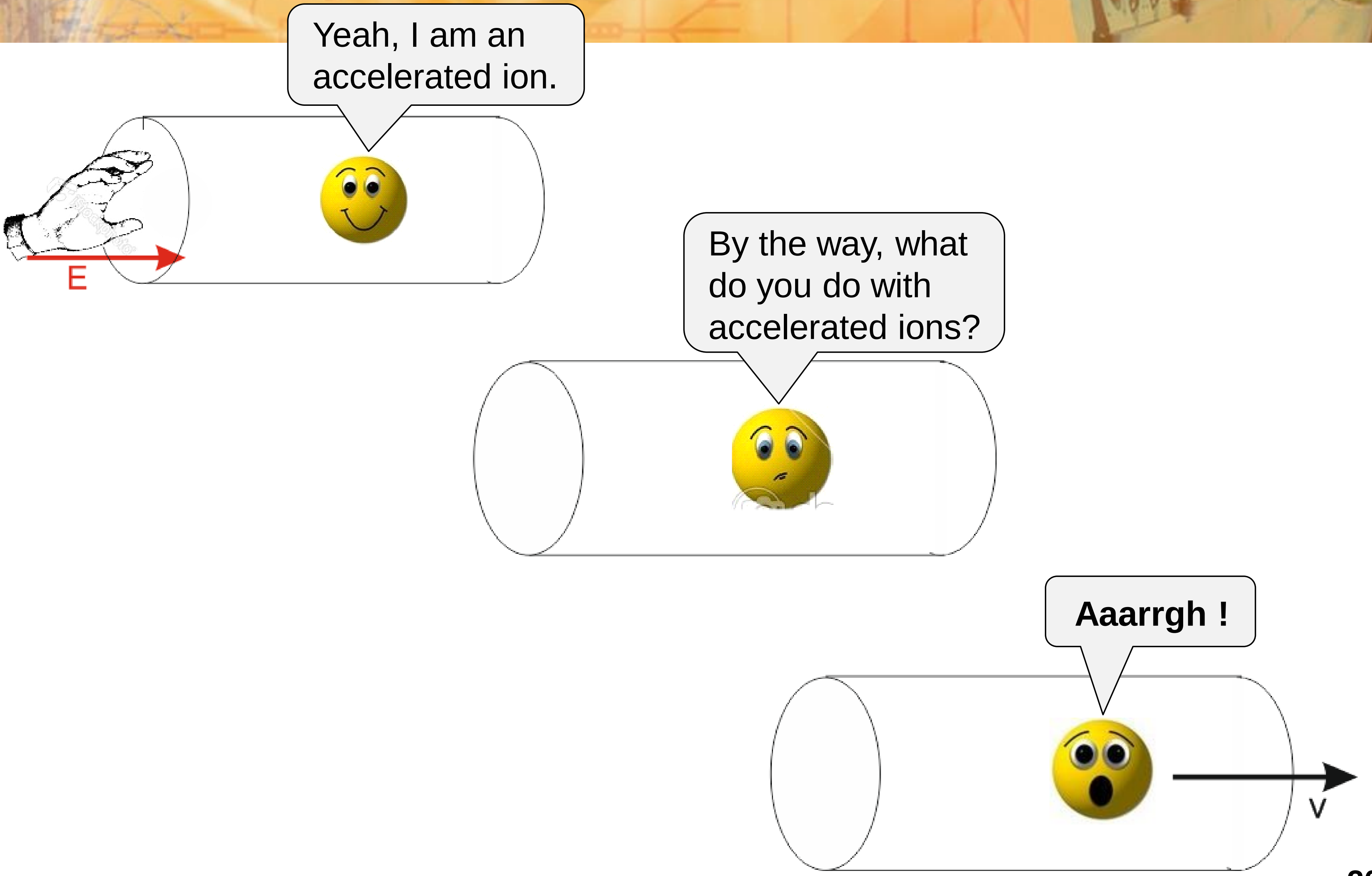
Diffraction Pattern (like for a wave after a single slit).
Extract radius of nucleus by fitting theory with parameters.



Physica Scripta T116 (2015) 014005.

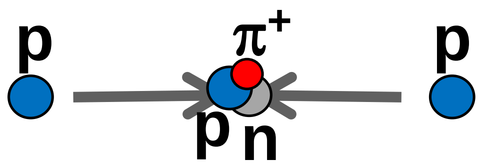
EXL collaboration, first such investigation for RIBs.

The fate of accelerated ions



Particle Production

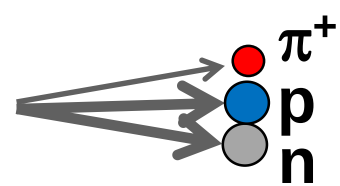
pion (rest mass $m_{\pi+}$ ~ 140 MeV/c^2)
We need a collision in which at least this energy is set free.



central collision with E_{kin} > 70 MeV,
β > 0.367

Transform motion from center-of-mass system (CoM) to laboratory (Lab).

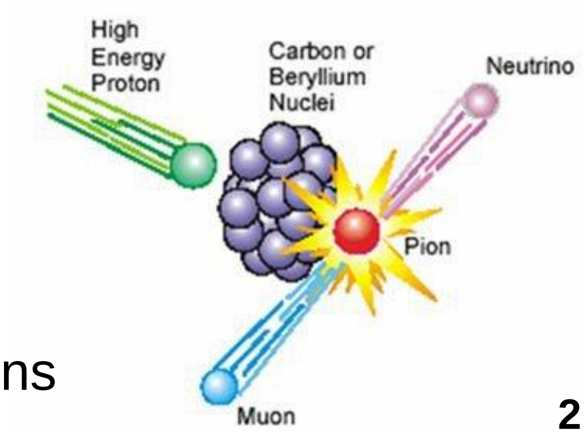
$\beta > 0.647 = (\beta+\beta_{CoM}) / (1+\beta\beta_{CoM})$
E_{kin} > 290 MeV



Not all kinetic energy can be transferred to new particle
some remains kinetic energy of collision partners.

$$p + p \rightarrow p + n + \pi^+$$

$$p + n \rightarrow p + p + \pi^-$$

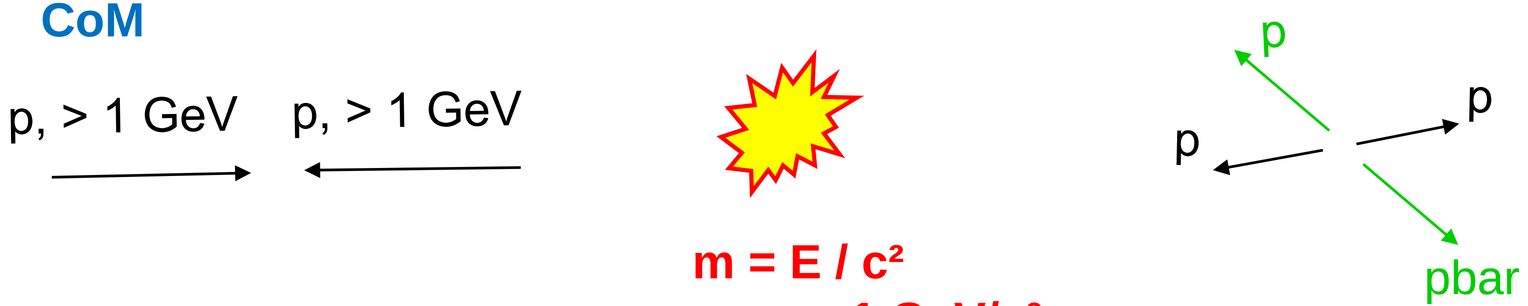


pions then decay into muons

Creation of Antiprotons

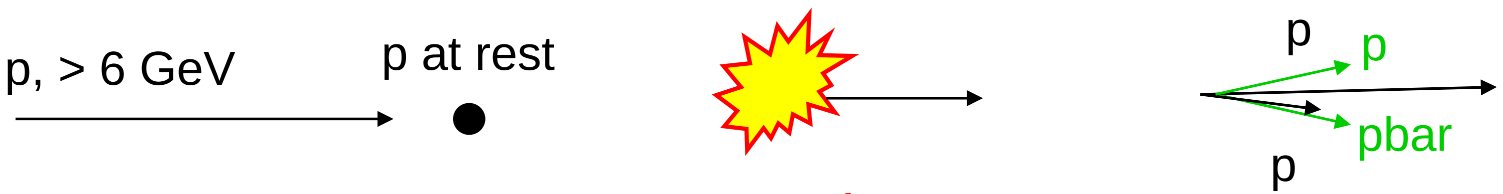
Charge must be conserved and number of baryons
➔ creation of pairs of p and pbar.

CoM



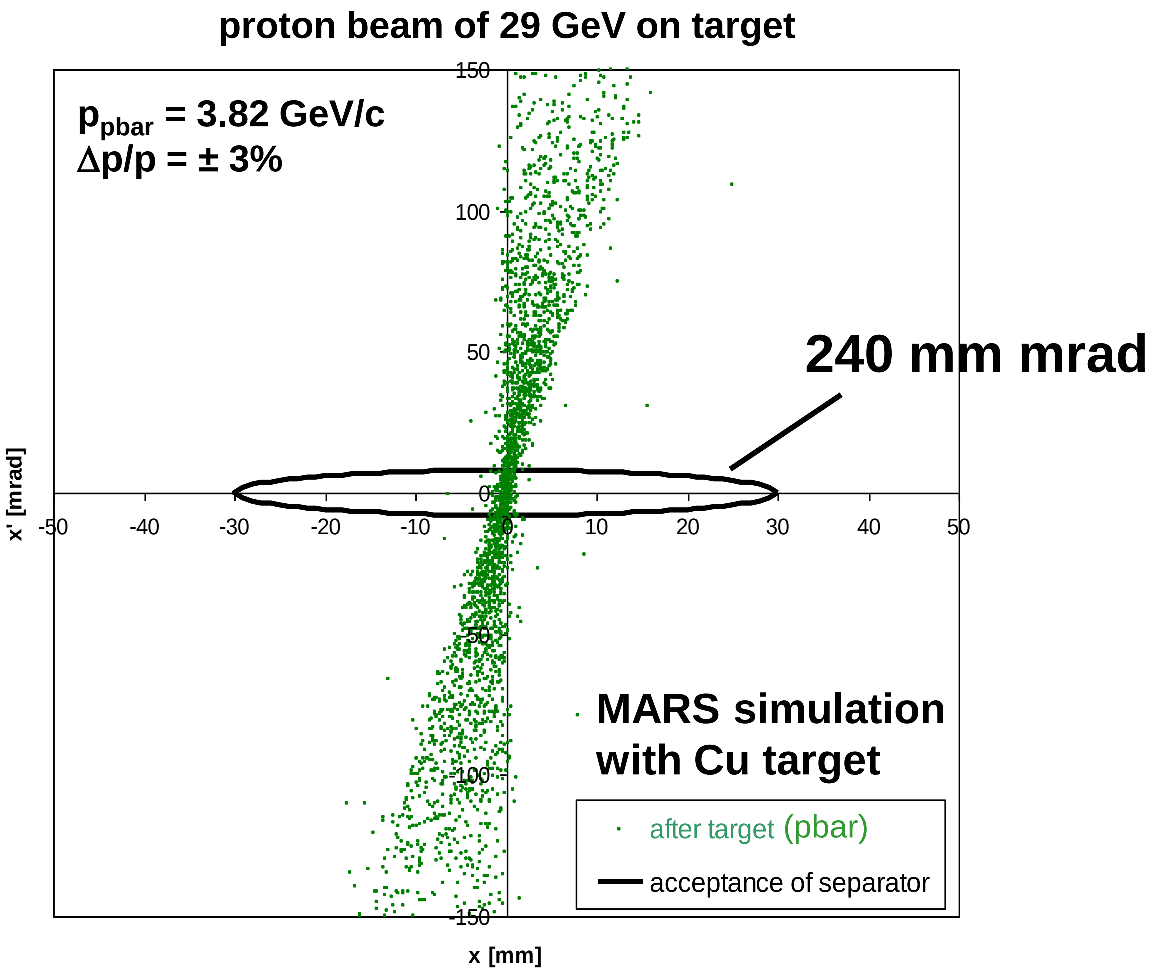
$m = E / c^2$
$m_p = m_{pbar} \approx 1\ GeV/c^2$

Lab



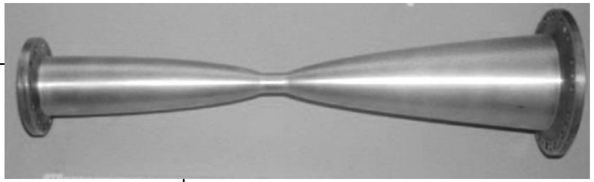
$m = E / c^2$
$E_{kin} > 6\ GeV$

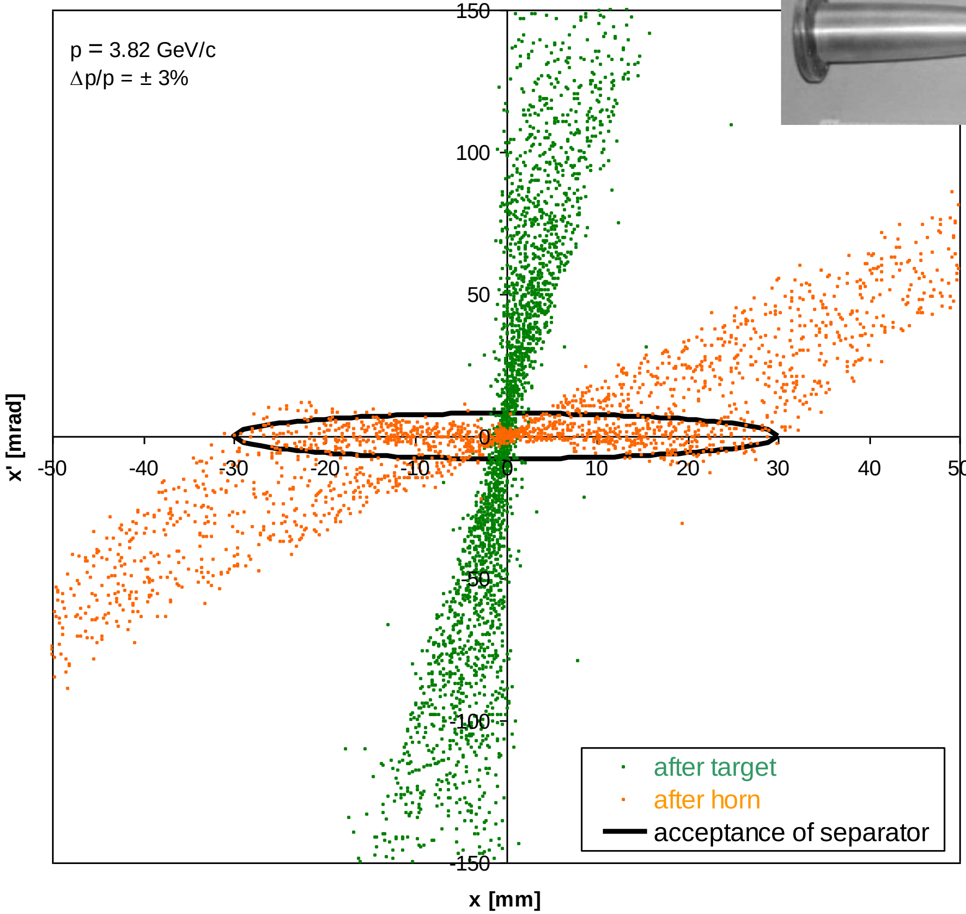
pbar distribution after target



from Klaus Knie

pbar distribution after magnetic horn





$$\text{yield} = \frac{\text{pbars in the ellipse}}{\text{primary protons}}$$

$$= 2 \times 10^{-5}$$

Optimize Yield

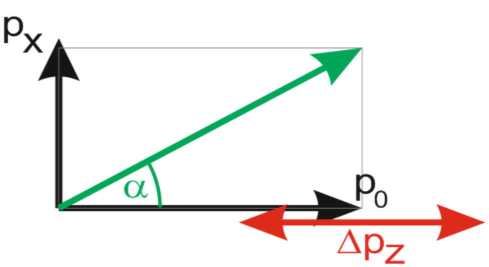
Higher energy ?
+ larger cross section
up to certain energy.
+ more forward focused
- higher Bρ

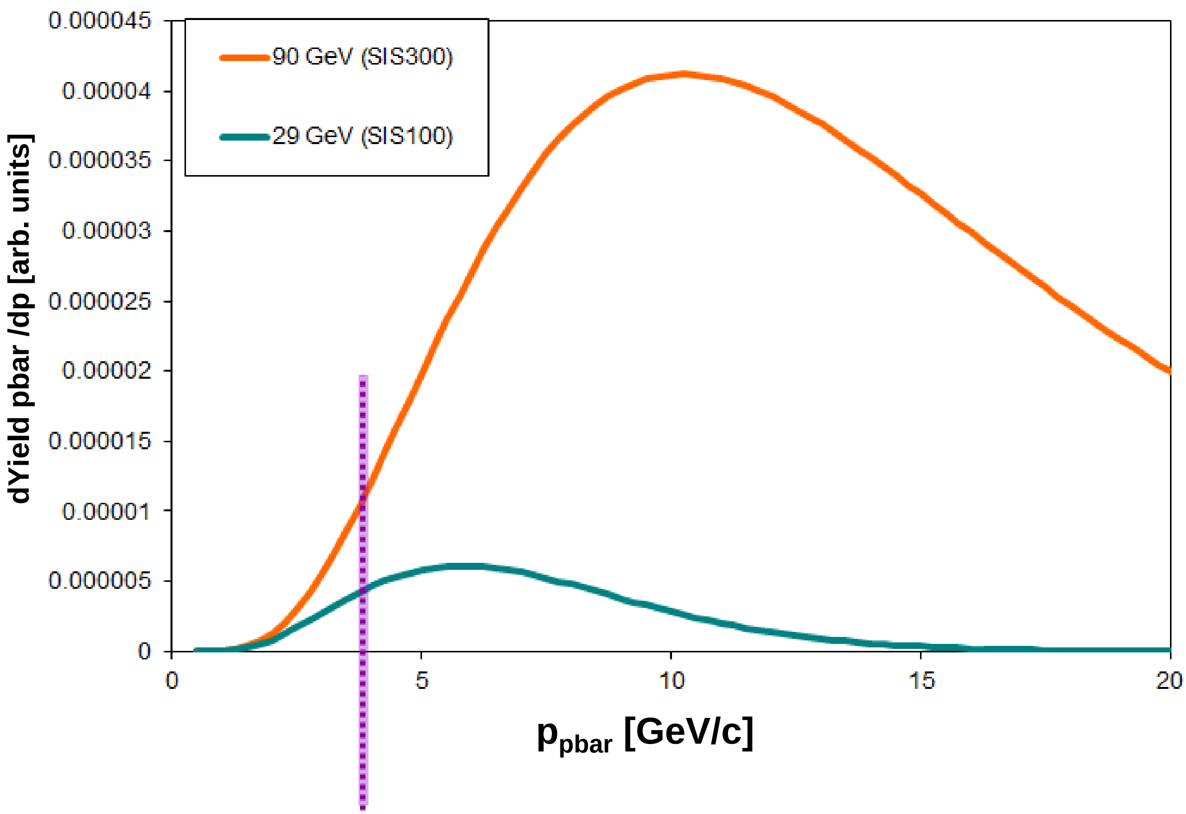
$p_0 = \gamma\, v\, m_0$

$\tan(\alpha) = p_x / p_0$

$\Delta p/p = p_z/p_0 - 1$

$= \gamma\, p_z(\gamma=1)/p_0 - 1$





p = 3.82 GeV / c, E = 3 GeV, Bρ = 13 Tm

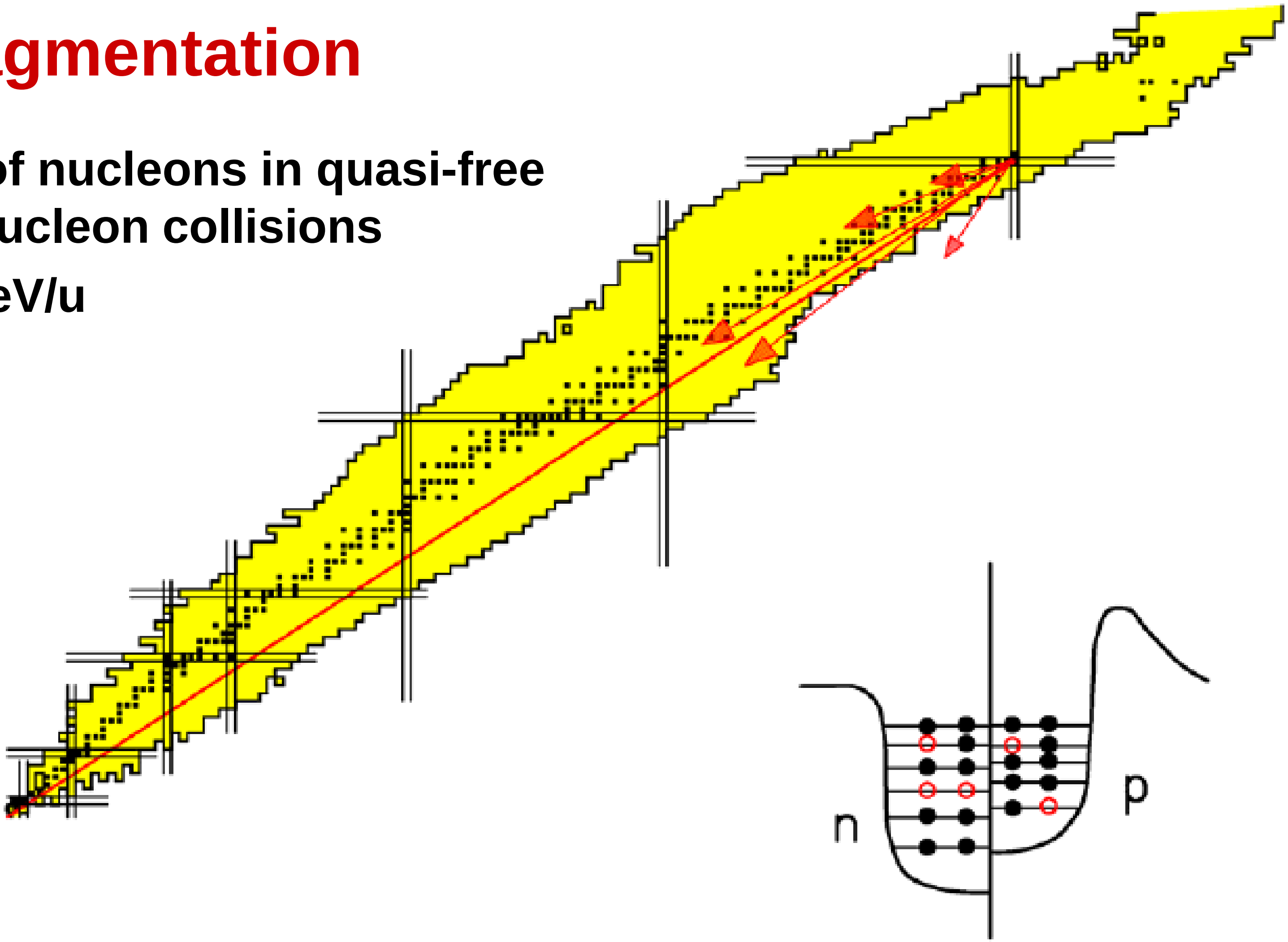
from Klaus Knie
based on Duperray et al.,
Phys. Rev. D 68, 094017

How to produce Rare Isotopes ?

Fragmentation

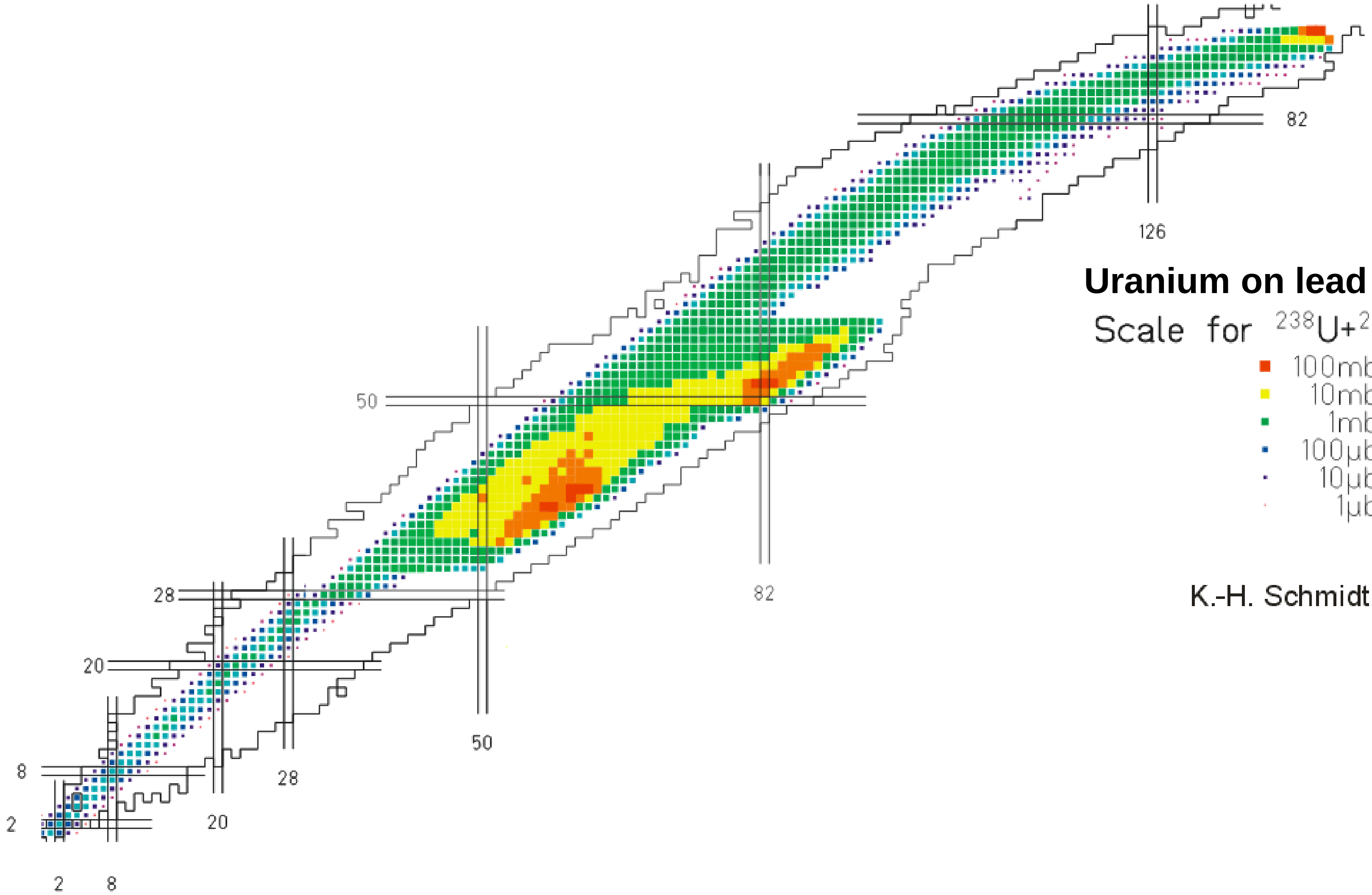
Removal of nucleons in quasi-free nucleon-nucleon collisions

$E \gtrsim 100$ MeV/u



average binding energy ~8 MeV/nucleon

Distribution of Fragments



Uranium on lead target

Scale for $^{238}U + ^{208}Pb$

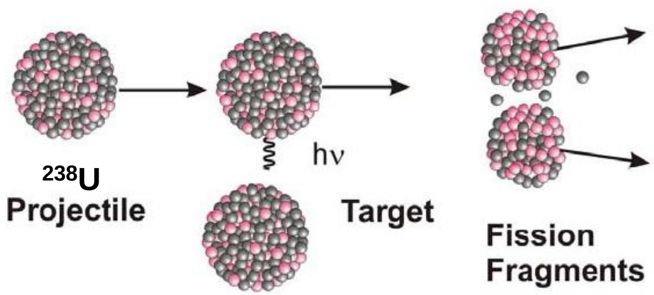
- 100mb
- 10mb
- 1mb
- 100μb
- 10μb
- 1μb

K.-H. Schmidt et al.

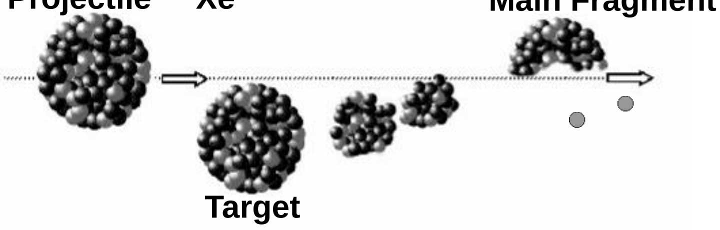
Production Cross sections

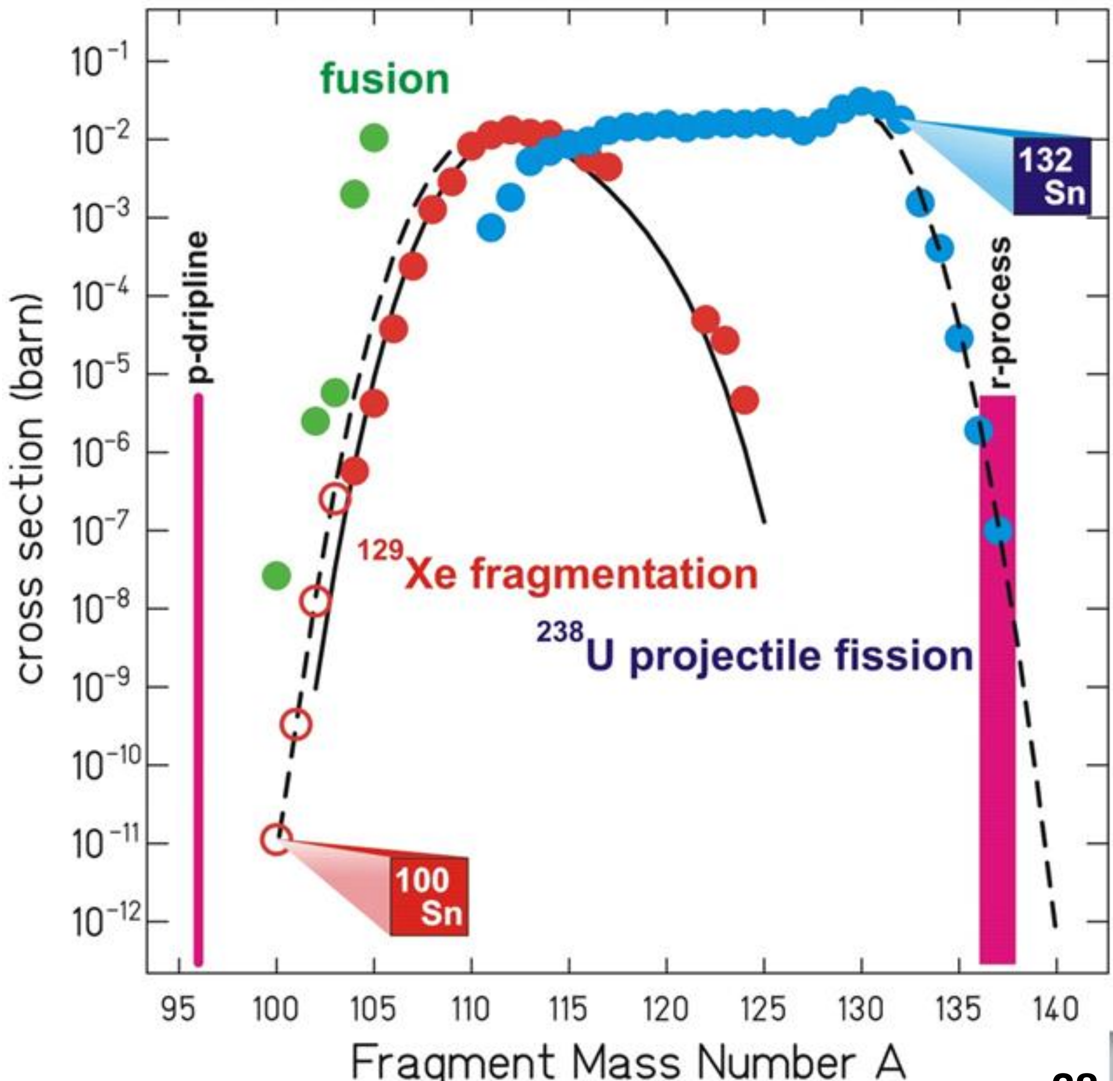
Tin isotopes by different methods

Projectile fission



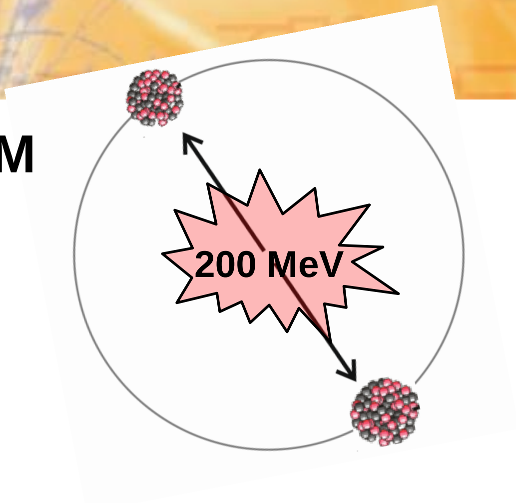
Projectile fragmentation





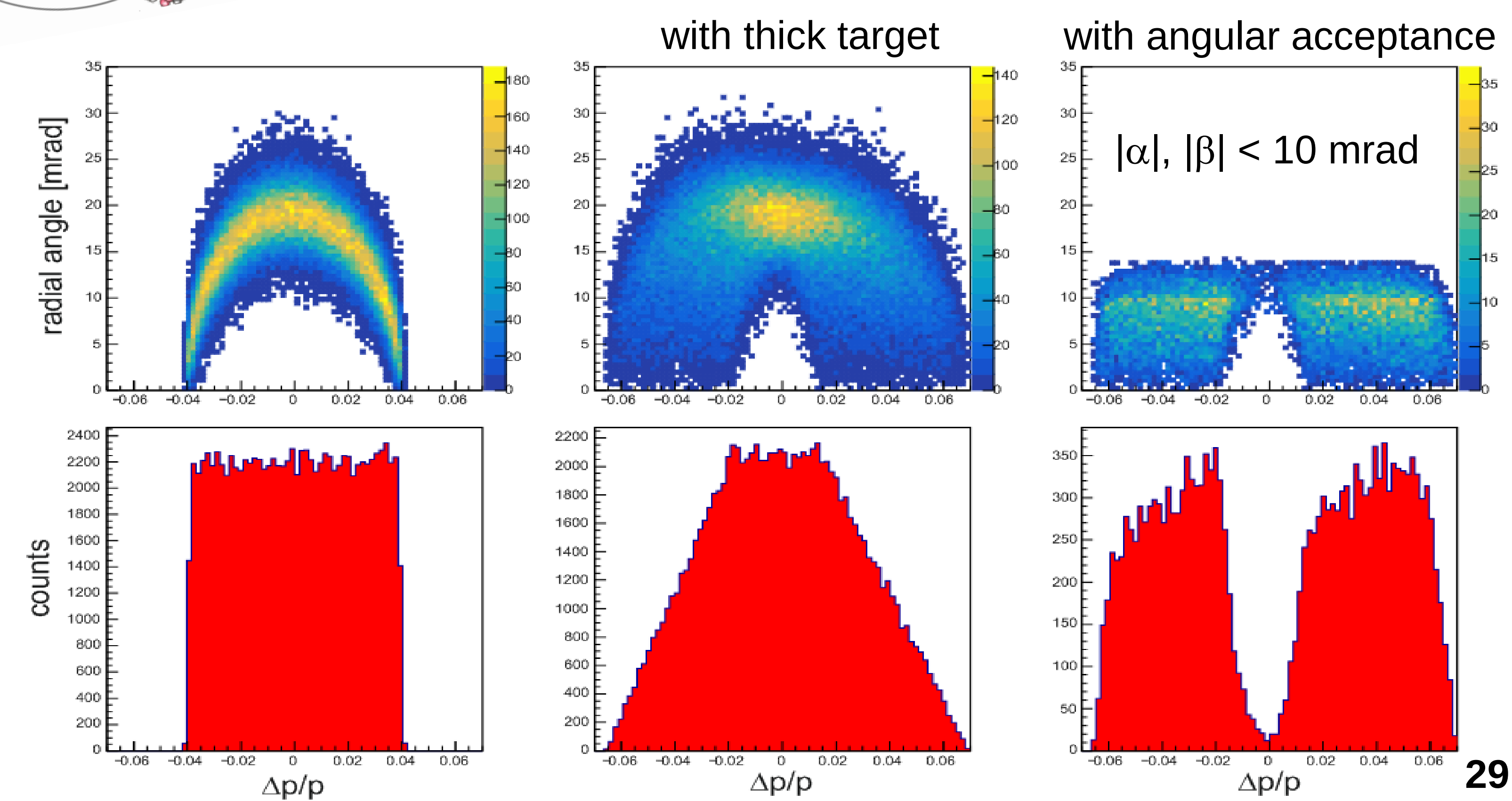
Fission Kinematics

CoM



in Uranium fission ~200 MeV are released

in Lab:
^{132}Sn from
^{238}U beam
at 1 GeV/u

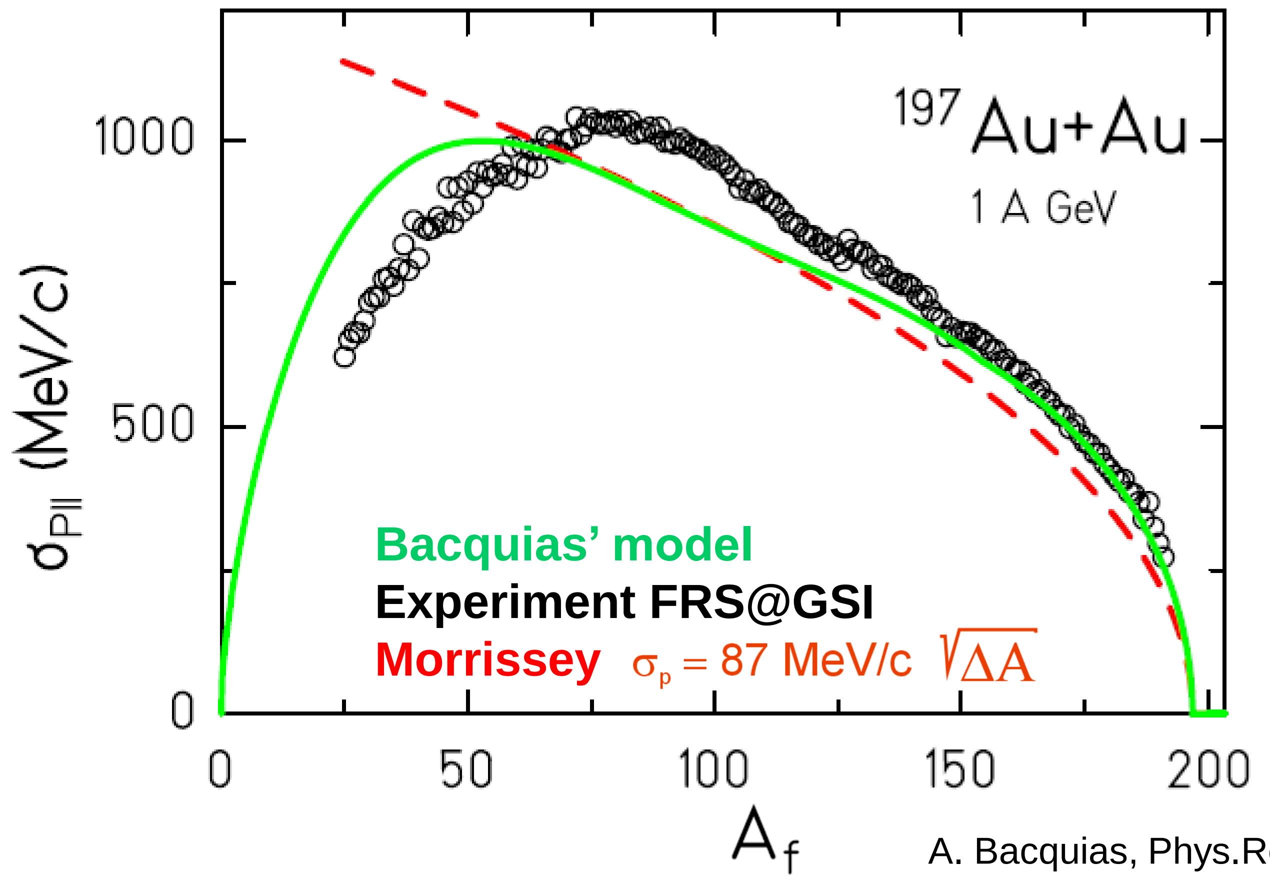


MOCADI simulation

Momentum Spread after Fragmentation Reaction

$$\sigma^2_{p_\parallel} = \sigma^2_{p_{\parallel Fermi}} + \sigma^2_{p_{\parallel recoil}} + \sigma^2_{p_{\parallel Coul}}$$

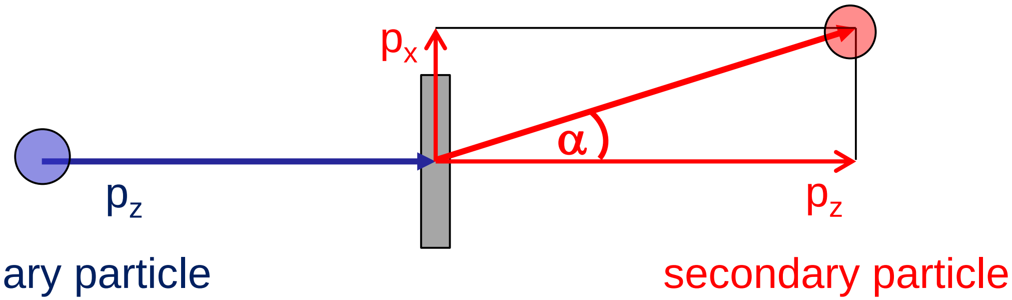
- Fermi momentum of bound nucleons
- Mom. transfer by evaporated nucleons
- Coulomb expansion in multi fragment.



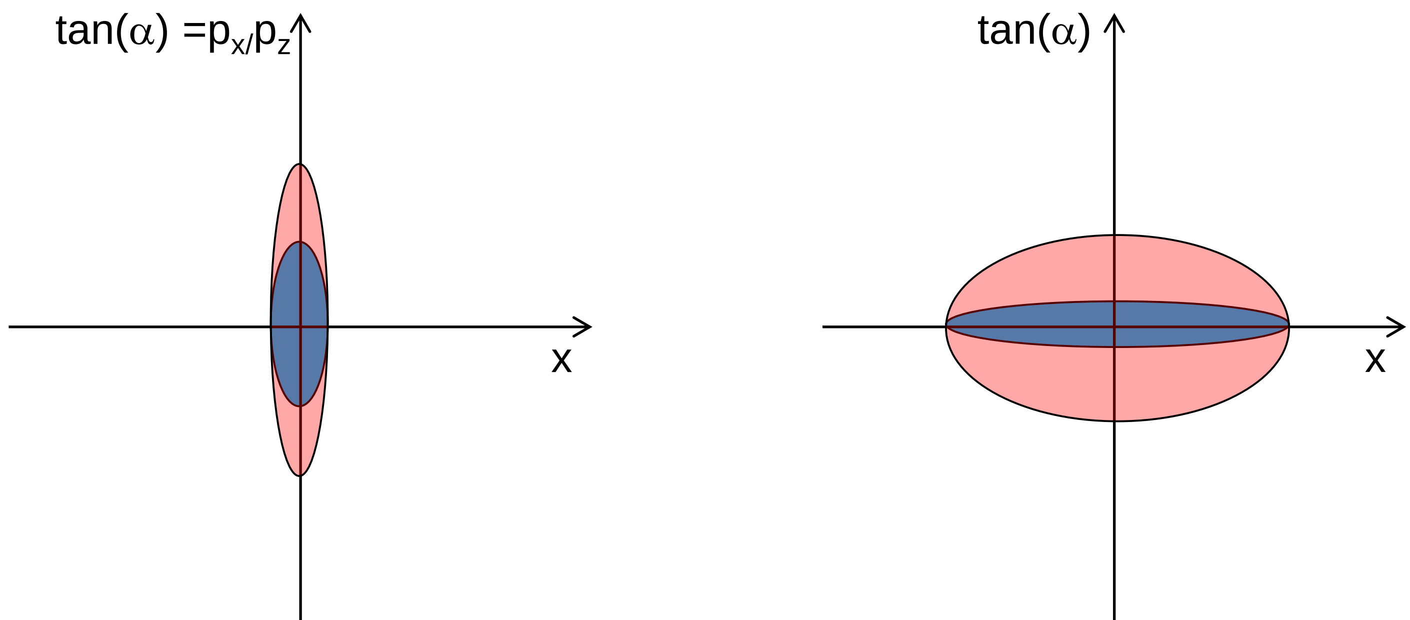
A. Bacquias, Phys.Rev.C 85, 024904 (2012)
exp. data V. Henzl, thesis, U. Prague

Emittance Growth with Targets

Reaction in target causes transverse momentum **p_x**,
but in a thin target **x** does not change much.



Make small beam spot to avoid large emittance for secondary beam

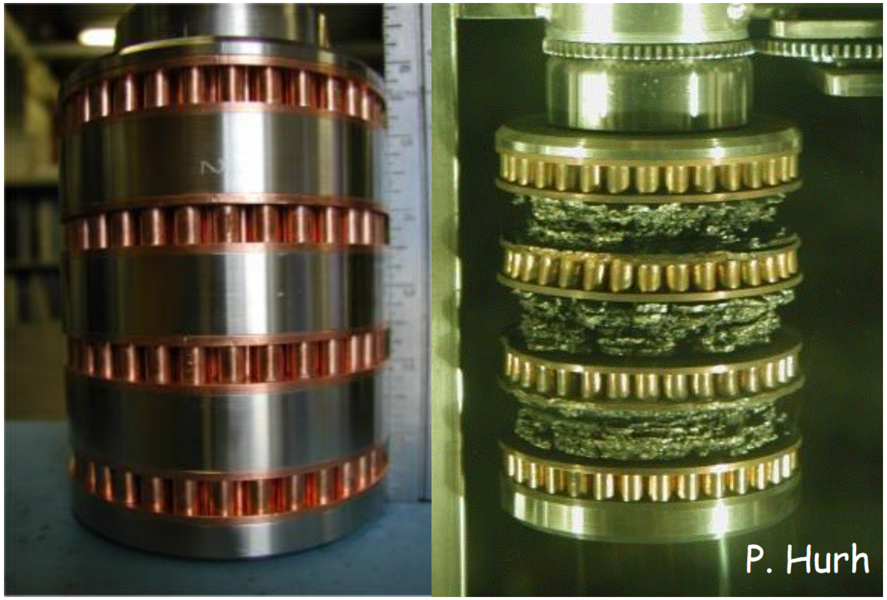


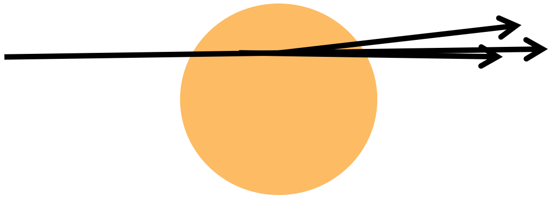
Limits by Targets
small spot and pulsed beam = ☹

Short pulse → no thermal conductivity, no mechanical motion.

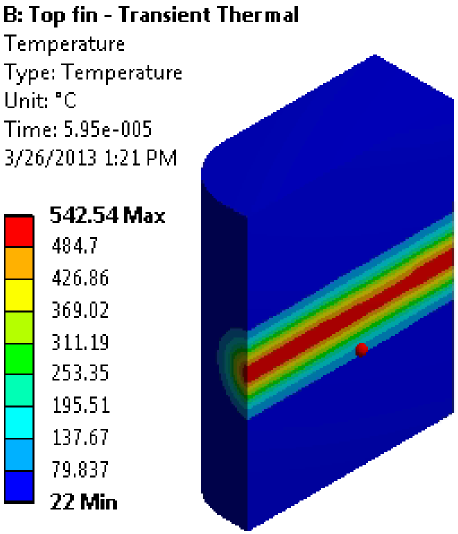
Heating → expansion → stress

rotating Fermilab copper/nickel target, fresh and after use for pbar production

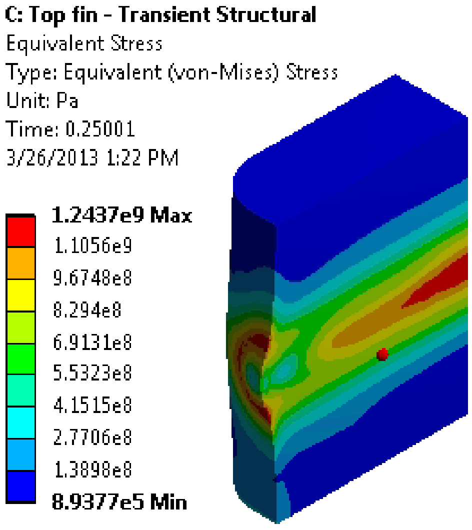




Calculation for new target



T [°C]



σ [Pa]

Patrick Hurh, Fermilab

Limits by Targets

Simple temperature and stress calculation

Instantaneous energy deposition

$$\frac{dQ}{dm} = \frac{dE}{\rho dx} \frac{n}{\Delta x \, \Delta y}$$

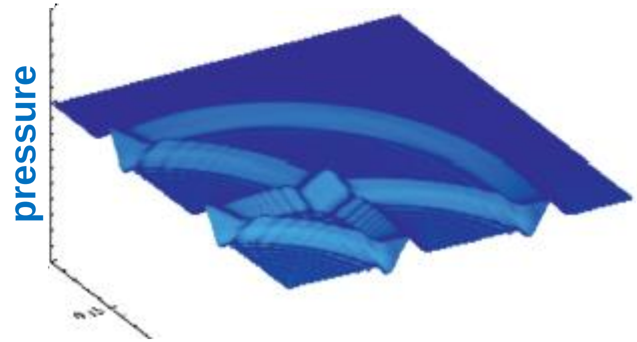
stopping power
number of ions
spot size

$$\Delta T = \frac{dQ}{dm} \frac{A}{c_{mol}}$$

molar mass
heat capacity

$c_{mol} \sim 25 \frac{J}{mol\,K}$

melting?



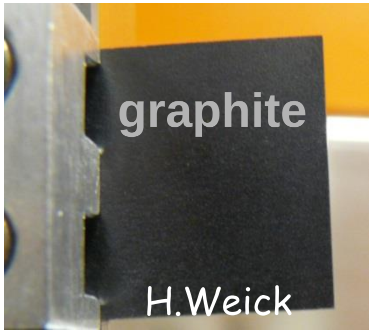
$$P = K \, \alpha \, \Delta T$$

bulk modulus
thermal expansion coeff.

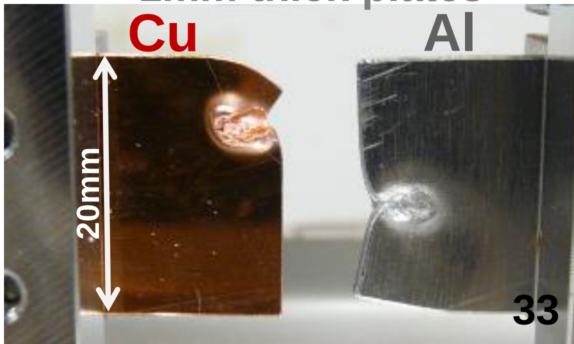
Initial compressive pressure P, wave propagates (v_{sound}) to target boundary → tensile stress.
P > spall strength? plastic deformation P > yield strength ?
not exactly elastic, cyclic stress, cracks?

Example (FRS at GSI):
10^{10} U/spill at 125 MeV/u on 1mm² spot,
→ dQ/dm = 2 kJ/g, ΔT = 4000 K (in Cu)

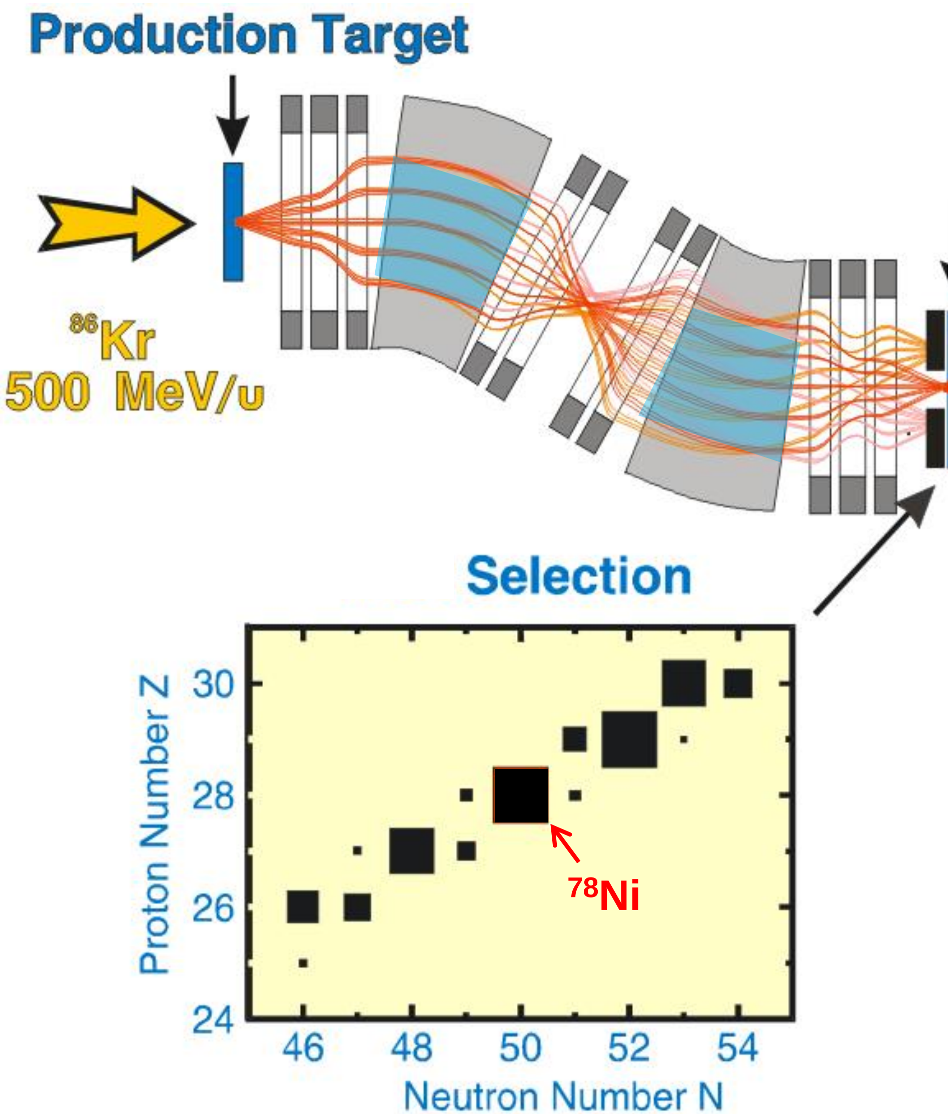
Super-FRS at FAIR 5×10^{11} U ions/spill
use graphite, but requires enlarged spot.



1mm thick plates



Bρ Separation



resolving power R = m/Δm or q/Δq

$$R = \frac{1}{x_0\, a_0} \int \frac{\vec{B}(s)}{B\rho}\, d\vec{f}$$

For given emittance $x_0 a_0$ the B-field covered by the beam defines R.

Limited by momentum spread

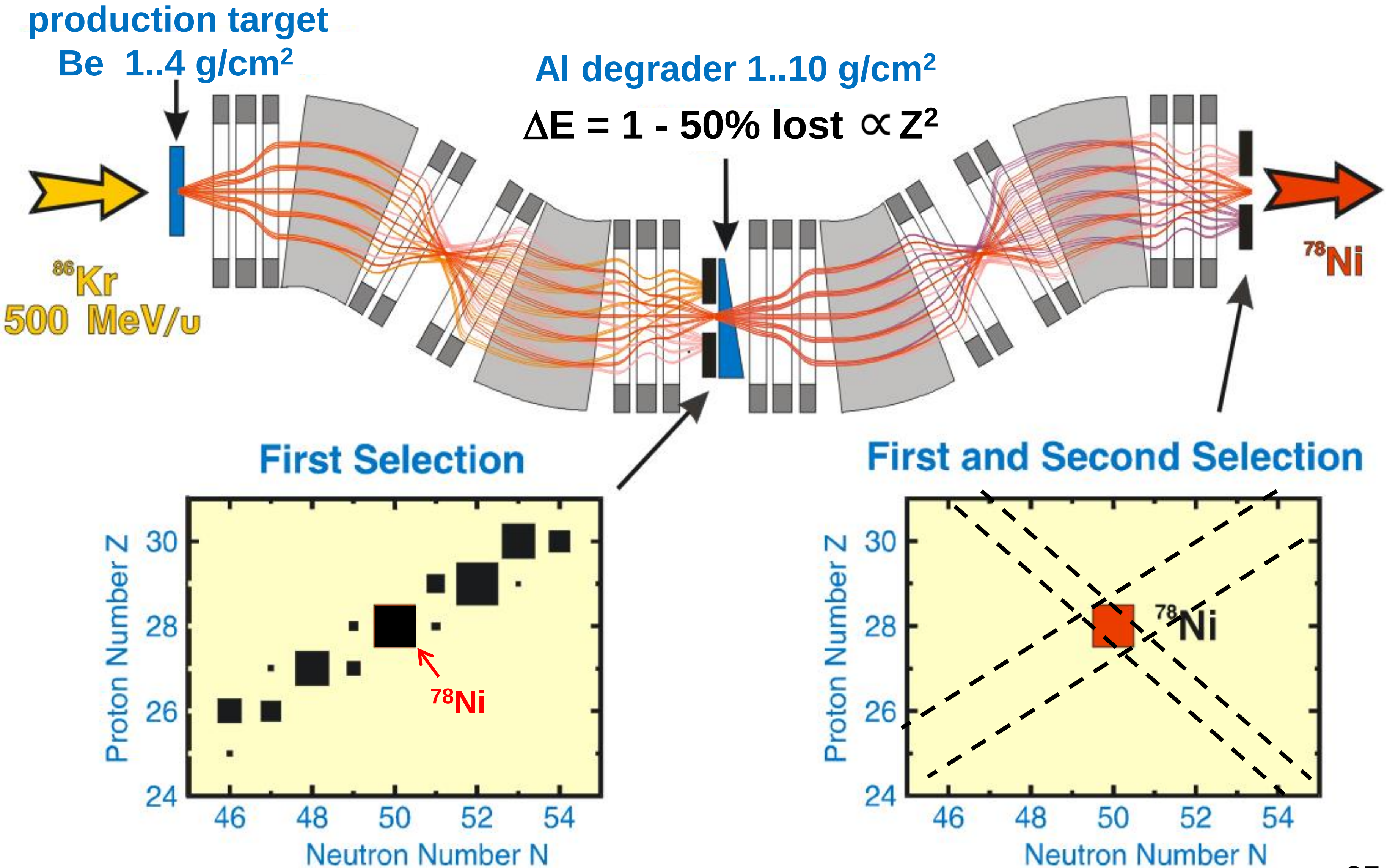
$\Delta p/p_{\text{nucl. reaction}} \sim 0.4 - 8\ \%$

$\Delta p/p_{\text{matter atomic}} \sim 0.05 - 0.3\ \%$

statistical energy-loss difference

Bρ-ΔE-Bρ Separation Method

scheme of FRS @ GSI, L=72m



Identification In-Flight

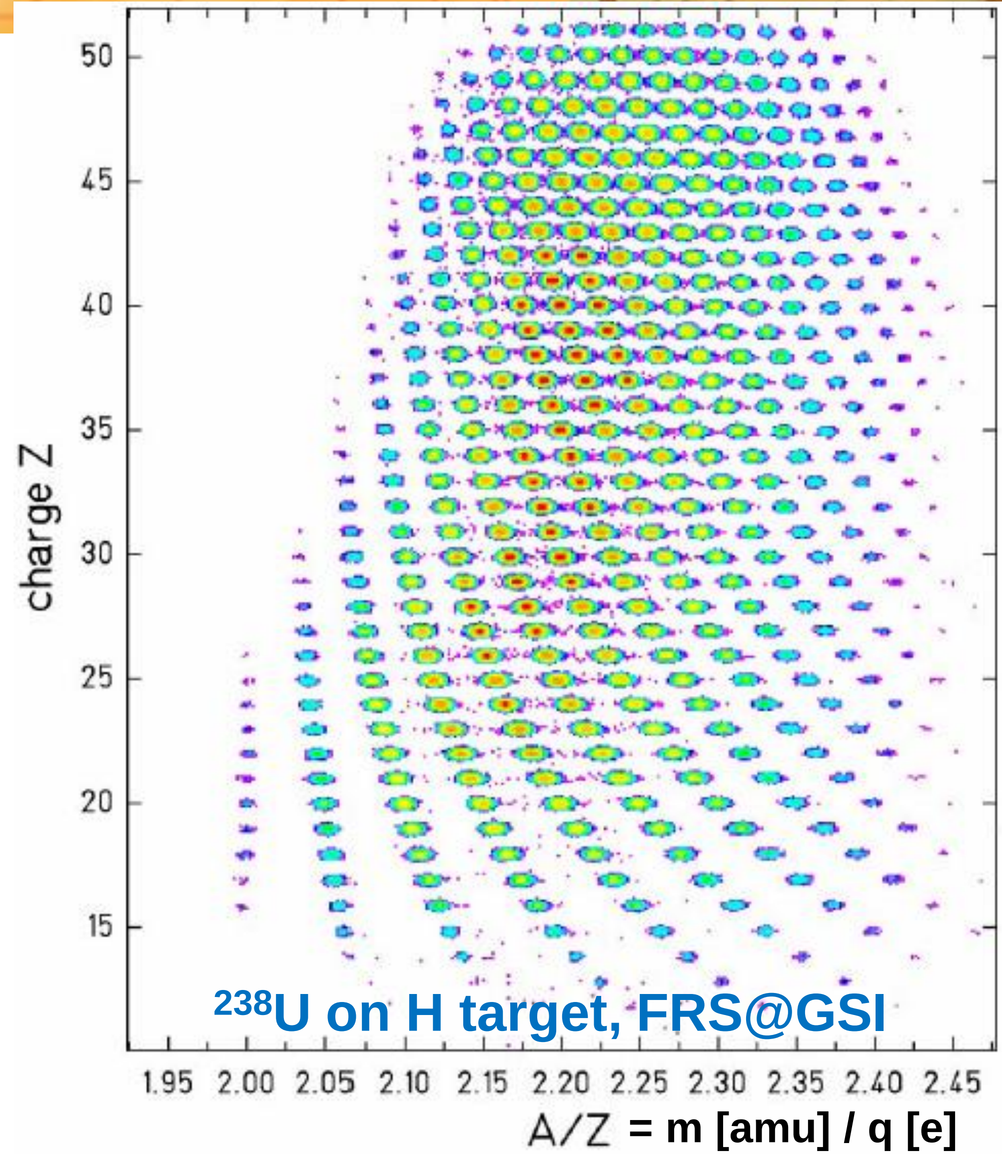
$B\rho = m/q \;\; \beta\gamma \;\; c_0$

- $B\rho$ from magnet setting and position detectors at dispersive focal planes (e.g. MWPCs).

- Velocity ($\beta\gamma$) from ToF over larger distance (10-100 m) mostly by plastic scintillators

- Z from ΔE in ionization chamber

But only with quasi DC beam !



thesis V. Henzl, CTU Prague 2005.

Diagnostics for Secondary Beams

Usual particle identification in-flight combines many detectors, and requires measurement of single ions in coincidence.

e.g. intense RIBs 10^6/spill, spill = 100ns ➔ rate = 10^{13}/s
max. coincidence rate ~ 10^6/s, limited by detectors and electronics.

Normal beam diagnostic for pulsed beam not selective, beam can be dominated by other particles.

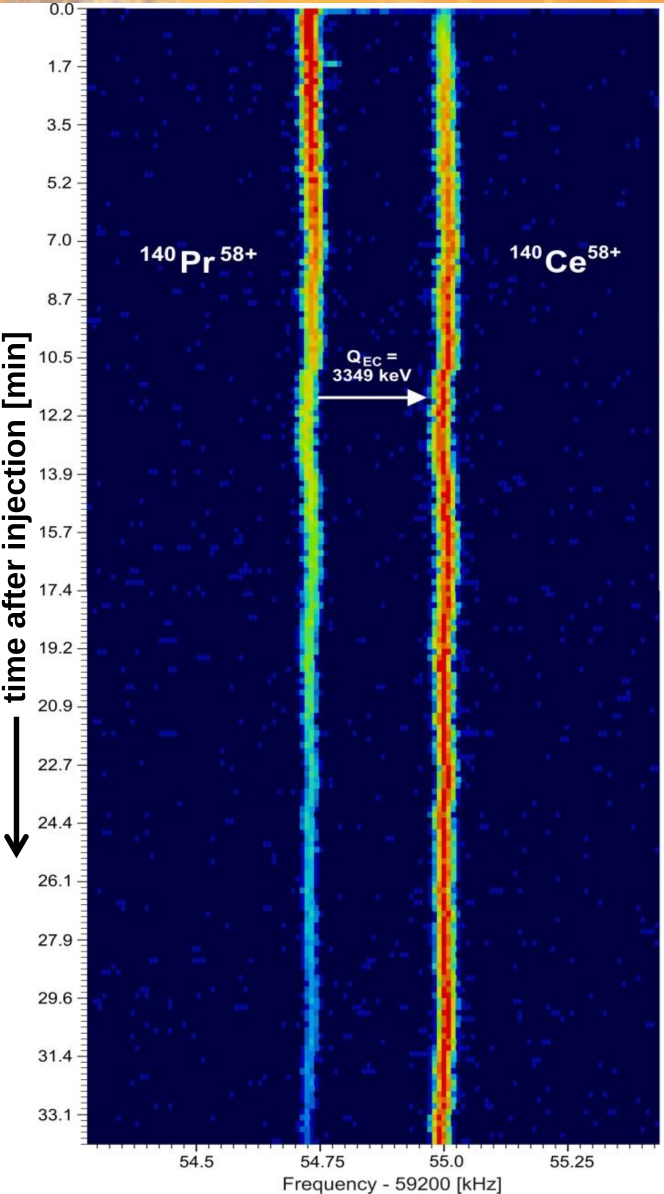
- **many pions along with pbars,**
- **many other nuclides in RI beam even with separator**

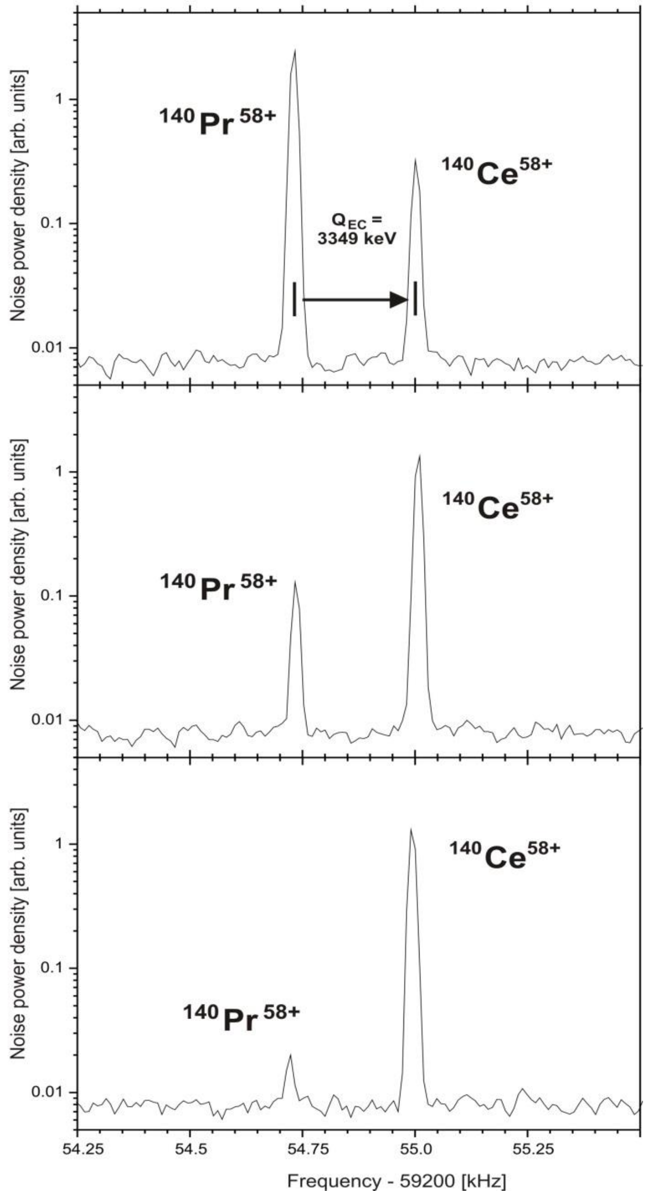
➔ We may measure the wrong beam parameters.

Special detectors blind for other particles ?

e.g. Cherenkov counter collecting light under limited angle only.
same Bρ in beamline -> different velocity -> different angle of light, so far only for large differences (p, d, He)

Schottky Diagnostics in Ring





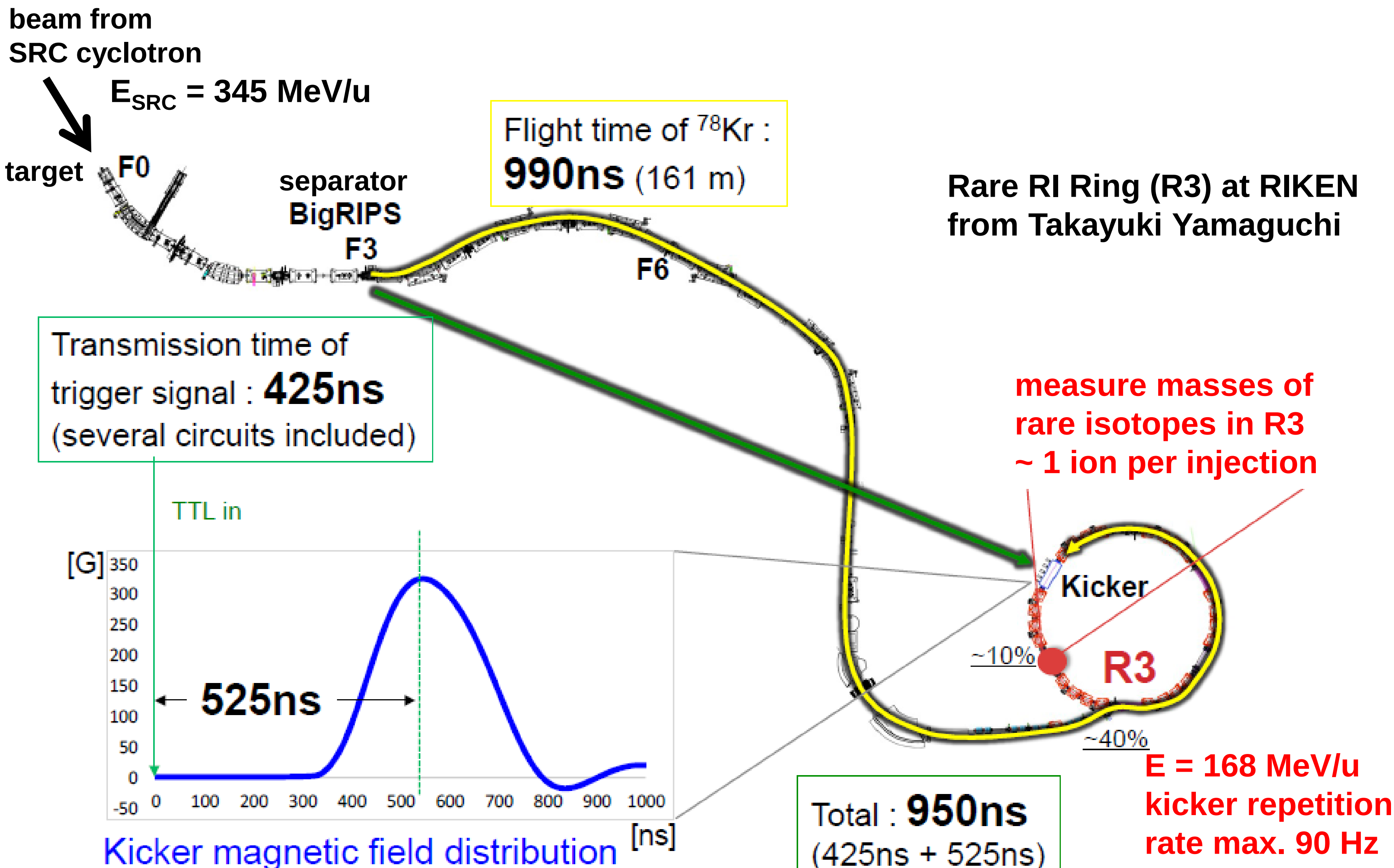
Measure revolution frequency from noise of pick-up.

Very sensitive down to single ions.

Example from ESR (electron cooled beam) relative mass difference
$\Delta m/m = 2.6 \times 10^{-5}$

Intensity changes with time due to EC decay
$^{140}Pr \rightarrow ^{140}Ce$.

Identification and Kicker for really rare isotopes



What is special about Secondary Beams for injection, extraction and transfer?

Provide high energy by annihilation at high luminosity, investigate the secondary particles (pbar+x, rare isotopes).

Secondary particles are produced in reactions with low probability, many other particles ➔ separate.

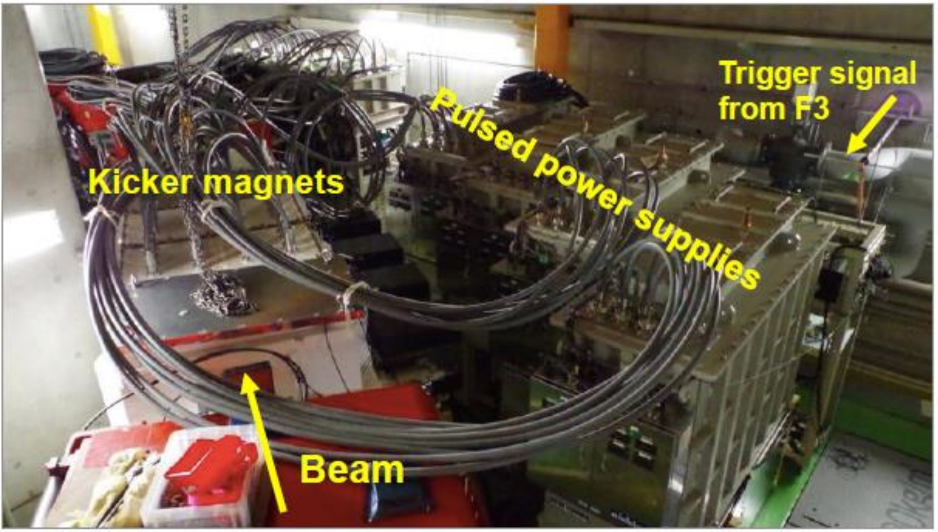
The reaction (and separation) process blows up the emittance.
➔ Handle as good as possible (strong lenses, matching).

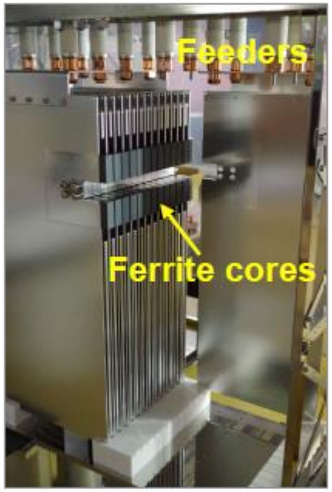
Limits by production targets.
Selective diagnostics for pulsed beams needed/wanted.

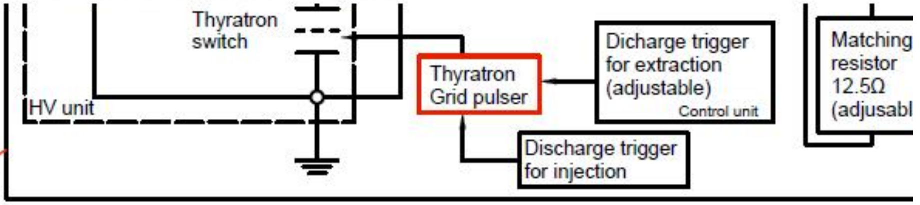
Back up slides only

R3 Kicker

Fast-kicker system







Fast-recharging mechanism

new hybrid charging system
to extract as soon as possible
using same kicker magnet
of injection.

Fast-response mechanism

new gate board for Thyratron
to excite a kicker magnet as fast as possible.

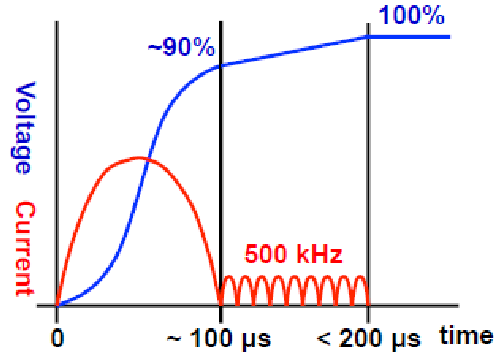
R3 Kicker

Fast-recharging mechanism

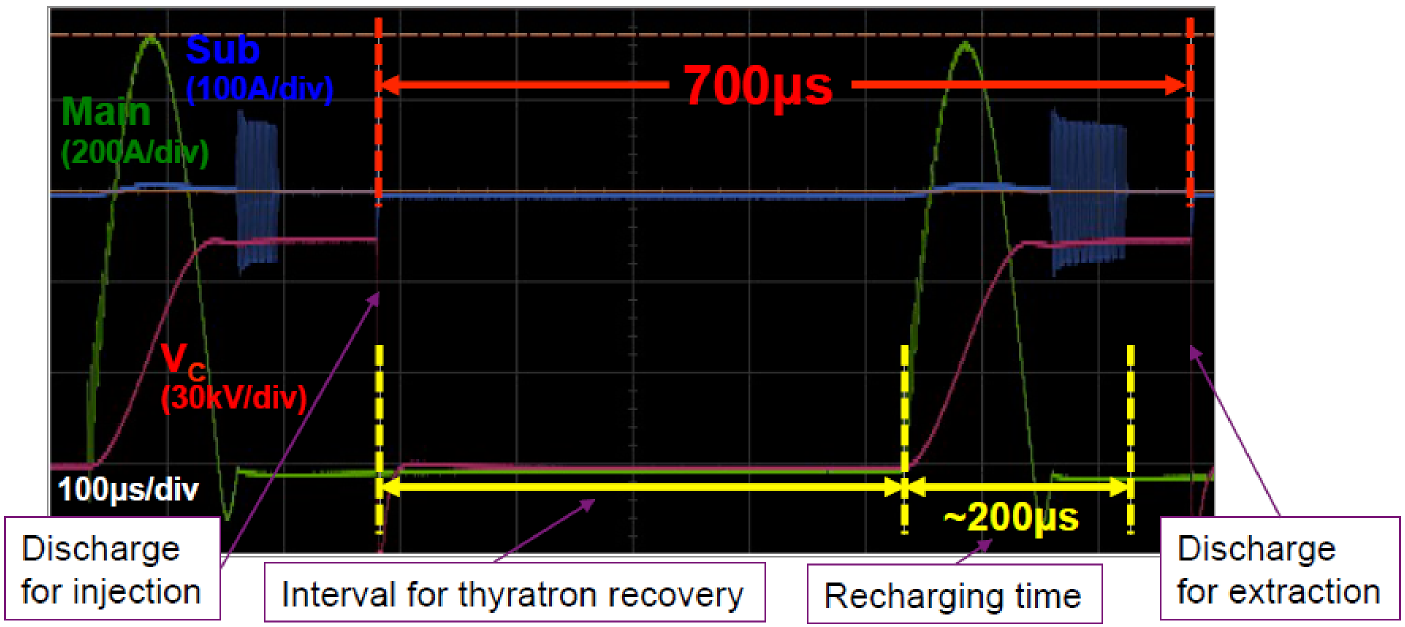
Hybrid charging system

Main charger
- Half sinusoidal waveform
- 90% charging in 100μs

Sub charger
- 500kHz resonance
- +10% charging within 100μs
- Keep V_C 100±1% to discharge at any time

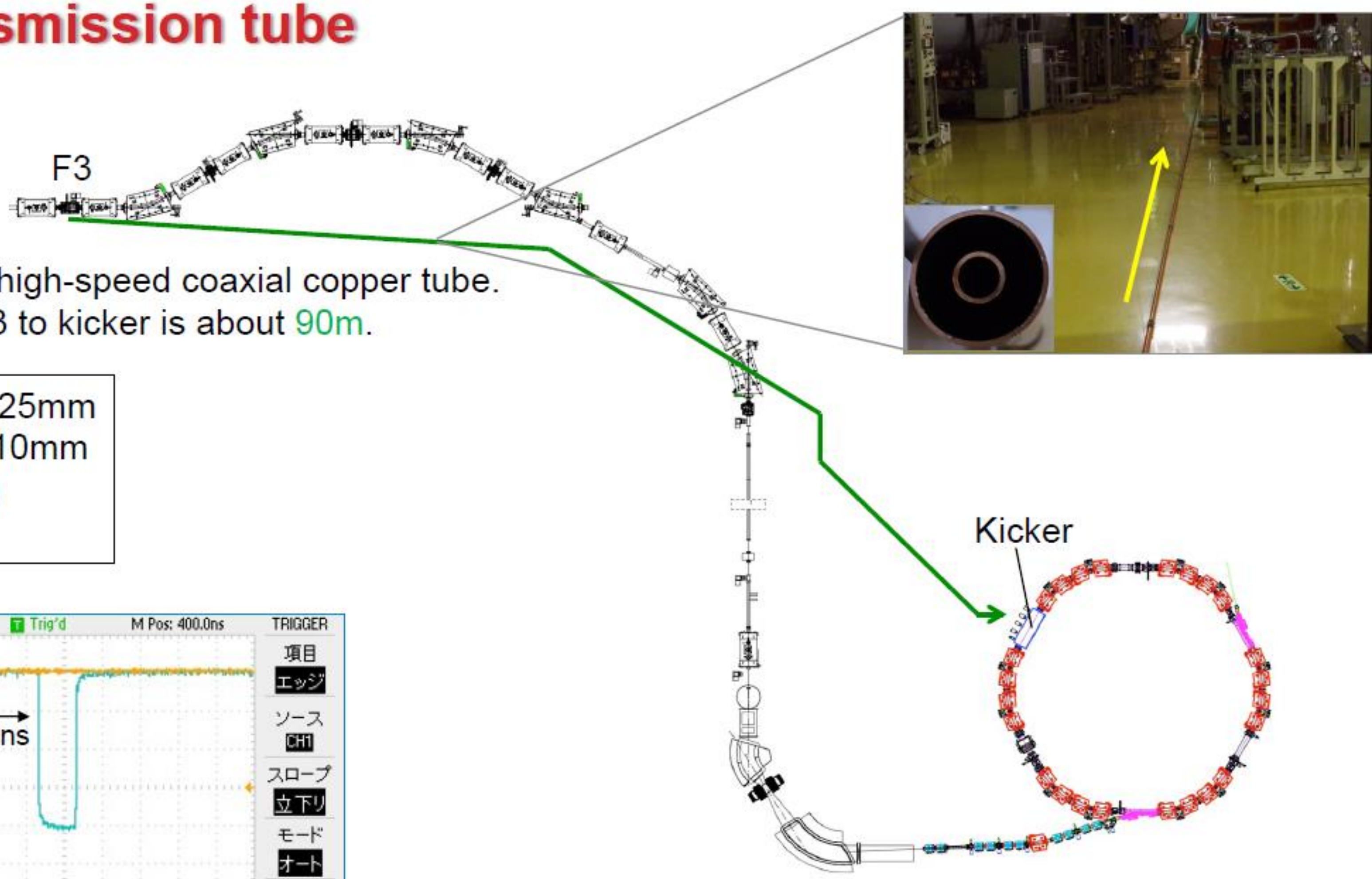


PFN charging waveform (1set)



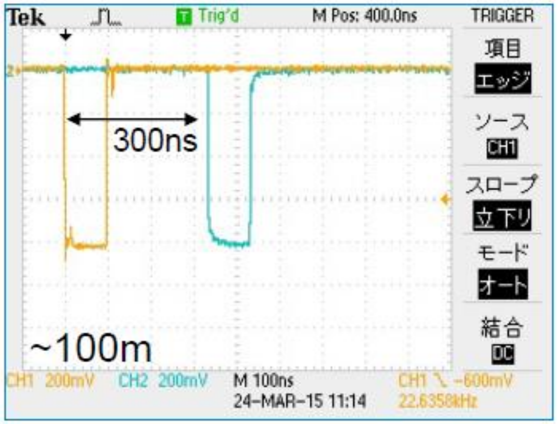
R3 Kicker

Trigger transmission tube



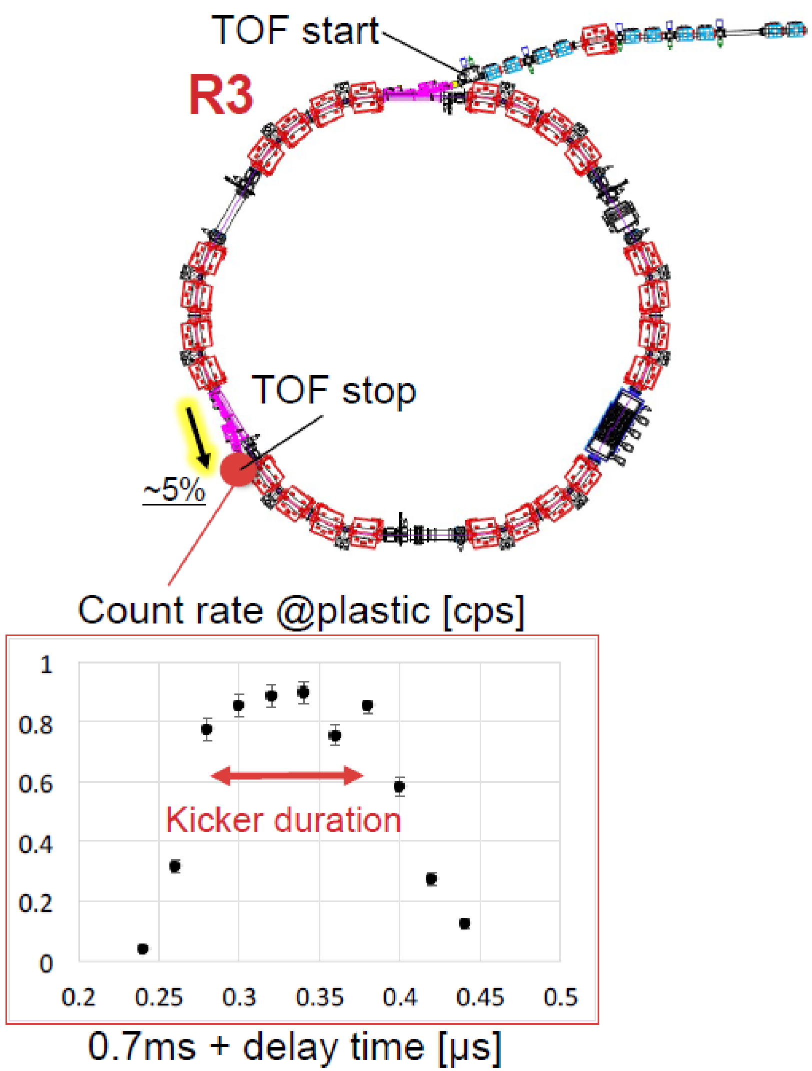
We fabricated the high-speed coaxial copper tube.
The length from F3 to kicker is about 90m.

Outer diameter : 25mm
Inner diameter : 10mm
Thickness : 1mm
β=v/c : 0.986

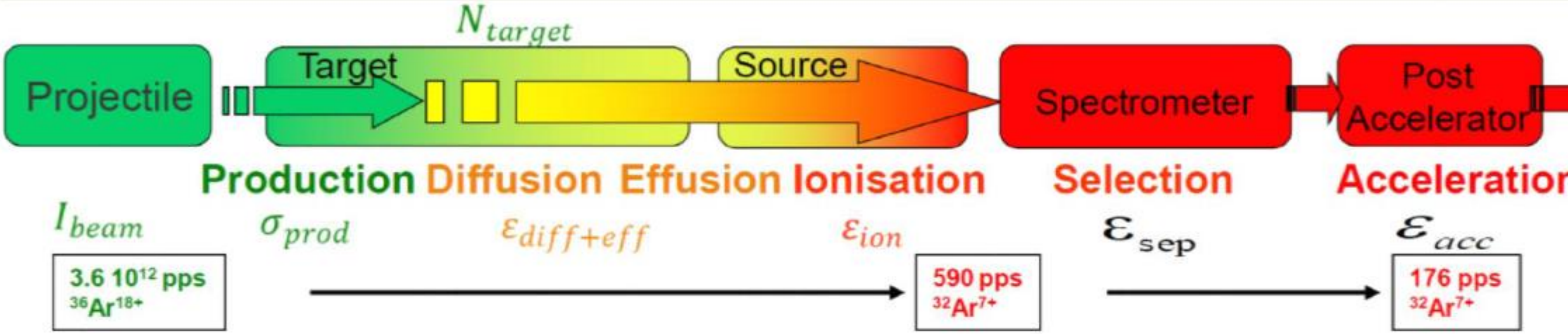


R3 Kicker

- **Extraction** (@MS01)

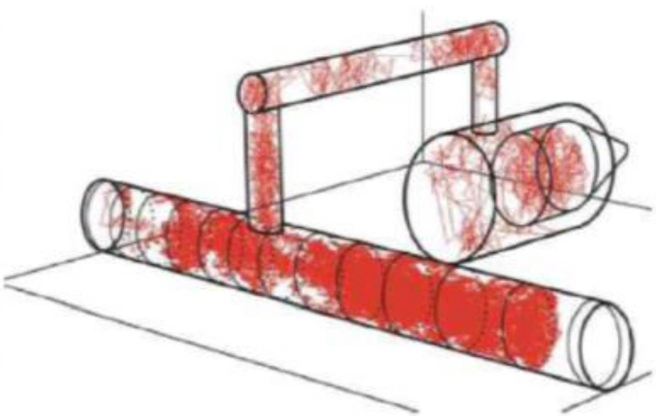


ISOL Method



$$I_{RIB} = \left(\sigma_{prod} \cdot N_{target} \cdot I_{beam}\right) \cdot \varepsilon_{diff+eff} \cdot \varepsilon_{ion} \cdot \varepsilon_{sep} \cdot \varepsilon_{acc}$$

$$\varepsilon_{diff+eff} \cdot \varepsilon_{ion} \; as \quad low \quad as \quad 10^{-6}$$



Path of an atom travelling out of a foil target to the ion source (RIBO code, (Santana-Leitner, 2005))