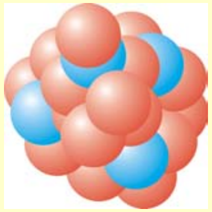
FASCI RADIOATTIVI
(ioni con nuclei Esotici)

Ioni instabili prodotti artificialmente(ovvero non esistenti in natura) con caratteristiche energetiche e spaziali tali da poter essere riutilizzati o come sorgente per un acceleratore o come un “normale” fascio ottenuto da un acceleratore per studiarne le proprieta’ o produrre reazioni.

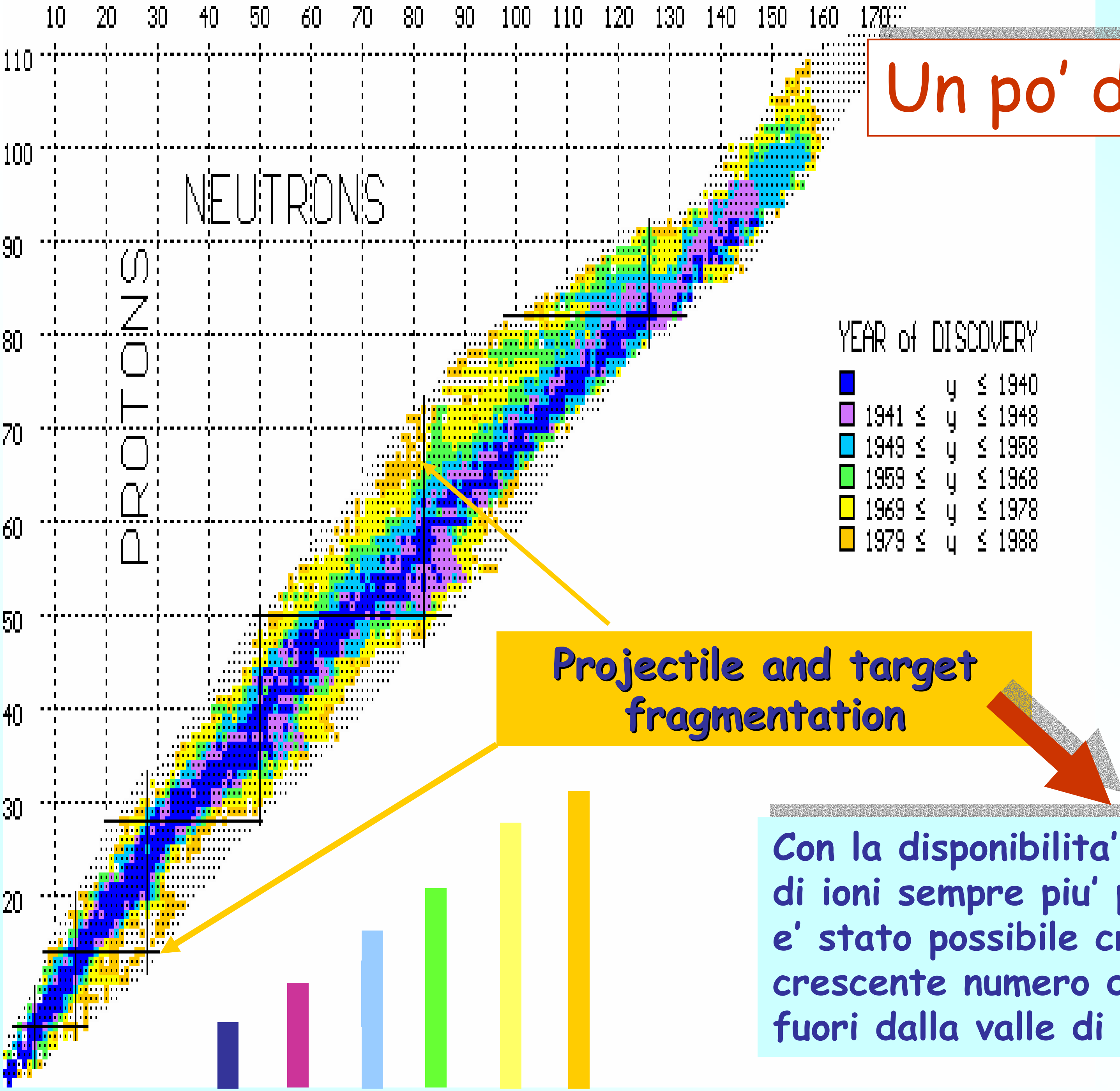
Cos'e' un nucleo esotico?

Normal Nucleus:	Exotic Nucleus:
	
6 neutrons	16 neutrons
6 protons (carbon)	6 protons (carbon)
^{12}C	^{22}C
Stable, found in nature	Radioactive, at the limit of nuclear binding

Characteristics of exotic nuclei:

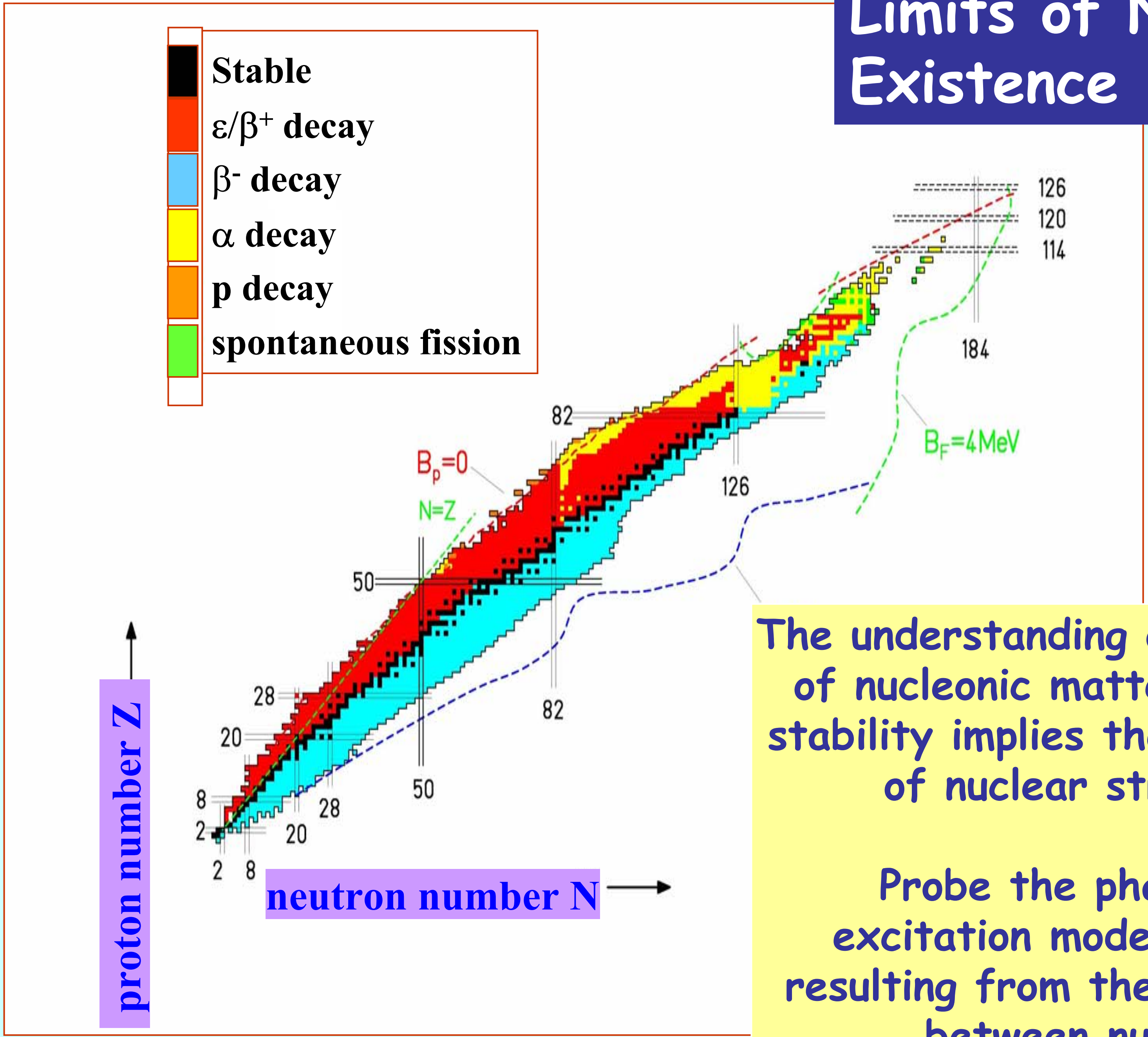
- ✓ Excess of neutrons or protons,
- ✓ short half-life,
- ✓ neutron or proton dominated surface,
- ✓ low binding

Un po' di storia



Con la disponibilita' di fasci di ioni sempre piu' pesanti e' stato possibile creare un crescente numero di nuclei fuori dalla valle di stabilita'

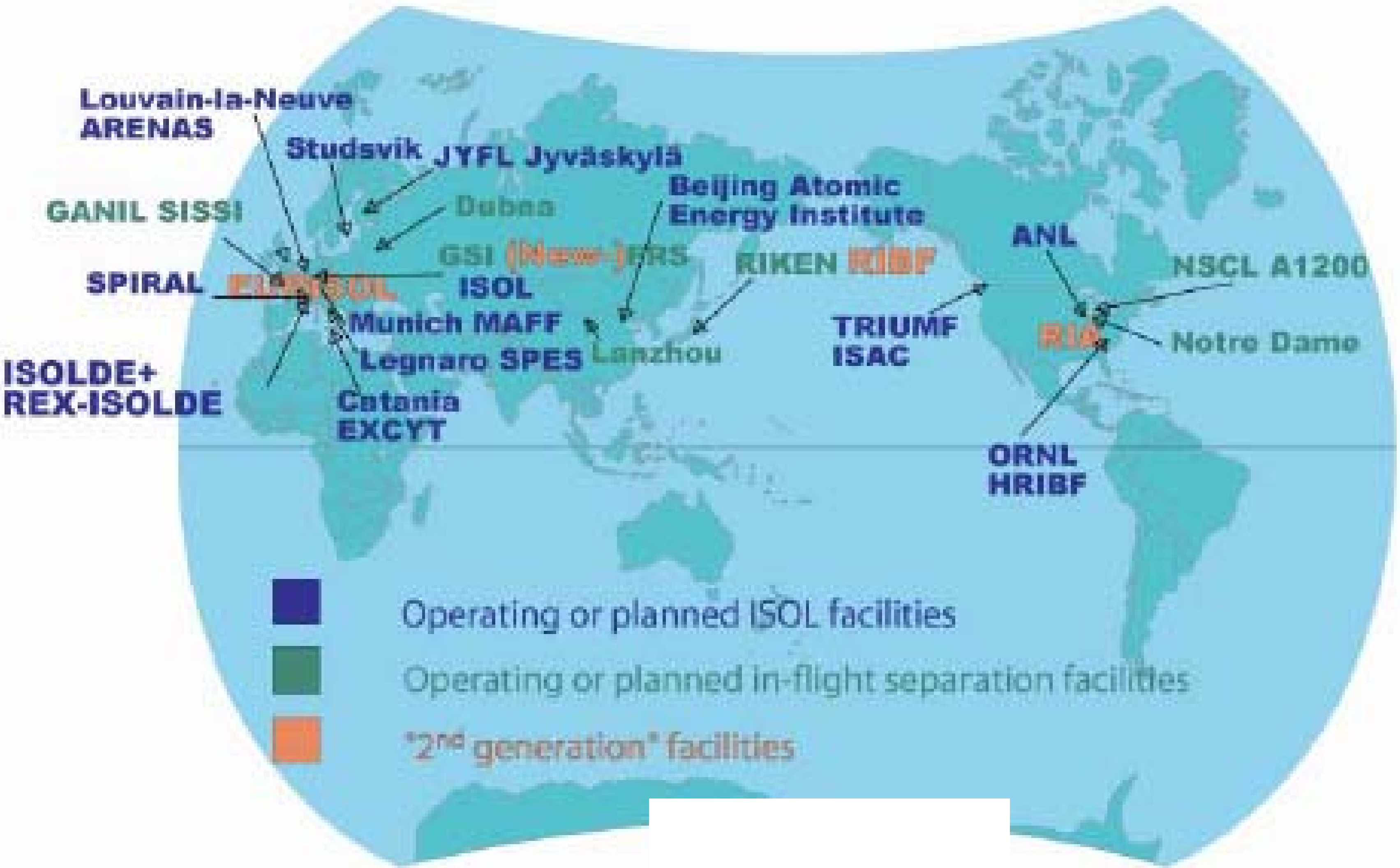
Limits of Nuclear Existence



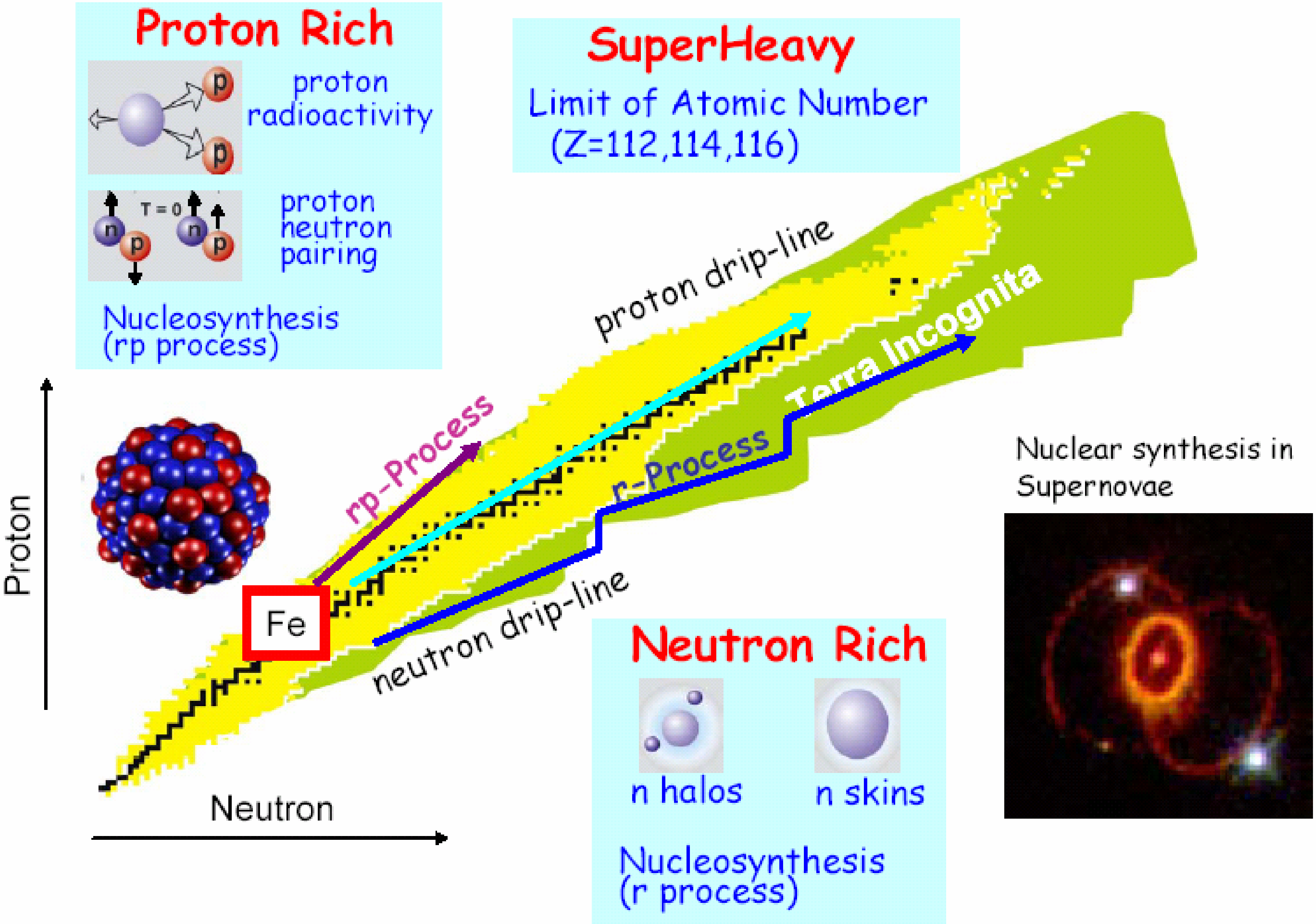
The understanding of the nature of nucleonic matter far from stability implies the exploration of nuclear structure:

Probe the phases and excitation modes of nuclei resulting from the interactions between nucleons

World Wide Radioactive Beam Facilities

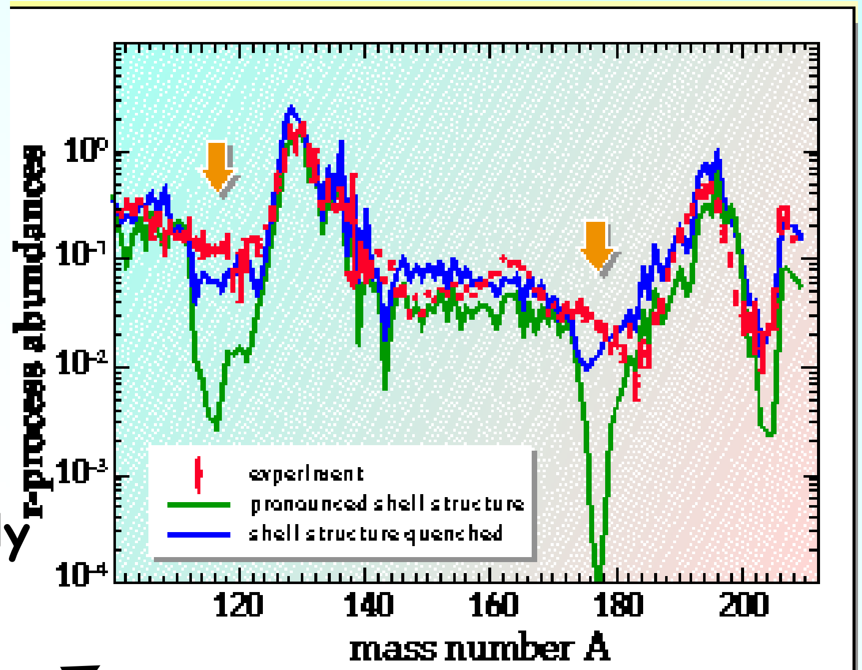


Frontiers of Nuclear Structures: Exotic Nuclei

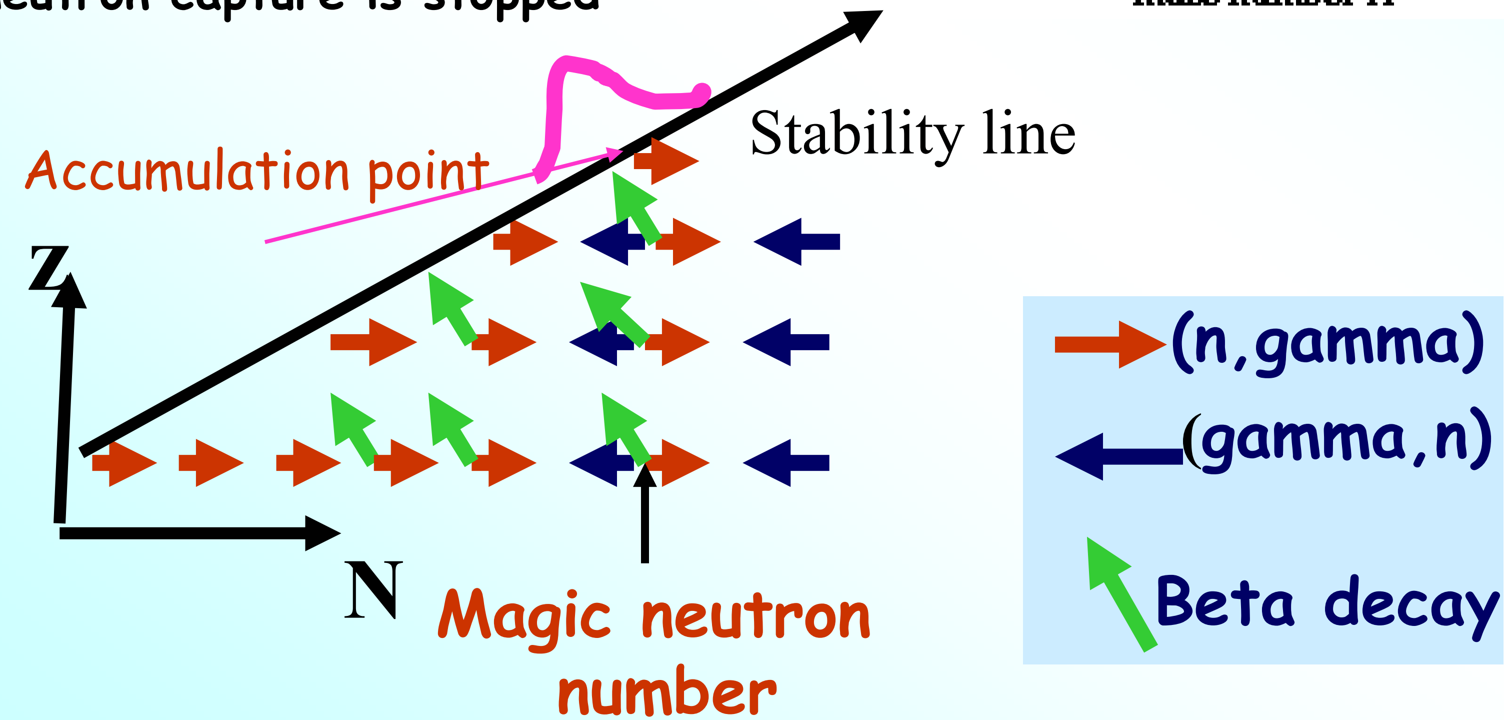


The r-process

Abundance peak in the r-nuclei distribution

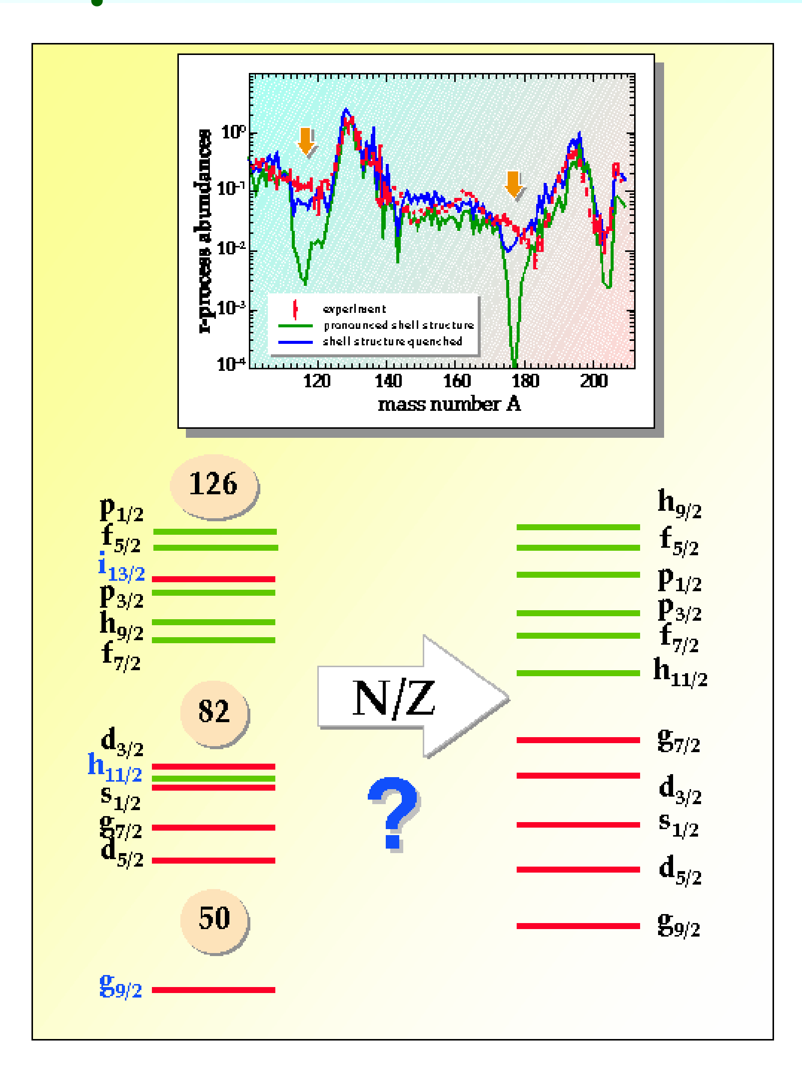


→ **Decrease of Sn**
Photodisintegration competes with neutron capture and eventually Equilibrium is reached and then neutron capture is stopped



Nuclear physics in r-process

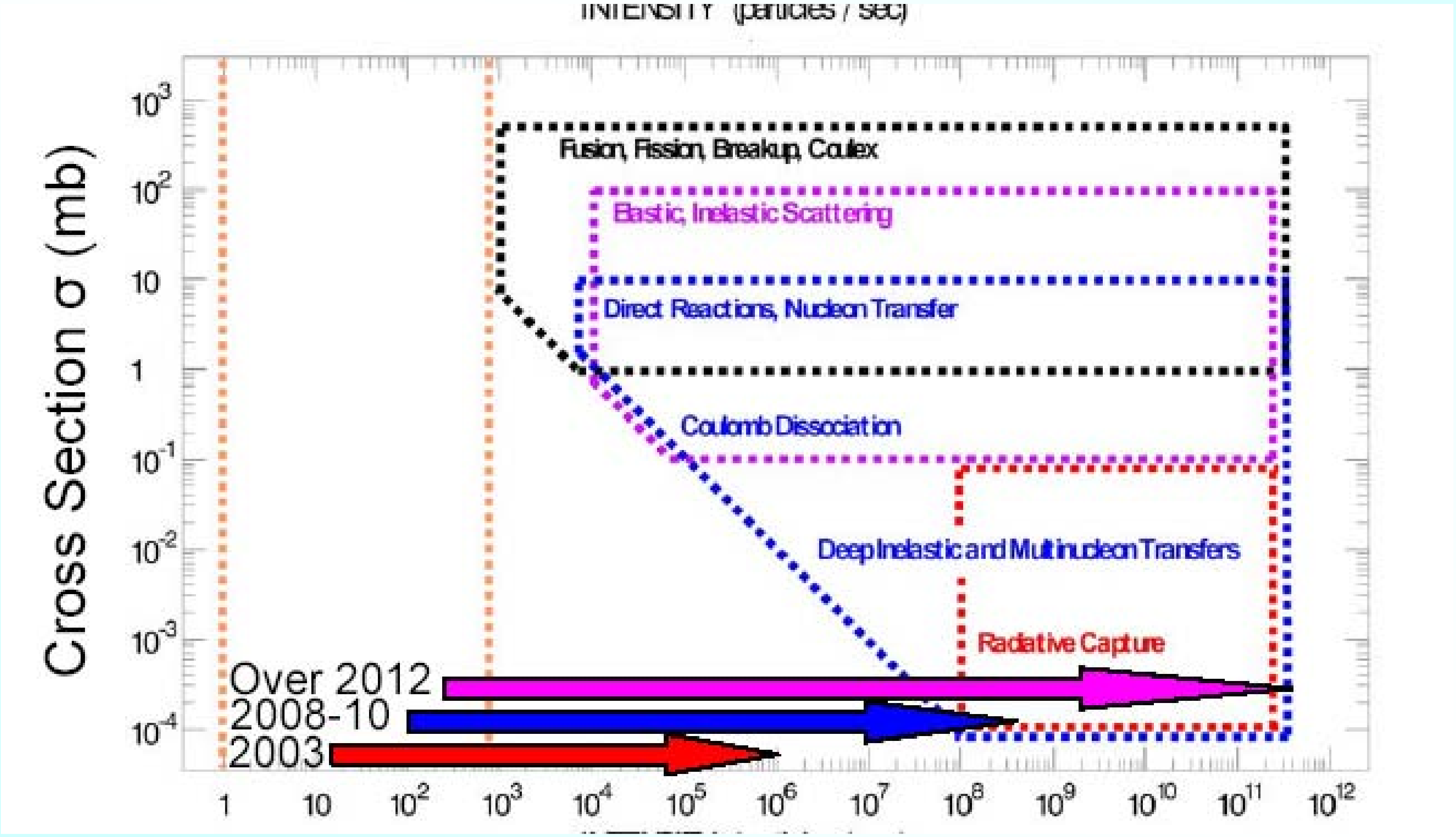
R-process involves many unstable exotic nuclei and their properties needsto be known:



- Ground state properties
- Optical potential
- Level densities
- Gamma-ray strength function
- Reaction rates
- Beta-decay rates
- Shell structure and its evolution with N/Z

Produce and accelerate RIB to undertake this program

The different nuclear structure properties (or excitation modes) Needs the use of different reaction mechanisms which correspond to cross sections varying over 8 order of magnitude



Method	Part /sec	Physics
Detection and identification	10 –5	Limits of nuclei, Existence
Stripping reactions	10 4	Nuclear properties beyond the drip lines
Mass measurements	10 –2	Masses, explosive nucleosynthesis
Interaction cross section	10 –2	Radii, nuclear size
Knockout reactions	10 5	Halos, cluster models, spectroscopic factors
Heavy-ion collisions	10 5	Nuclear compressibility, EOS, supernovae
Giant dipole resonance	10 6	Nuclear size and shape, r-process
Nuclear size and shape, r-process	10 7	Nuclear compressibility, EOS, neutron stars, supernovae
Coulomb excitation (2+)	1	Evolution of shell structure, r-process
Elastic scattering	10 3	Radii, density distributions
Inelastic scattering	10 3	Nuclear structure, rp-process
Nuclear structure, rp-process	10 4	Proton drip line, rp-process
Charge exchange	10 6	Gamow-Teller strength, supernova core evolution,
Lifetimes/β-decay studies	10 –3	Nuclear deformation, shell evolution, explosive nucleosynthesis, r-process,
β–NMR	10	Ground-state moments
Micro-second isomers	10 –3	Shell structure, single particle states

Programma sperimentale vasto che riguarda :

- **Produzione dei nuclei radioattivi**
  - Acceleratori e bersagli di produzione (selezione della regione di A)
    - Masse e altre proprietà dello stato fondamentale
    - (Spin, momenti magnetici, momenti di quadrupolo)
    - Decadimenti (beta e alpha per i nuclei pesanti)

- **reazioni con fasci radioattivi** per studiare le proprieta' di struttura e indagare i vari aspetti e la complessita' del problema a multicorpi

Basse energie (Fino a circa 20 MeV/u)
- Reazioni di trasferimento (proprieta' di particella singola)
- Fusione (proprieta' collettive)
- Eccitazione Coulombiana (Proprieta' collettive)

Alte energie (E> 50 MeV/U)
- Knock out , frammentazione
- eccitazione coulombiana

- **strumentazione** per la spettroscopia associata, particelle cariche, neutroni, gamma e spettrometri di massa e di momento)

Primo problema:

Intensita' dei fasci di ioni radioattivi da usare come fasci secondari :

- **Quali sono i problemi tecnici per avere fasci con intensita' paragonabili con quella di ioni con nuclei stabili?**

(10^{10-11} ioni/s)

- perche' servono alte intensita' ?

$$N_{prod} = N_{inc} \quad N_{targ} \quad \sigma$$

[ions/sec] [ions/sec] [nucl/cm²] [cm²]

$$N_{prod} = \frac{I(eA)}{Z_{proj}\ e\ [coul]} \ \frac{N_A \ \chi\ [gr/cm^2]}{A_{targ}\ [gr]} \ \sigma\ [cm^2]$$

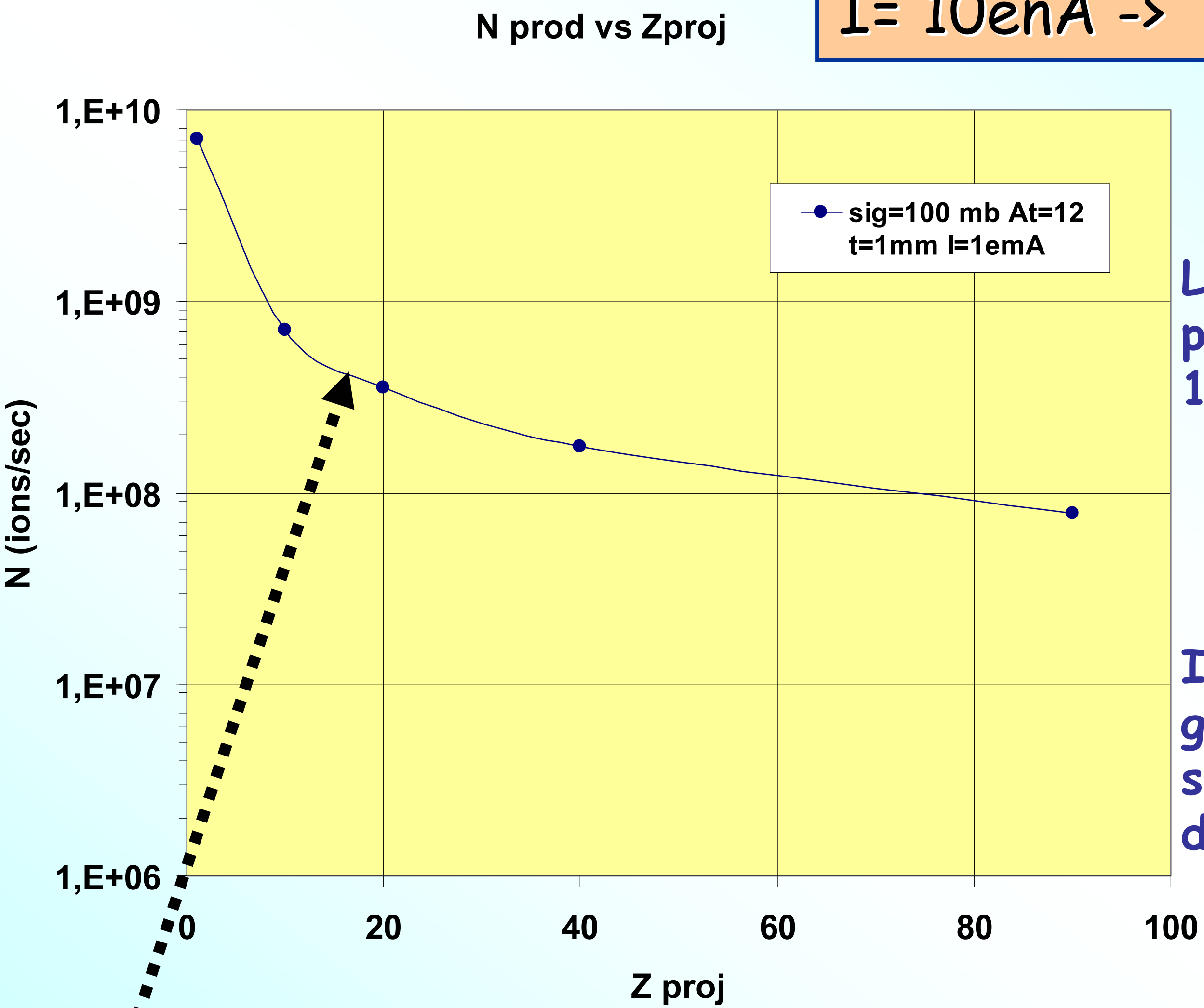
$$N_{prod} = \frac{I(enA)\ 10^{-9}\ 10^{19}}{Z_{proj}\ 1.602} \ \frac{6.02\ 10^{23}\ \chi\ [\mu gr/cm^2]\ 10^{-6}}{A_{targ}} \ \sigma\ [mbarn]\ 10^{-27}$$

$$N_{prod} = \frac{3.76\ I(enA)\ \chi\ [\mu gr/cm^2]\ \sigma\ [mbarn]}{Z_{proj}\ A_{targ}}$$

$$\chi\ [\mu gr/cm^2] = \rho\ [gr/cm^3]\ t[\mu m]\ 10^2$$

Esempio : ρ= 2 gr/ cm³ e t= 1 mm χ = $2\ 10^5\ \mu gr/cm^2$ = 200 mg/cm²

I= 10enA -> 0.6 10^{11} protons/sec

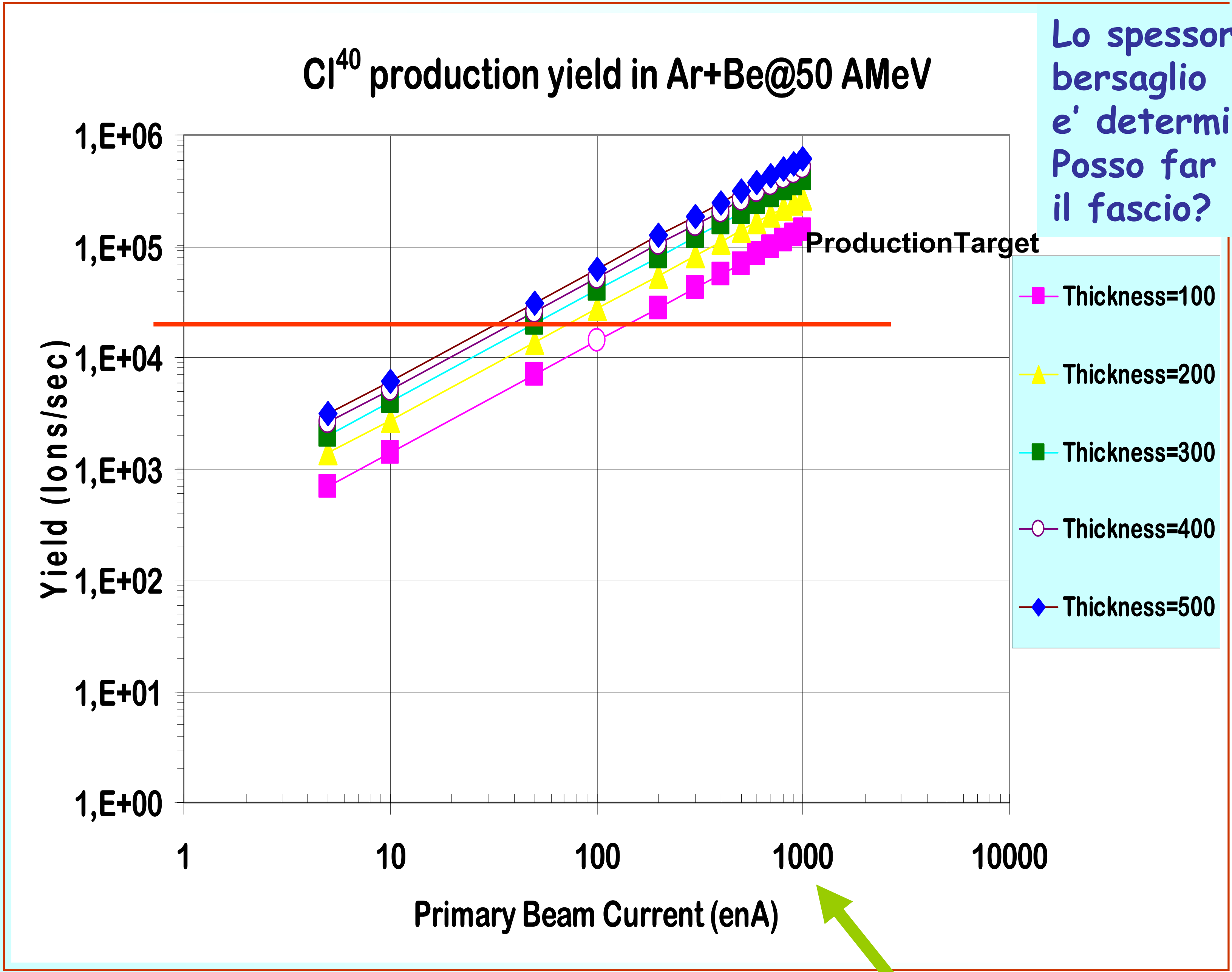


La fisica con i fasci di ioni pesanti si fa con intensita' 10^9-10^{11} ioni al secondo

I fasci secondari di seconda generazione con 10^8 ioni al secondo potenze del'ordine di 100 kWatt!

Potenza (W)= I V = I (Energy/Charge state)

Es: I=1mA E=50 A MeV di O^{16} completamente strippato (O^{8+}) :
P = 1 10^{-3} (50 16/8) 10^6 =100 kW



Lo spessore del bersaglio e' determinante : Posso far fermare il fascio?

≈ 1 kWatt

Fasci radioattivi prodotti utilizzando ioni pesanti

- Con ioni pesanti, dovuto al breve range non posso fare bersagli spessi se voglio utilizzare direttamente i prodotti di reazione

- Se aumento l'energia in modo da poter fare uscire i prodotti dal bersaglio cambiano i meccanismi di produzione !

✓Quindi a secondo dei nuclei di interesse devo studiare:

1) quale sono le reazioni migliore per produrli (tipo ed energie)

2) l'energie d'interesse alle quali voglio avere i nuclei radioattivi per studiarne le loro caratteristiche eccitandoli con reazioni nucleari

Metodi di produzione

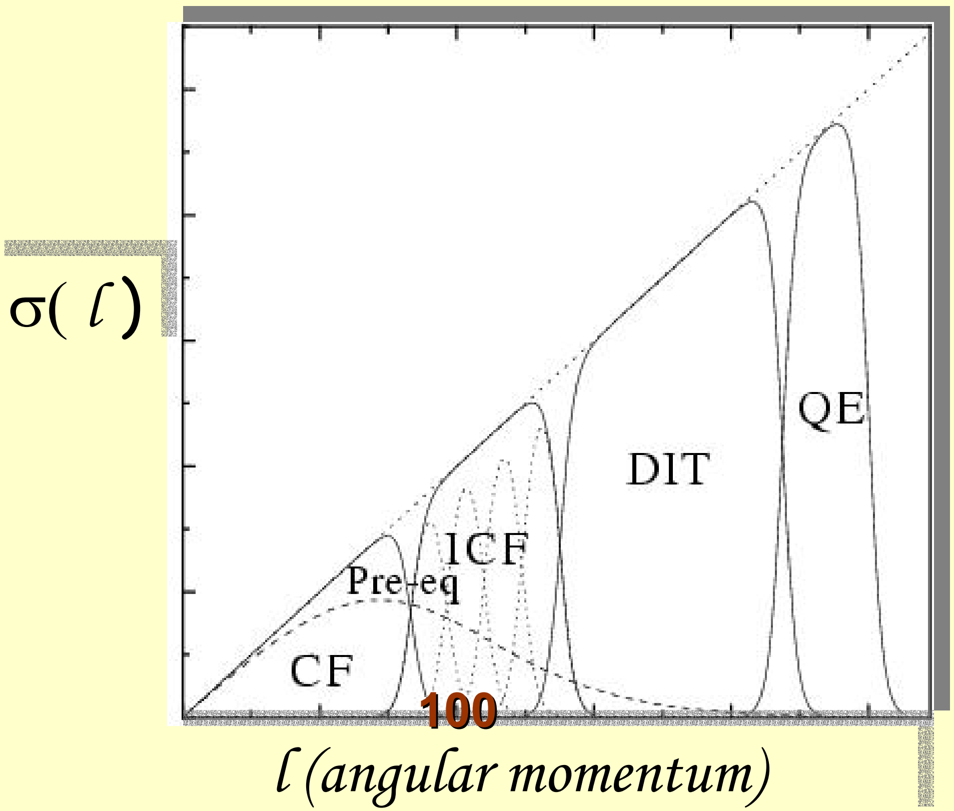
ISOL

Isotope separation on line
fascio primario p, n, d, …ioni pesanti di massa intermedia (energie da 10 di MeV fino a GeV)

In flight

Ioni pesanti (medio pesanti – pesanti)
con energie da circa 100 MeV

Reazioni di Produzione



•Bassa Energia (Fusione, Fissione, Reazioni dirette , Deep Inelastic)

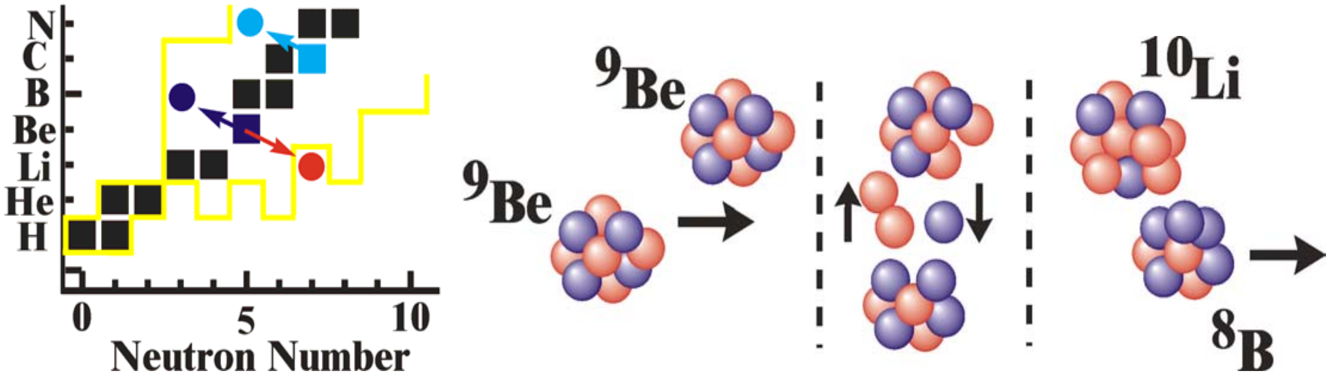
•Alta Energia (Frammentazione Proiettile o Targhetta, Spallation, Fissione in volo)

- peripheral elastic and quasi-elastic (QE) collisions
- semi-peripheral deep-inelastic collisions (DIT) collisions
- incomplete (ICF) and complete (CF) fusion in central collisions
- pre-equilibrium emision typically preceding ICF/CF and DIT

Reazioni di Produzione
Transfer Reactions

$$^{9}Be + {}^{9}Be \longrightarrow {}^{8}B + {}^{10}Li$$

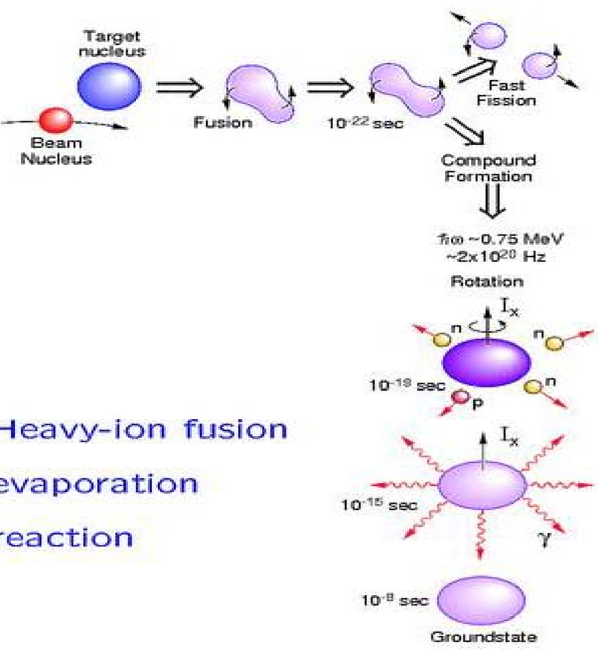
$$^{13}C + {}^{9}Be \longrightarrow {}^{12}N + {}^{10}Li$$



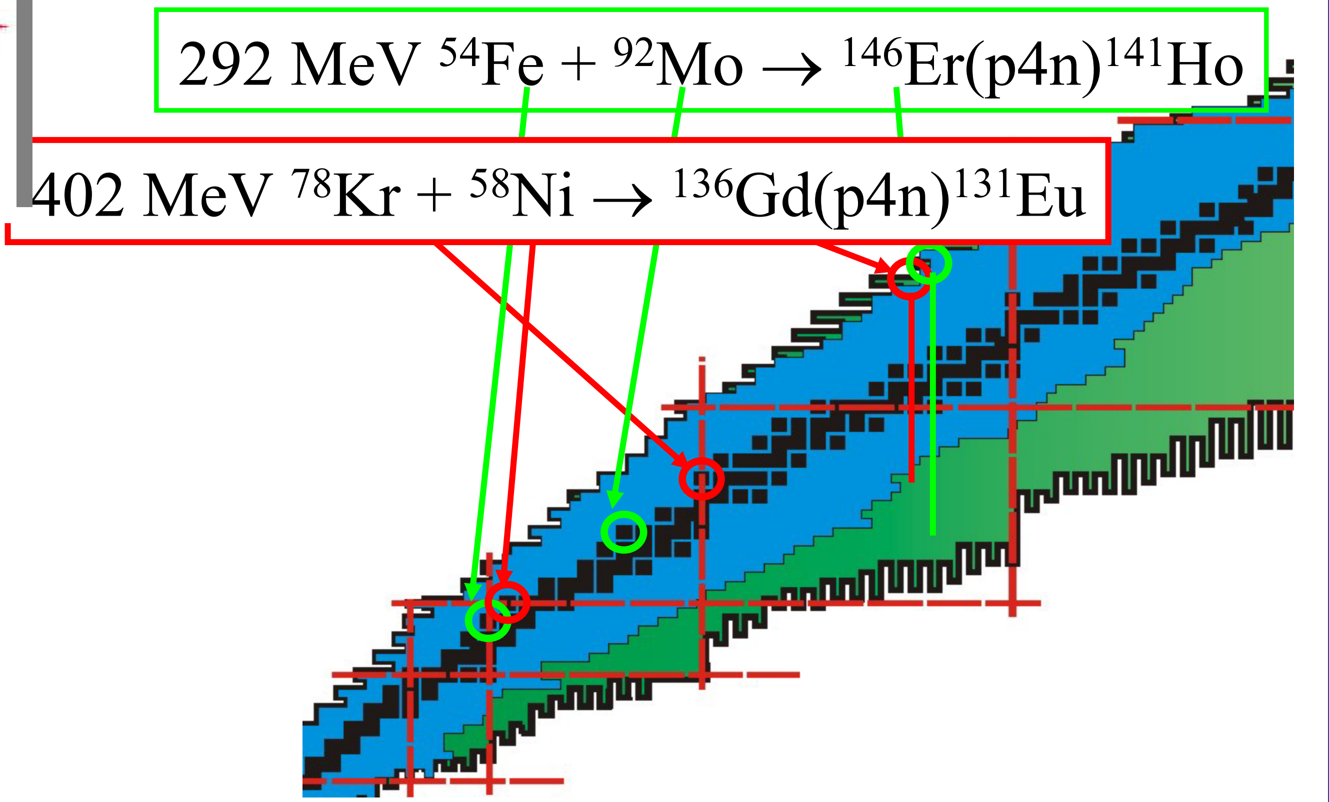
In generale:

- Piccate ad angoli in avanti
- $\sigma \cong 10^{-1}$ – 10 mbarn a 10-50 MeV/u

Reazioni di Produzione: Fusione

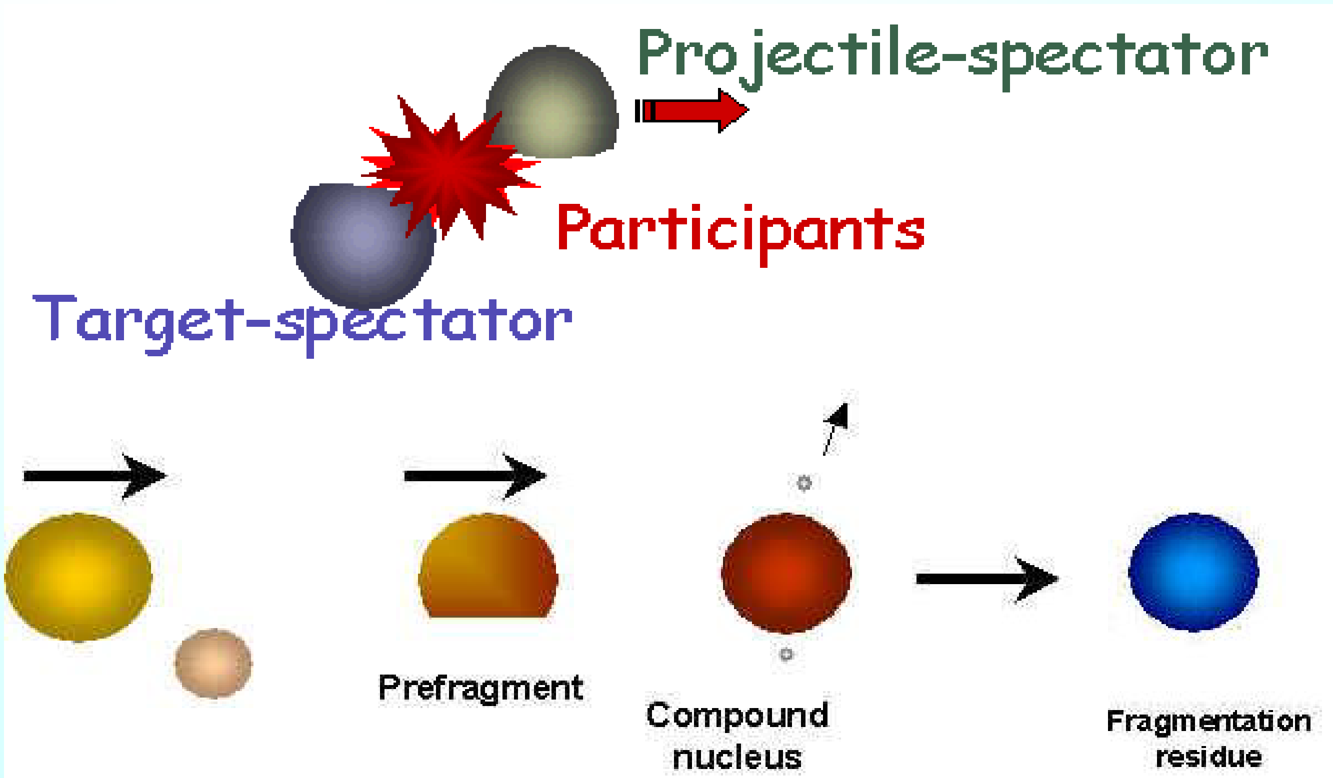


Energie ione stabile
5-15 MeV/u



A.A. Sonzogni *et al.*, Phys. Rev. Lett. **83** 1116 (1999)
D. Seweryniak *et al.*, Phys. Rev. Lett. **86** 1458 (2001)

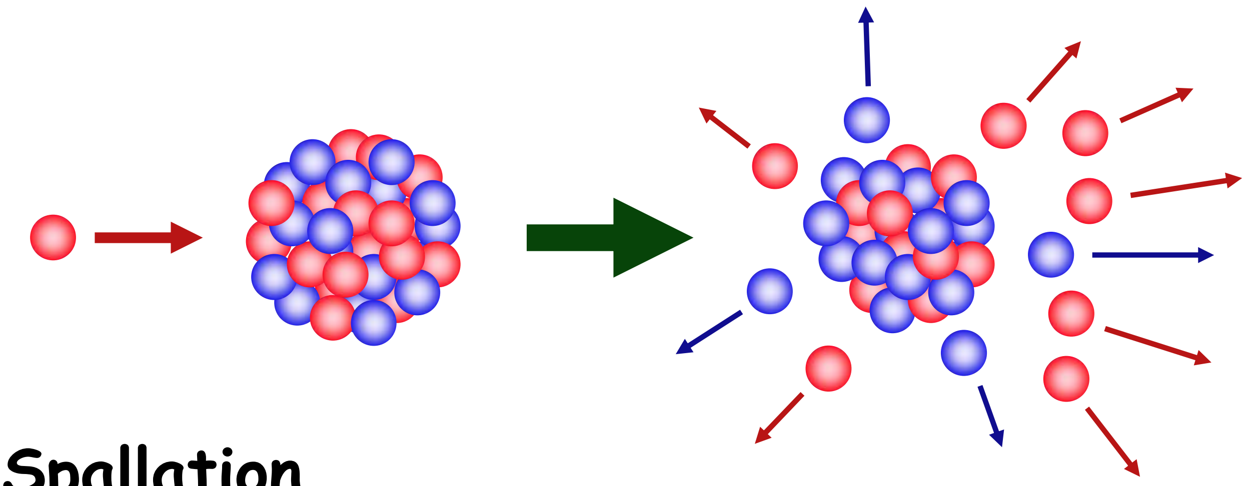
Participant-spectator reactions at relativistic energies (above 100 AMeV)



Reazioni di Produzione Frammentazione del Proiettile

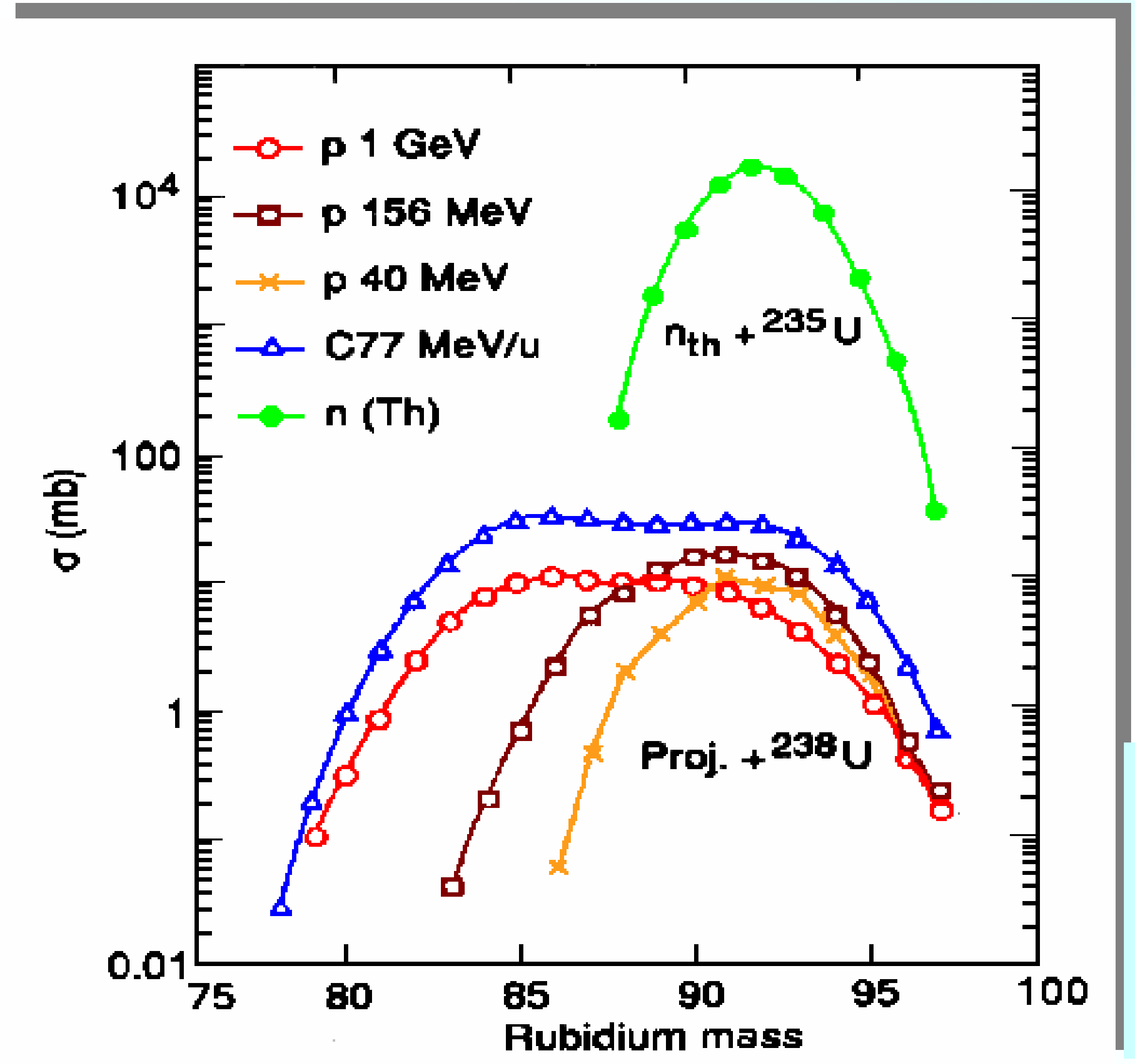
Reazioni di Produzione Frammentazione della Targhetta

Random removal of protons and neutrons from heavy target nuclei by energetic light projectiles (pre-equilibrium and equilibrium emissions).



Spallation

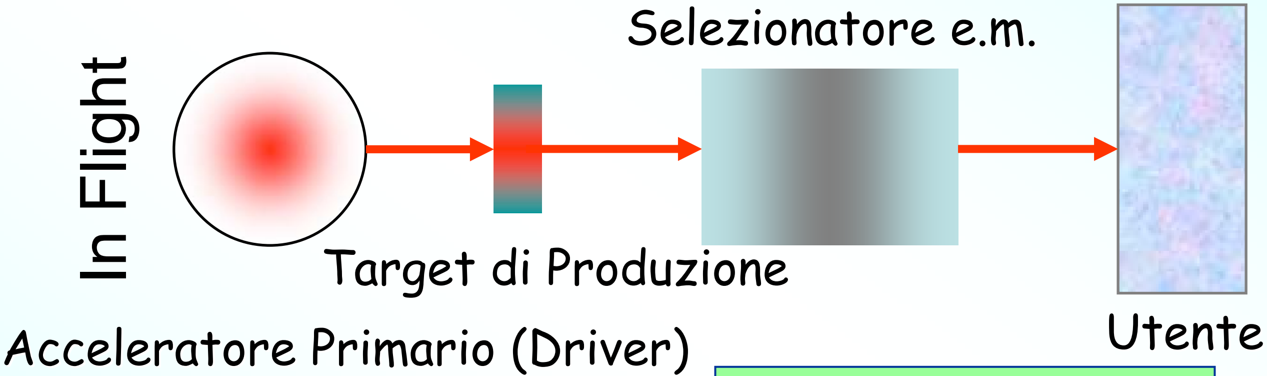
Reazioni di Produzione



Gli isotopi stabili del Rubidio hanno
A= 85 e A=87

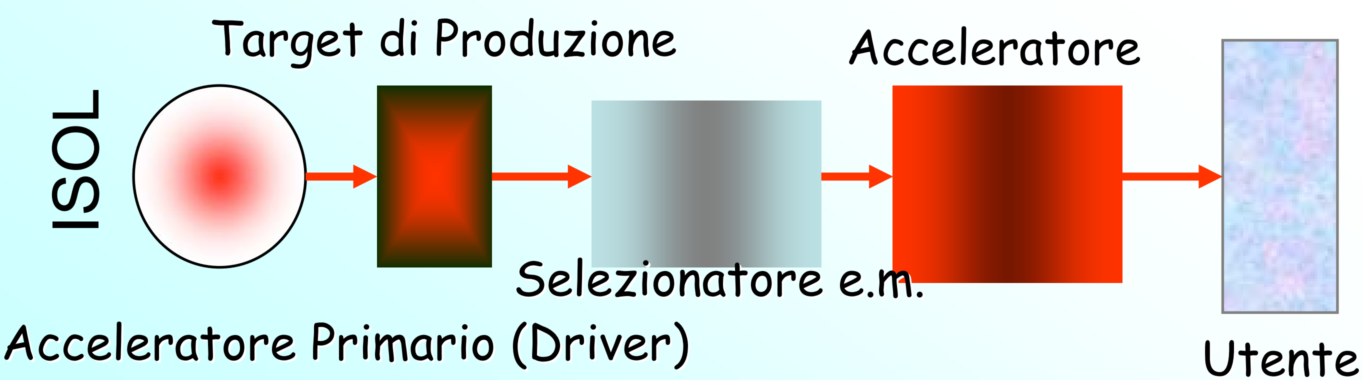
Metodi di Produzione

•In-Flight (Fascio prodotto direttamente nella reazione)

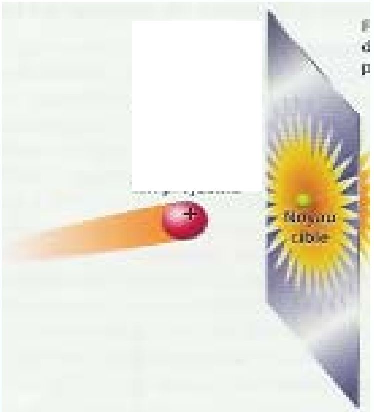


•Degraders
•Tagging

•ISOL (Prodotti di reazione accelerati in un secondo acceleratore)

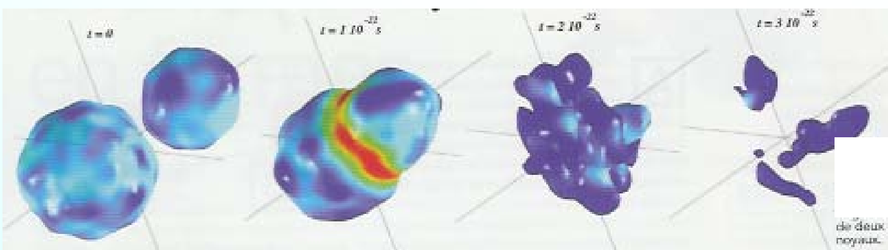


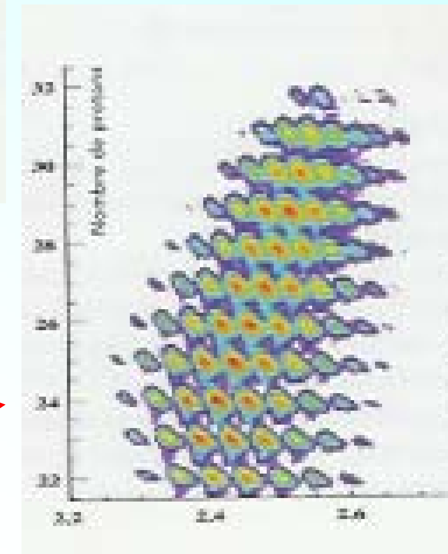
FRAGMENTATION METHOD



Thin target

FRAGMENT SEPARATION

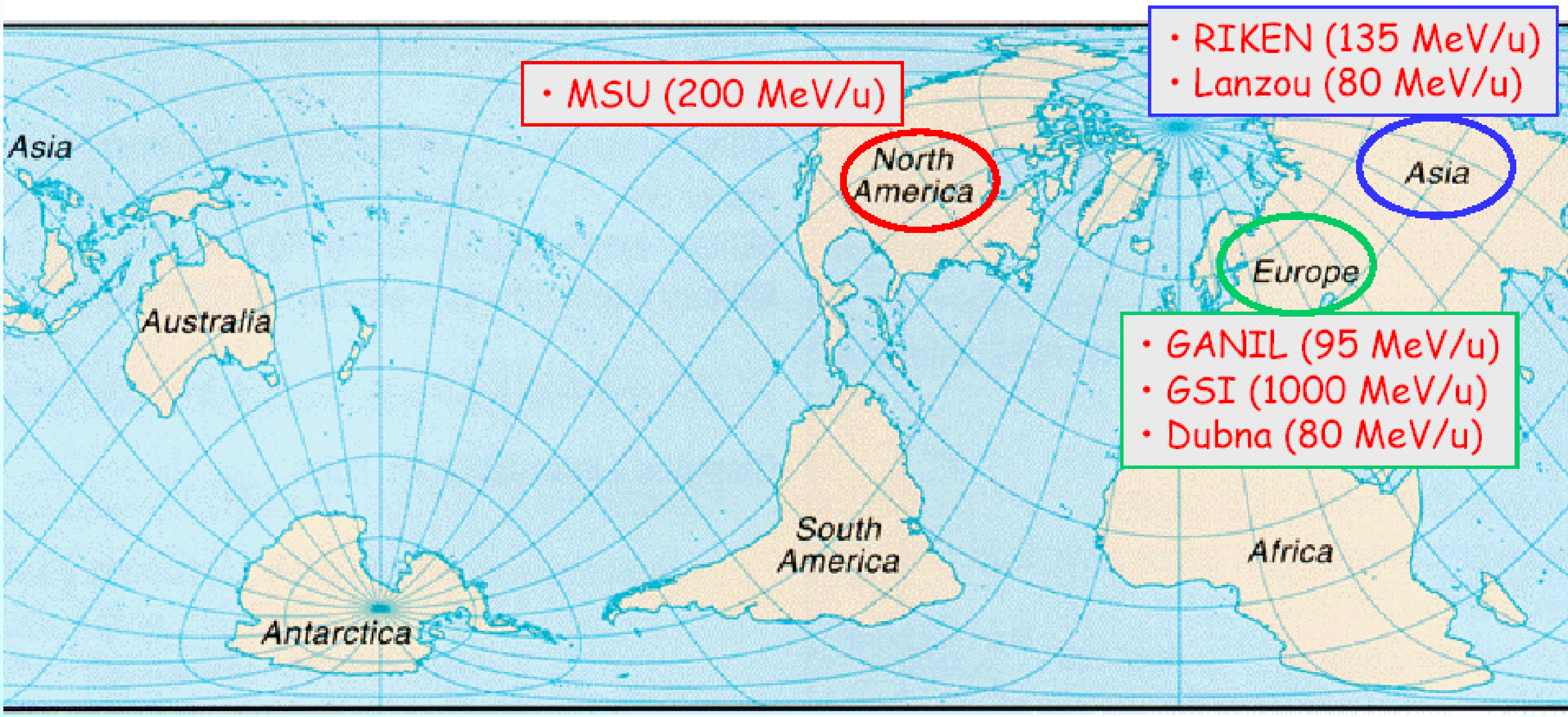




High energy beams
Large spot size and beam cocktails
Exotic Nuclei with short lifetimes < 1ms

Existing facilities:
GSI
GANIL
MSU
RIKEN

In-Flight facilities



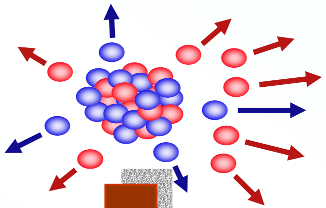
In Flight

Laboratory	Accelerators	RIB Separator	RIB Energies
GANIL	C Cycl.	SISSI+LISE	<95 A MeV
NSCL-MSU	C Cycl.s	A1200	<200 A MeV
GSI	SIS	FRS or ESR	<1.2 A GeV
RIKEN	Cycl.	RIPS	<150 A MeV
DUBNA	C Cycl.s	ACCULINNA&COMBAS	<100 A MeV
LANZHOU	Cycl.	RIBLL	<80 A MeV
LNS	Cycl.	FRS-CT	<50 A MeV

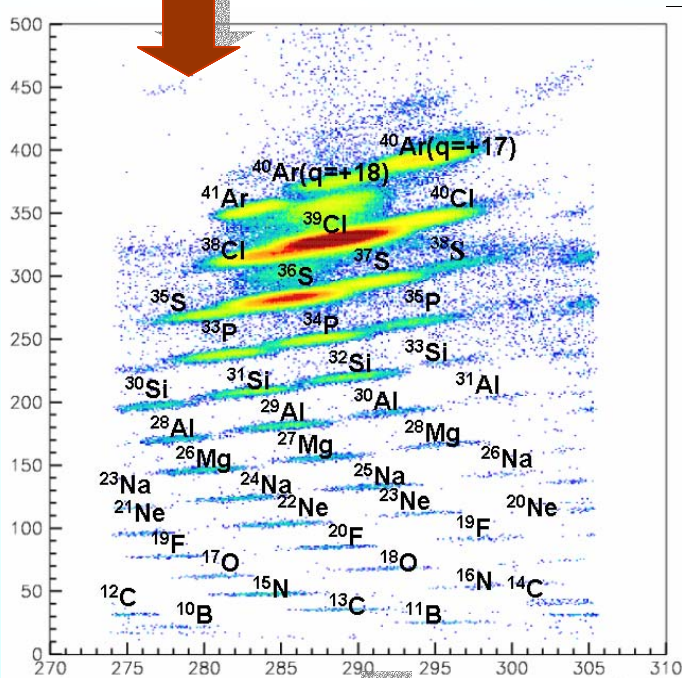
RIBs IF–Running Facilities

Fragment Separators

	ΔΩ (msr)	ΔP/P (%)	MaxBρ(Tm)	Length (m)
FRIBs	4.0	+/- 1.1	4.0	23
Present	1.1	+/-0.65	2.7	23
GANIL-LISE	1.0	+/-2.5	3.2	18
GSI-FRS	0.7-2.5	+/-1	9-18	74
RIKEN	5.0	+/-3	5.76	21
NSCL-A1200 (A1900)	0.8- 8	+/-1.5	5.4	22
JINR	6.4	+/-1	4.5	14.5



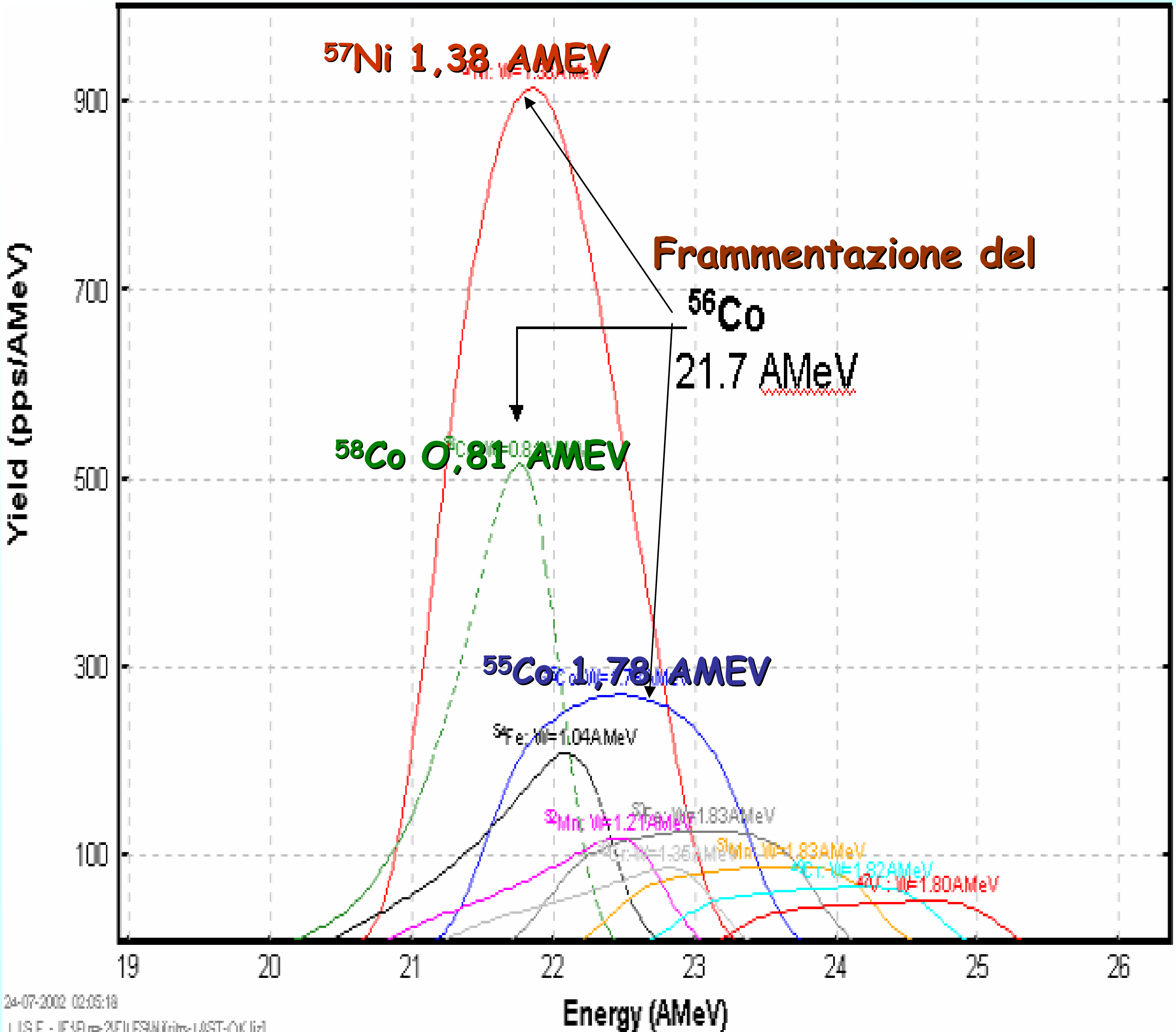
Metodo In-Flight



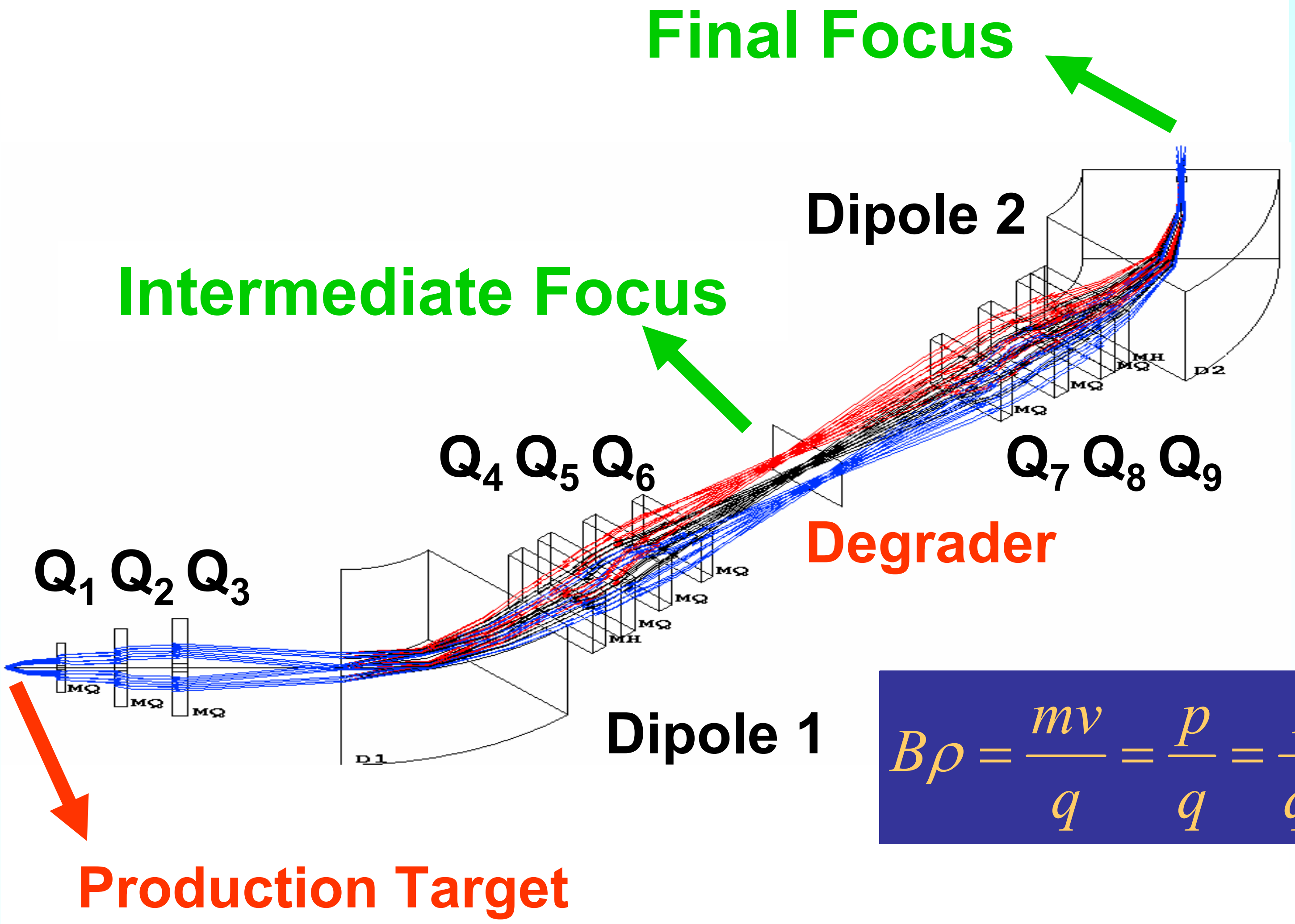
- Relativi problemi di radioattività
- RIBs con vite medie piccole (<msec)

- RIBs non "monoenergetici"
- Energia fascio dopo la frammentazione
  → NON REGOLABILE

- Separazione ElettroMagnetica (Coktail di RIBS)
- Uso di "Degrader"



57Ni 1,38 AMEV
58Co 0,81 AMEV
55Co 1,78 AMEV
Frammentazione del
56Co
21.7 AMeV
54Fe: W=1.04AMeV
52Mn: W=1.21AMeV
53Fe: W=1.83AMeV
51Mn: W=1.83AMeV
50Cr: W=1.82AMeV
49V: W=1.80AMeV
Yield (pps/AMeV)
900
700
500
300
100
19
20
21
22
23
24
25
26
Energy (AMeV)
24-07-2002 02:05:18



$$B\rho = \frac{mv}{q} = \frac{p}{q} = \frac{Av}{qc^2}$$

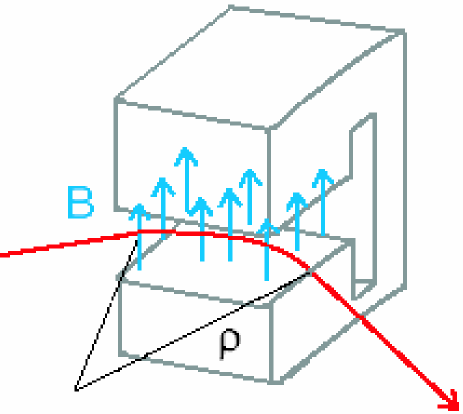
Overview of the Fragment Separation Technique

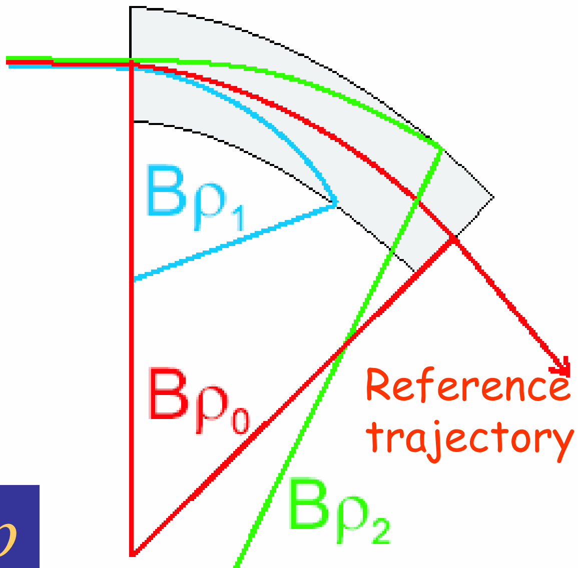
Magnetic Dipole

✓ A dipole is the ion-optical equivalent of a prism

✓ A dipole introduce dispersion, i.e. a relation Between momentum and position

✓ A/q selection with a certain acceptance in momentun width

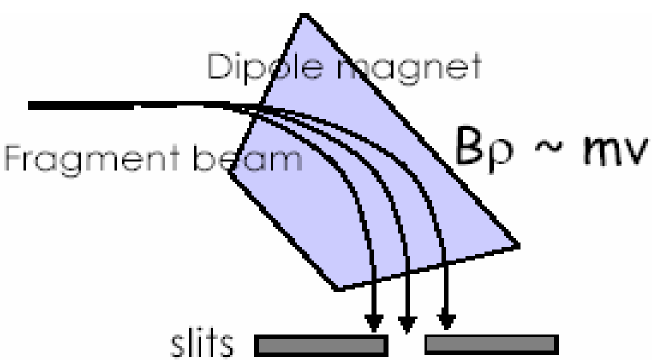




$$\delta = \frac{p - p_0}{p_0} = \frac{\Delta p}{p_0}$$

Reference momentum

DIPOLE SELECTION



$$F = qvB = \frac{mv^2}{\rho}$$

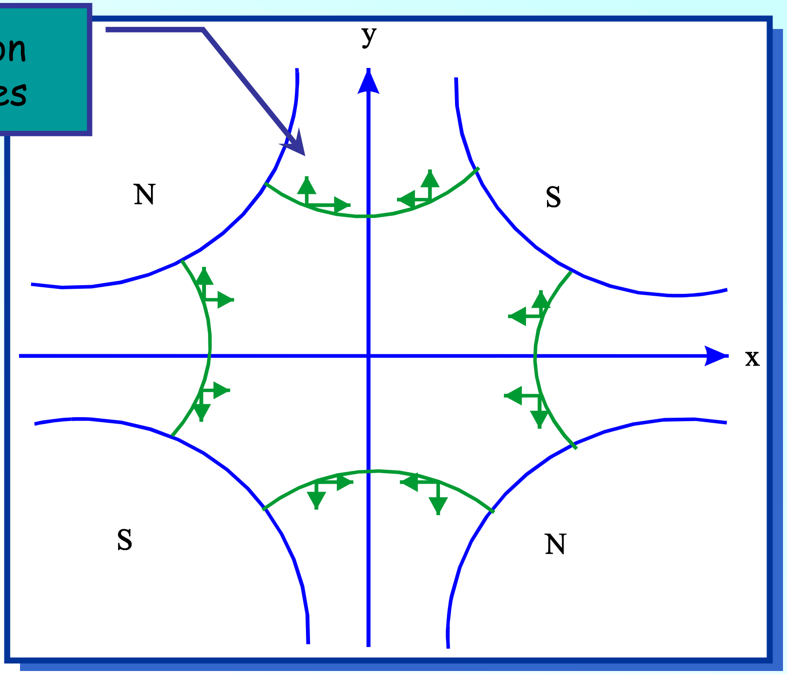
$$B\rho = \frac{mv}{q} = \frac{p}{q} = \frac{Av}{qc^2}$$

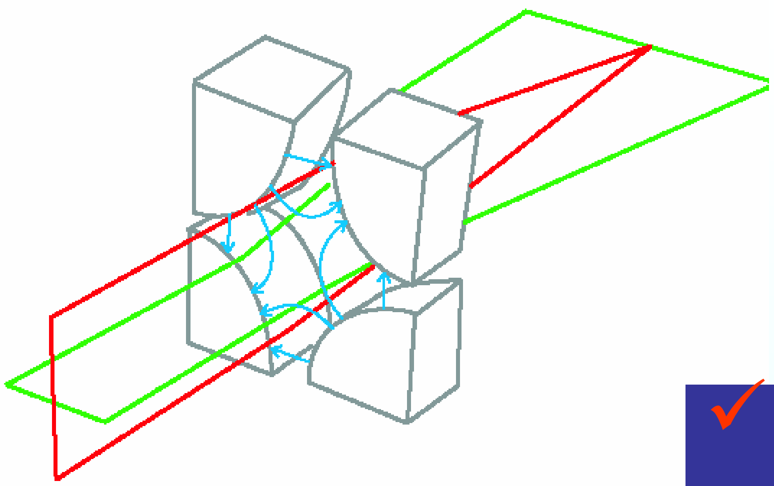
Magnetic rigidity: Bρ = 3.3356·p [T·m] (if p is in [GeV/c])

Quadrupole

✓ On the x-axis (horizontal) the field is vertical and given by: $B_y \propto x$
✓ On the y-axis (vertical) the field is horizontal and given by: $B_x \propto y$

Force on particles



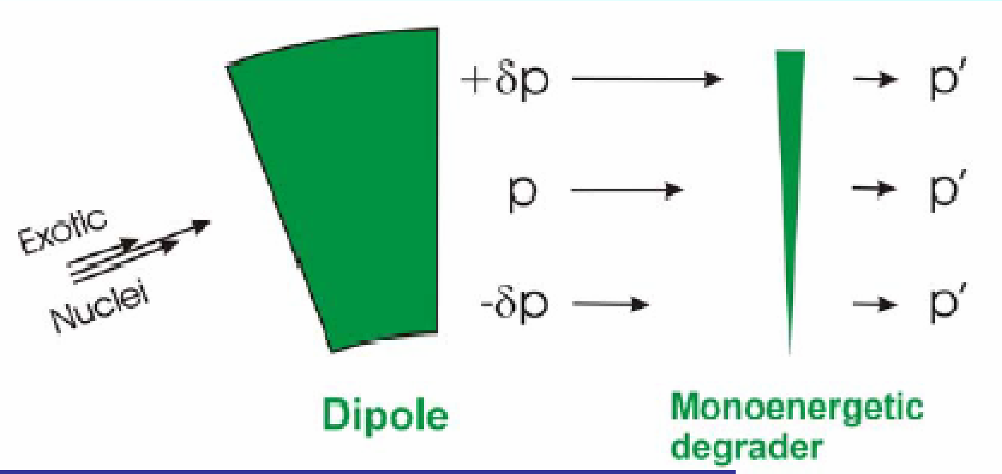


✓ It focuses the beam horizontally and defocuses the beam vertically.

✓ Rotating this magnet by 90° will give a vertical focusing and an horizontal defocusing

Degrader

$$B\rho = \frac{Av}{qc^2}$$



- ✓ Located in an intermediate focal plane on the beam line
- ✓ Better separation of isotopes with the same A/q ratio
- ✓ Reduction of "contaminants"
- ✓ The relative energy loss in the degrader is given by:

$$\frac{dE}{E} \cong eK\frac{A^3}{Z^2}$$

With K: constant typical of the degrader
e: thickness of the degrader

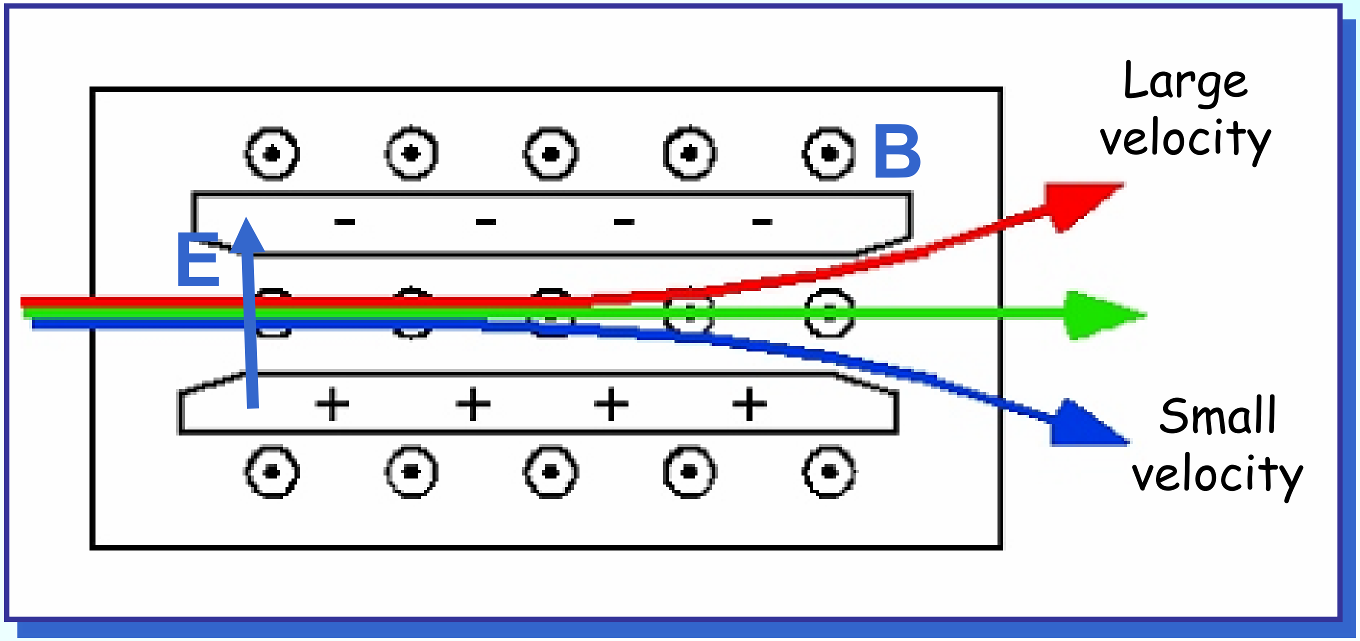
A: nucleus mass
Z: atomic number

☹ ENERGY STRAGGLING

☹ ANGULAR STRAGGLING

☹ NUCLEAR REACTIONS

→ INTENSITY LOSS



Wien Filter

✓ For the selected nucleus the forces due to the two fields compensate each other:

$$qE = qvB \qquad v = \frac{E}{B}$$

✓ The other ions are deviated

✓ No p dispersion

Obiettivo principale con il metodi in-flight e' quello di separare il maggior numero di nuclei prodotti nella reazione di frammentazione dal fascio primario :

Separatore acromatico (focalizza nello stesso punto indipendentemente p)

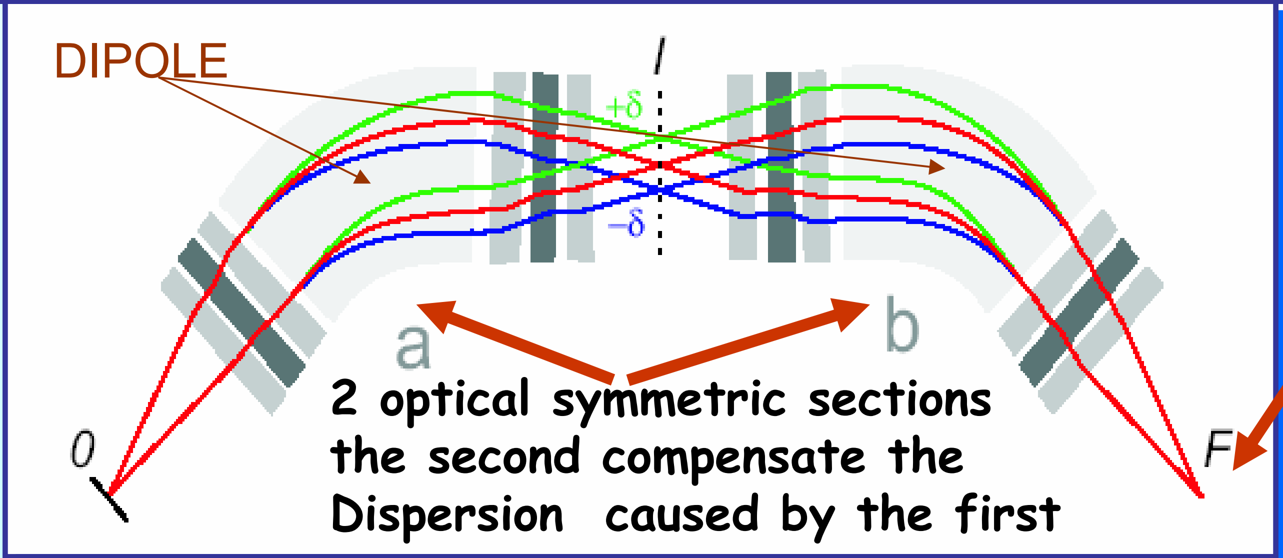
Selezionare un particolare A/Q

Achromatic Fragment Separator

WHAT WE WANT

- ✓ filter the nuclei of interest from other fragment
- ✓ collect as much as possible the nuclei of interest
- ✓ Produce an achromatic image of the primary beam spot for further transport through other beam lines
- ✓ ACHROMATIC: the total dispersion is zero

All nuclei produced on target entering the magnet are focussing on the same point

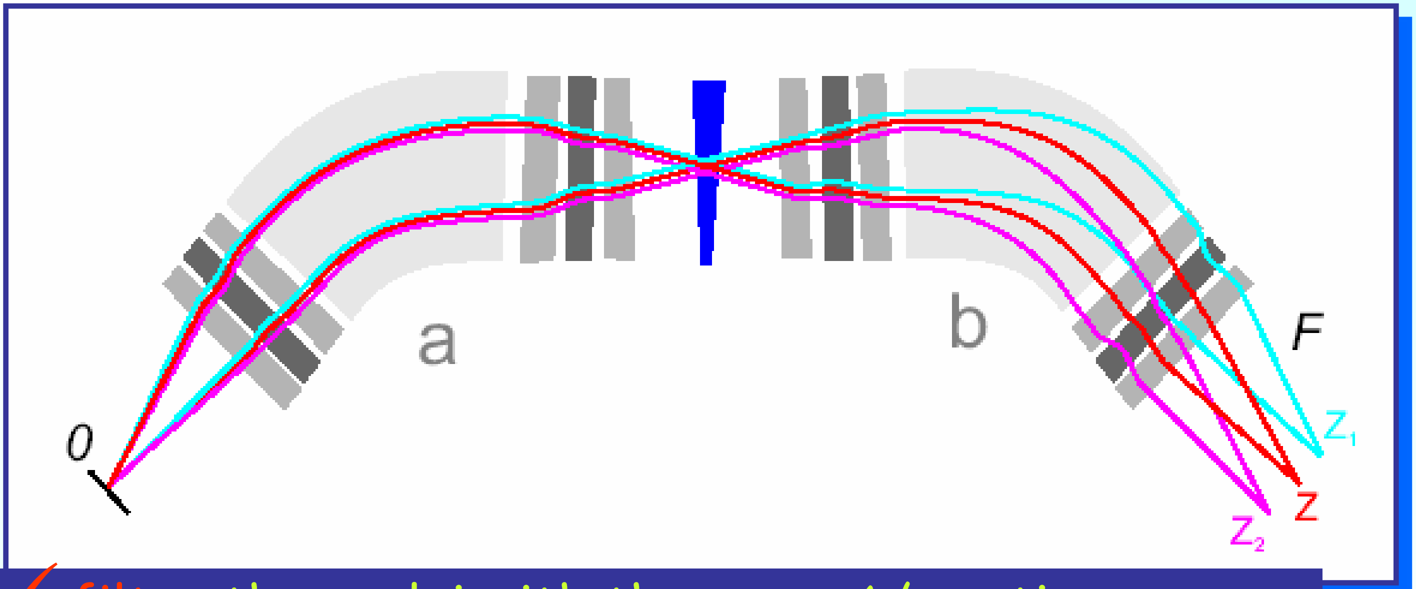


One-to-one image of the beam on target at the final focus

I nuclei che viaggiano in una fissata direzione prodotti dalle reazioni di frammentazione sono caratterizzati dall'avere diversi valori di Z

Voglio separare i diversi Z !

Wedge selection



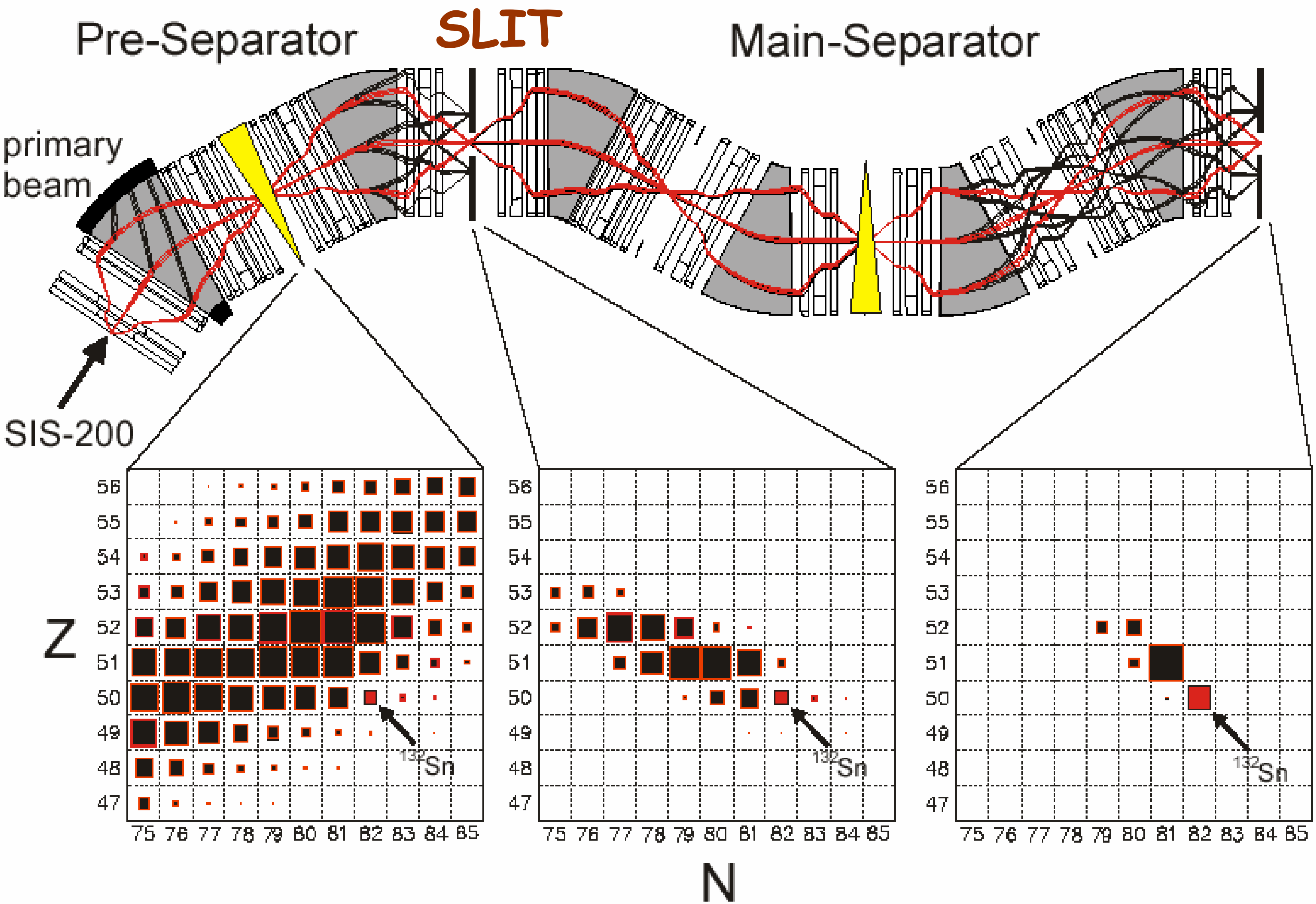
✓ filter the nuclei with the same A/q ratio
✓ preserve the achromaticity of the separator

→ WEDGE SHAPED $$\frac{dE}{E} \cong eK\frac{A^3}{Z^2}$$

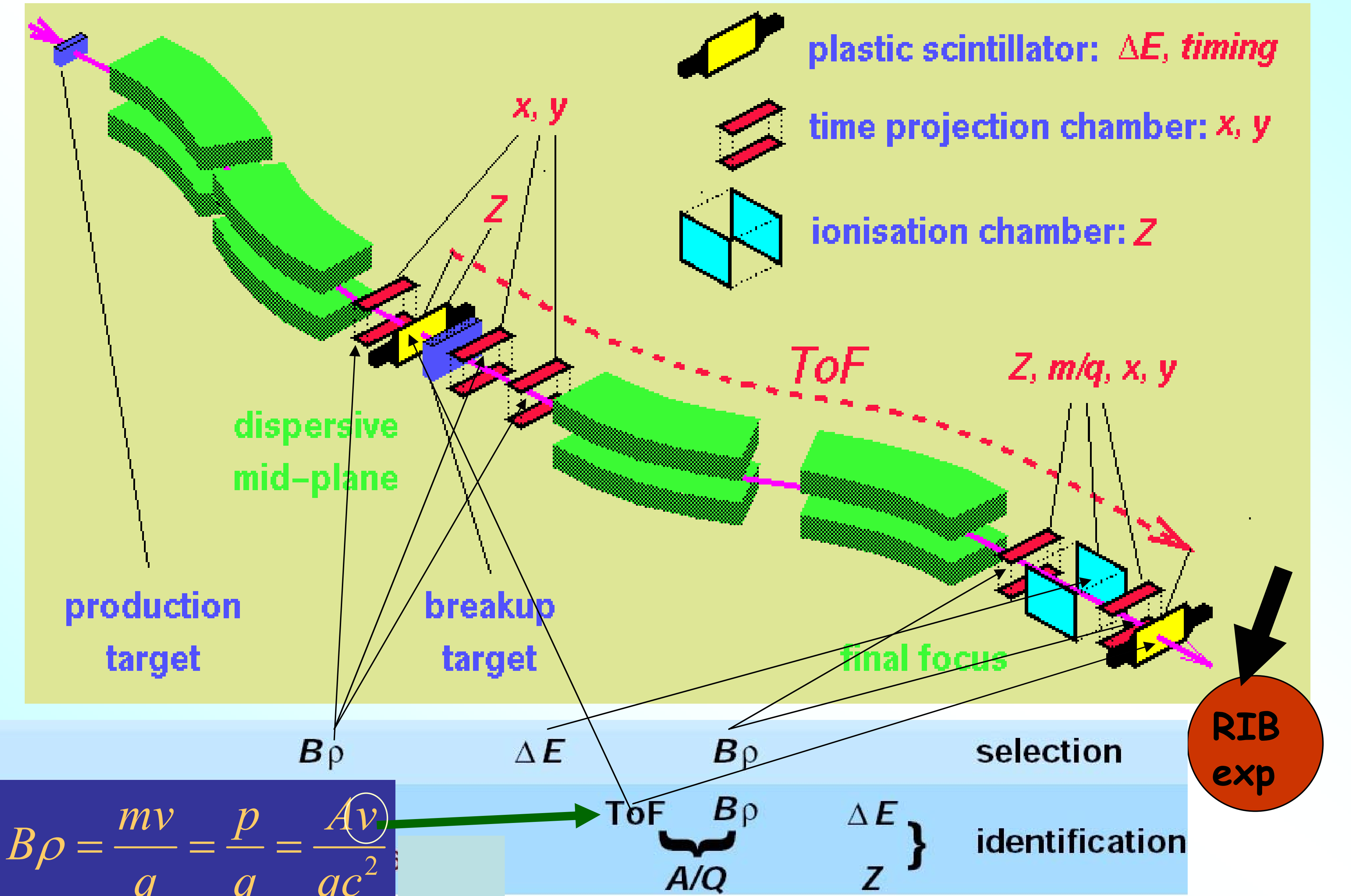
Thicker degrader at the high velocity side
Thinner degrader at the lower velocitity side

→ **Non voglio uccidere la dipendenza di dE/E da Z a causa del fatto che dE/dx (E)**

GSI Fragment separator



FSR@GSI :



$$B\rho = \frac{mv}{q} = \frac{p}{q} = \frac{Av}{qc^2}$$

MISURE A GSI :

SET up RISING Rare ISotope INvestigation at GSI

Campagne di Misure

Spettroscopia gamma con fasci fermati in un bersaglio :

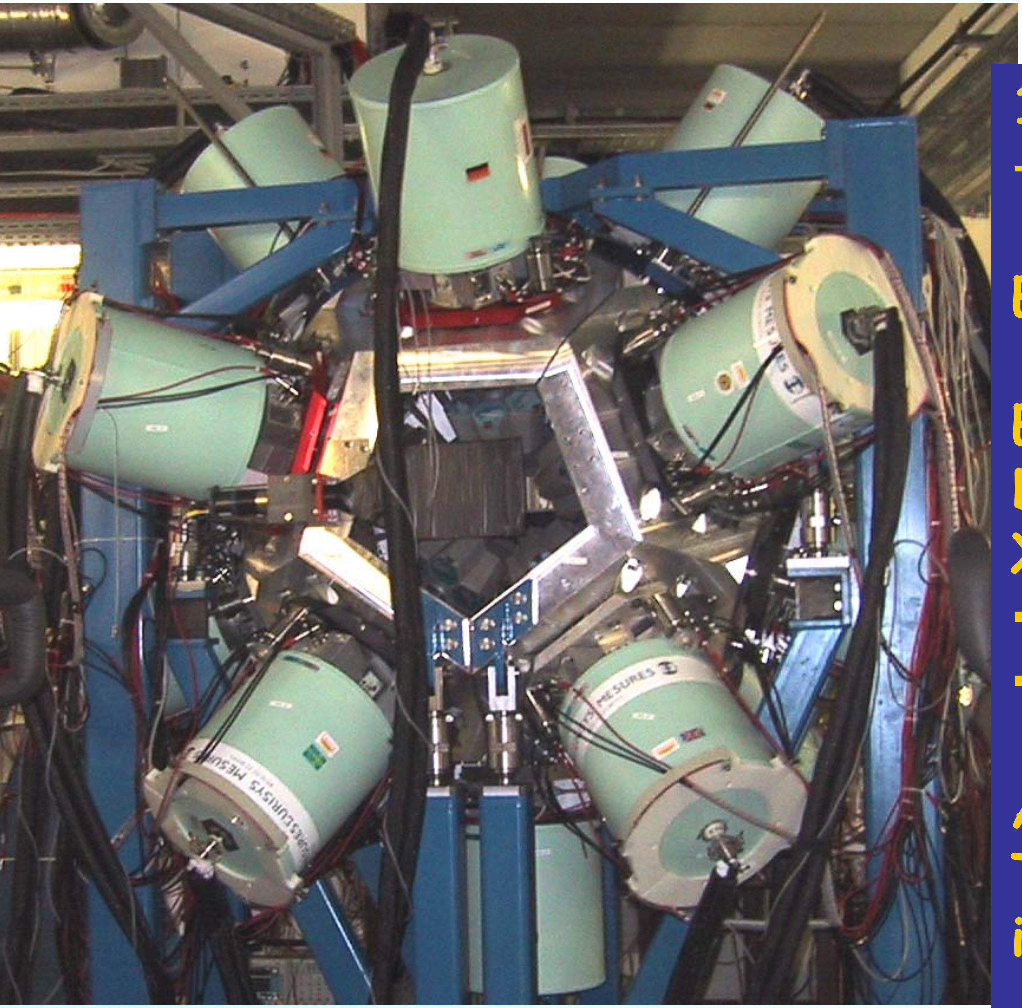
Limitato a studi di stati isomerici (con vite medie di microsecondi)
Ricerca di stati isomerici
(dovuti a eccitazioni che coinvolgono molti nucleoni)
Misure dei fattori giromagnetici

Spettroscopia gamma con fasci a energie 100-600 MeV/u

Eccitazione Coulombiana:
Stati vibrazionali di natura quadrupolare
Stati vibrazionali nuovi dovuti all'oscillazione dipolare della pelle di neutroni (Pygmy resonances)

Frammentazione :
Stati eccitati di nuclei speculari con T>1. Misura della mirror energy difference

Stopped Rising Array @ GSI:
high efficiency high granularity array



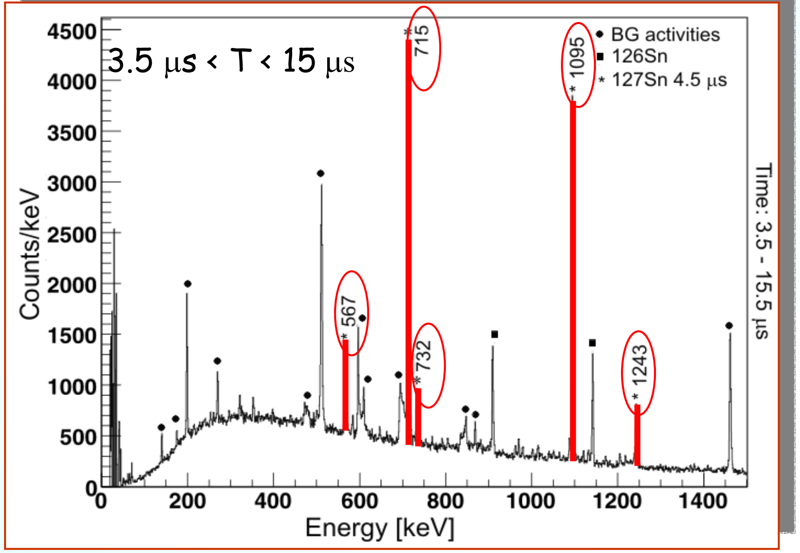
15 Euroball IV cluster
→105 crystals at 22cm

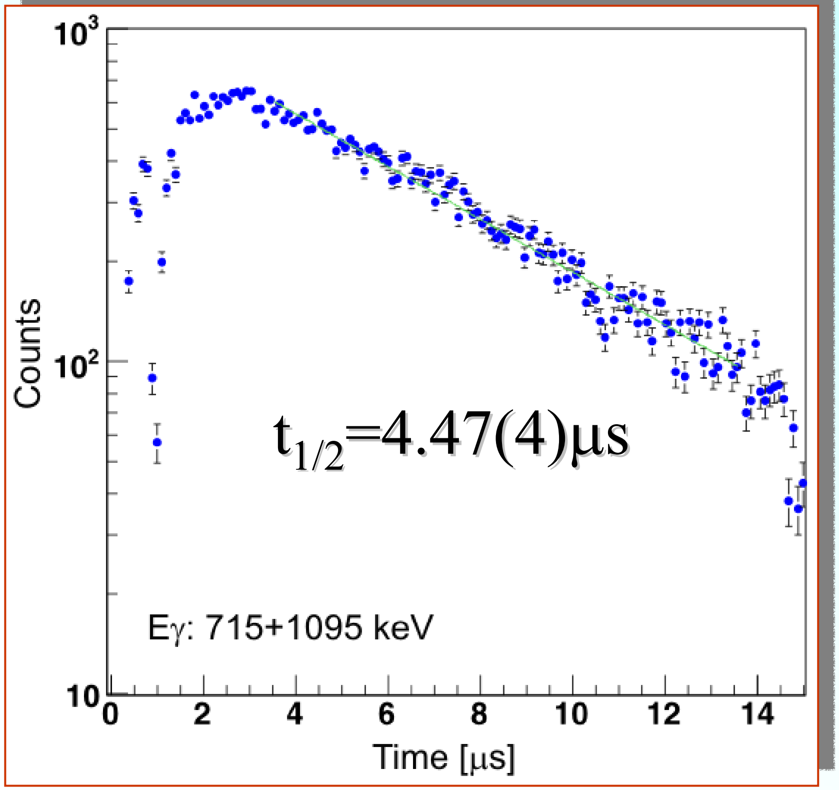
Efficency ~12% at 1.3MeV

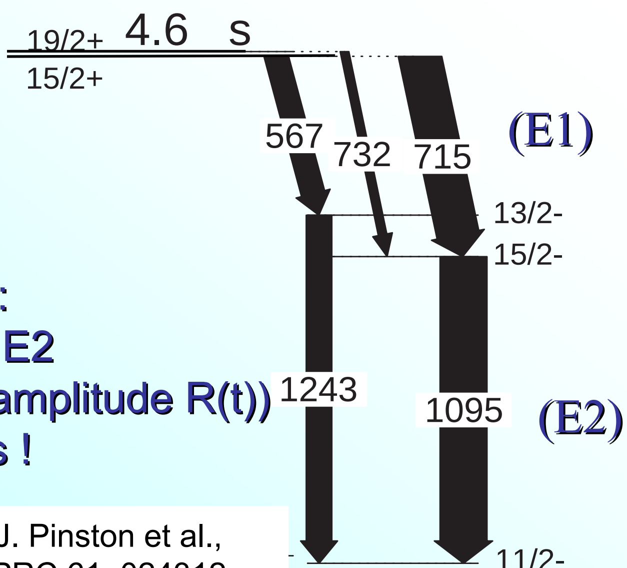
Electronic 2 branch :
Digital one (energy and time) :
XIA-DGF-4C (clock 25ns)
➔<3keV resolution (exp cond)
➔Paticle-γ correl up to 400ms

Analogue branch (time) :
TFA+CFD+TDC for shorter
isomers (0.3 ns/channel)

The case of ^{127}Sn: lifetime analysis for the 19/2$^+$ isomer







For R(t) analysis:

IF pure E1 and E2

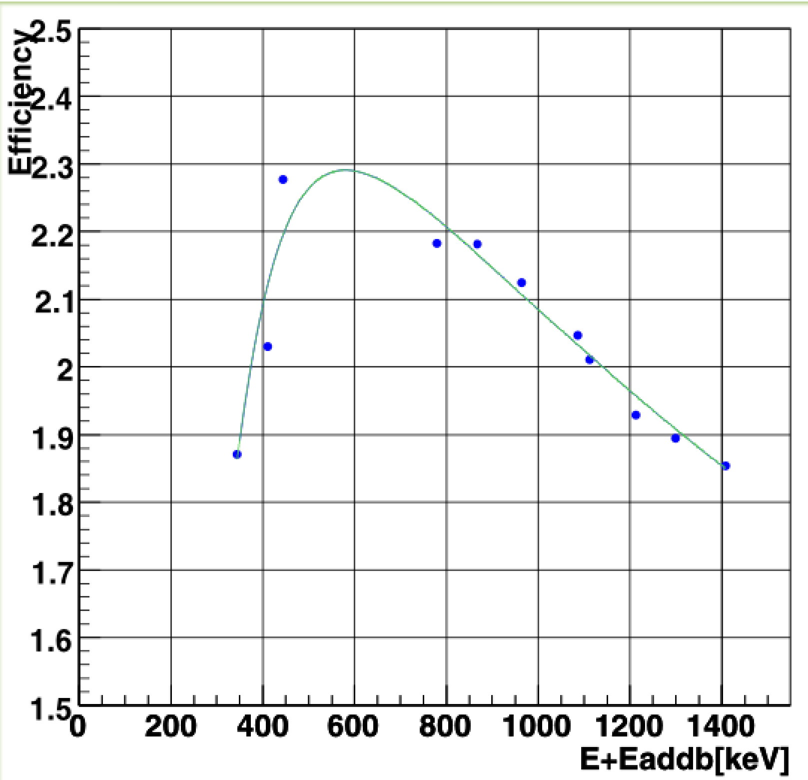
→ similar A_2 (~amplitude R(t))

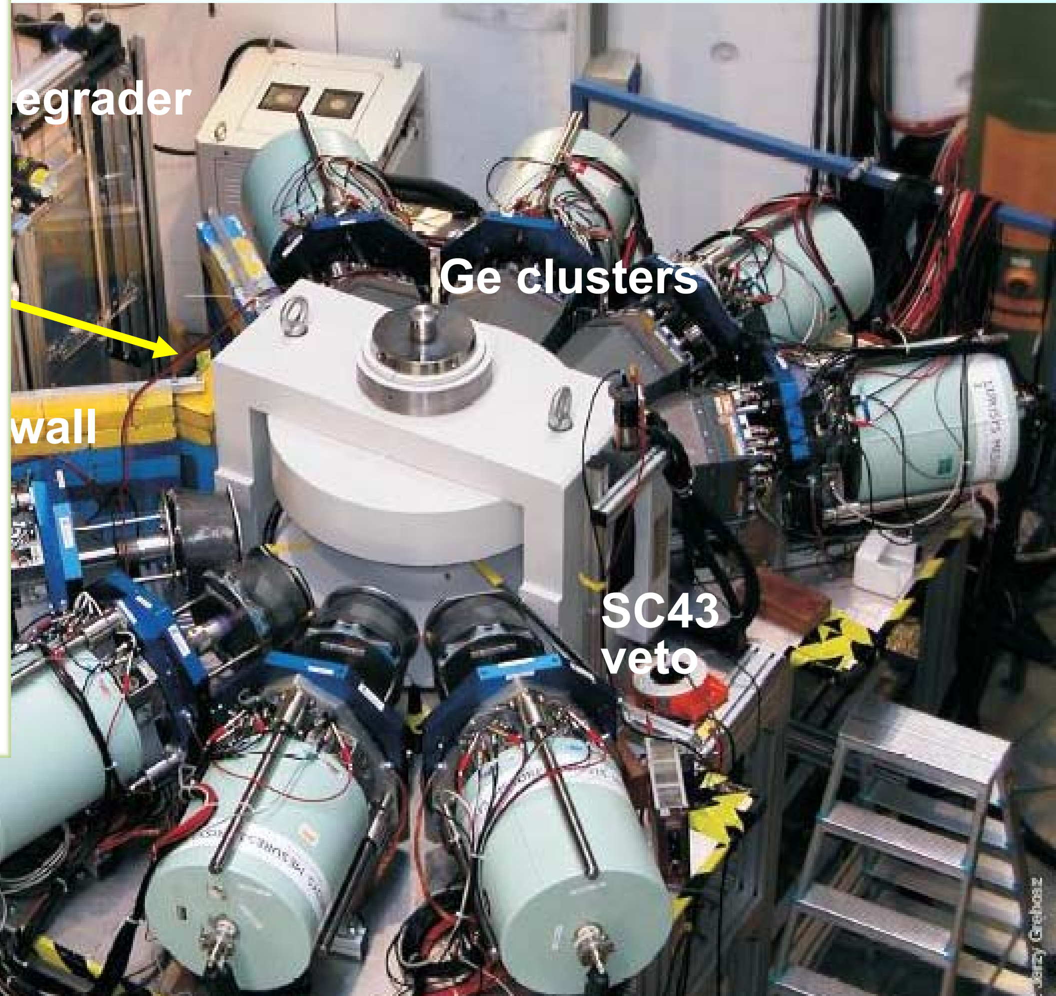
→ add statistics !

J. Pinston et al.,
PRC 61, 024312
(2000)

Total counts	Field up	Field down
715 keV A_2= -0.44 (15/2+ → 15/2-)	12790	12937
1095 keV A_2= -0.39 (15/2- → 11/2-)	12137	12613

Experimental set-up at the fragment separator FRS @ GSI





4 clusters with BGO anticompton shields and short collimators
4 clusters with the former RISING shields
Total efficiency (Eu source) = 1.9 – 2.3 %

Why measure g-factors at the FRS with RISING

(a) g-factors, magnetic dipole moment μ=g.I (in unit of μ_N)

→ information about the nuclear single particle structure:

wave function, spin, magnetic dipole operator, …

→ A probe to changes in nuclear shell structure far from stability

(b) spin-alignment - in relativistic fission of ^{238}U

- for projectile fragmentation beams with Z>30

→ never experimentally proven !

→ neutron rich nuclei become accessible for moments studies

WHY AT THE FRS ?

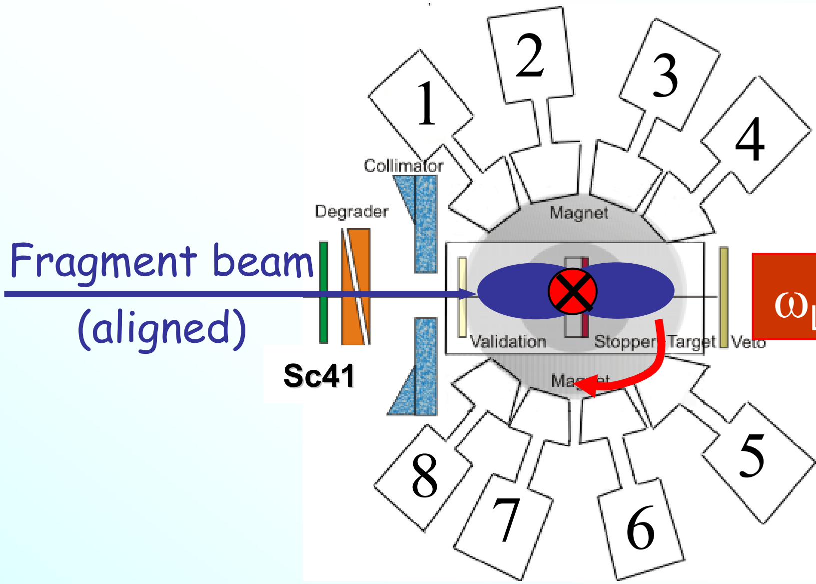
= unique facility to study g-factors and quadrupole moments of **spin-aligned isomeric beams** hardly or not accessible at other places:

- lifetime range 100 ns – 50 μs (not at ISOL facilities)
- in neutron rich nuclei with mass A>70
  (not with intermediate energy fragmentation)
  (not with fusion-evaporation)

Method: Time Differential Perturbed Angular Distribution (TDPAD)

Measure isomeric decay (τ) + Larmor precession ω_L:

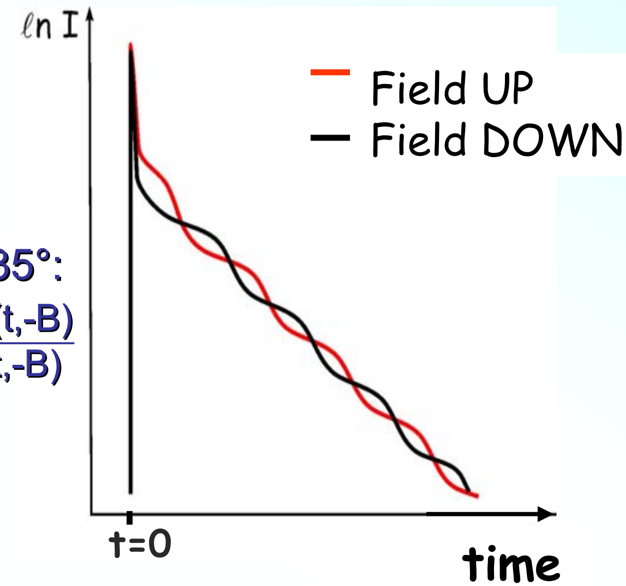
$$I(\theta,t) \sim e^{-t/\tau}\,(1 - A\,P_2[\cos(\theta-\omega_L t)])$$



$$\omega_L = -\,g\mu_N B/\hbar$$

B=0.700(7) T

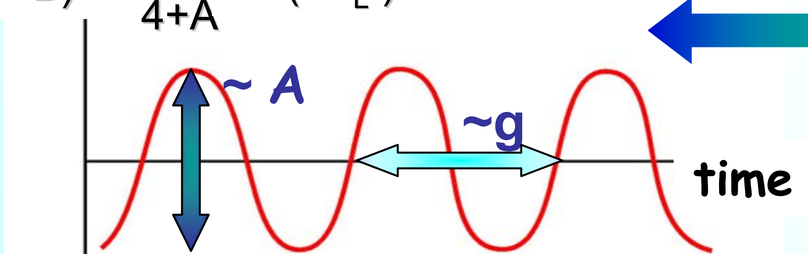
Start (t=0): ion arrives in Sc41
Stop: γ detected in 1 … 8
time range: 15 μs



detectors at ±45° and ±135°:

$$R_i(t) = \frac{I_i(t,+B) - I_i(t,-B)}{I_i(t,+B) + I_i(t,-B)}$$

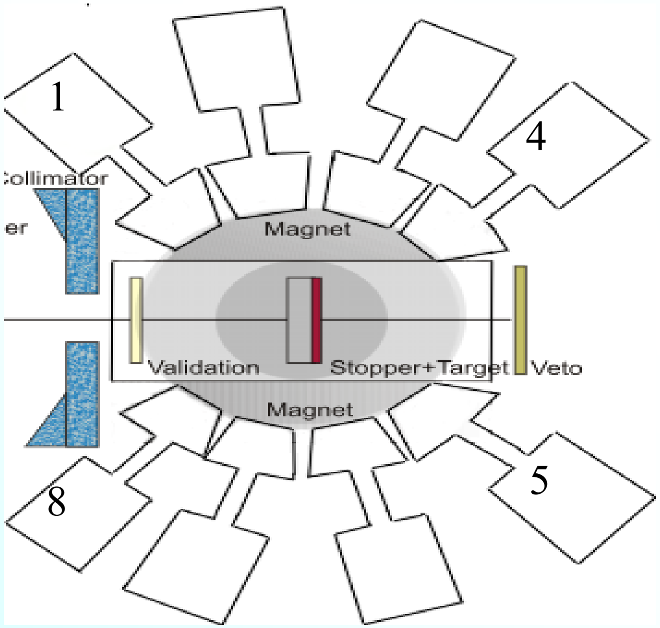
$$R(t, \pm B) = \frac{3A}{4+A}\sin(2\omega_L t)$$



Phase depends on g-factor and detector position (θ)

→ need to consider this to construct R(t) with all detectors !!!

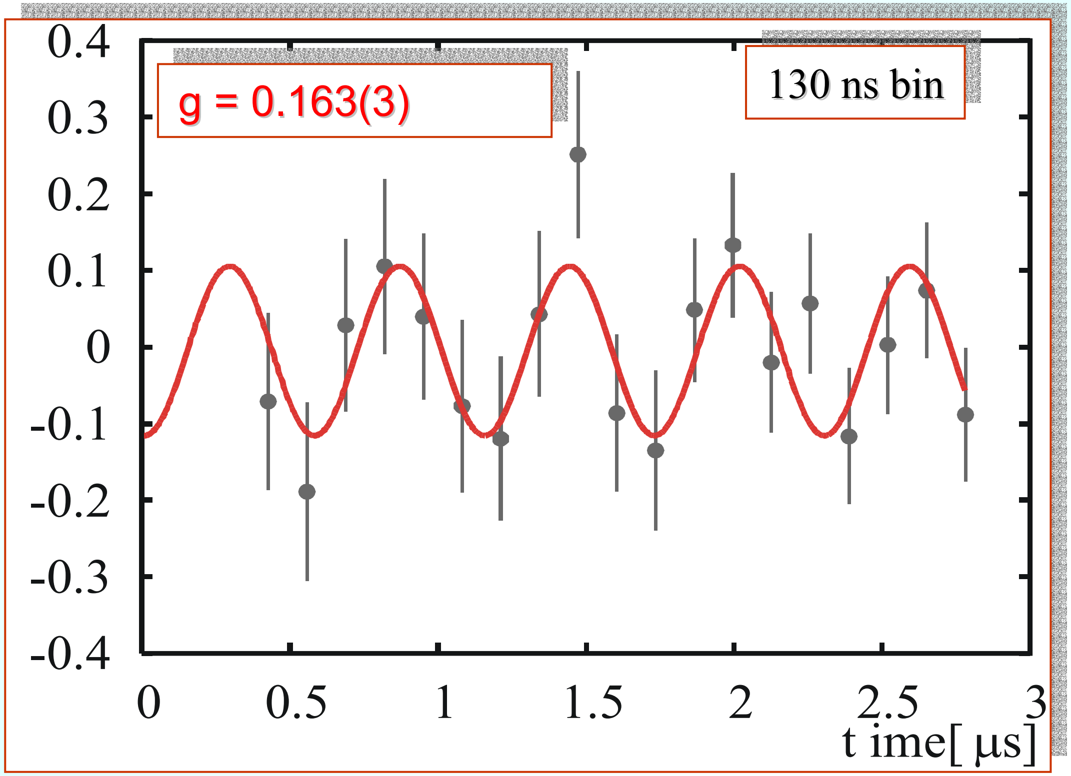
The case of ^{127}Sn: R(t) analysis for the 4.5 μs isomer



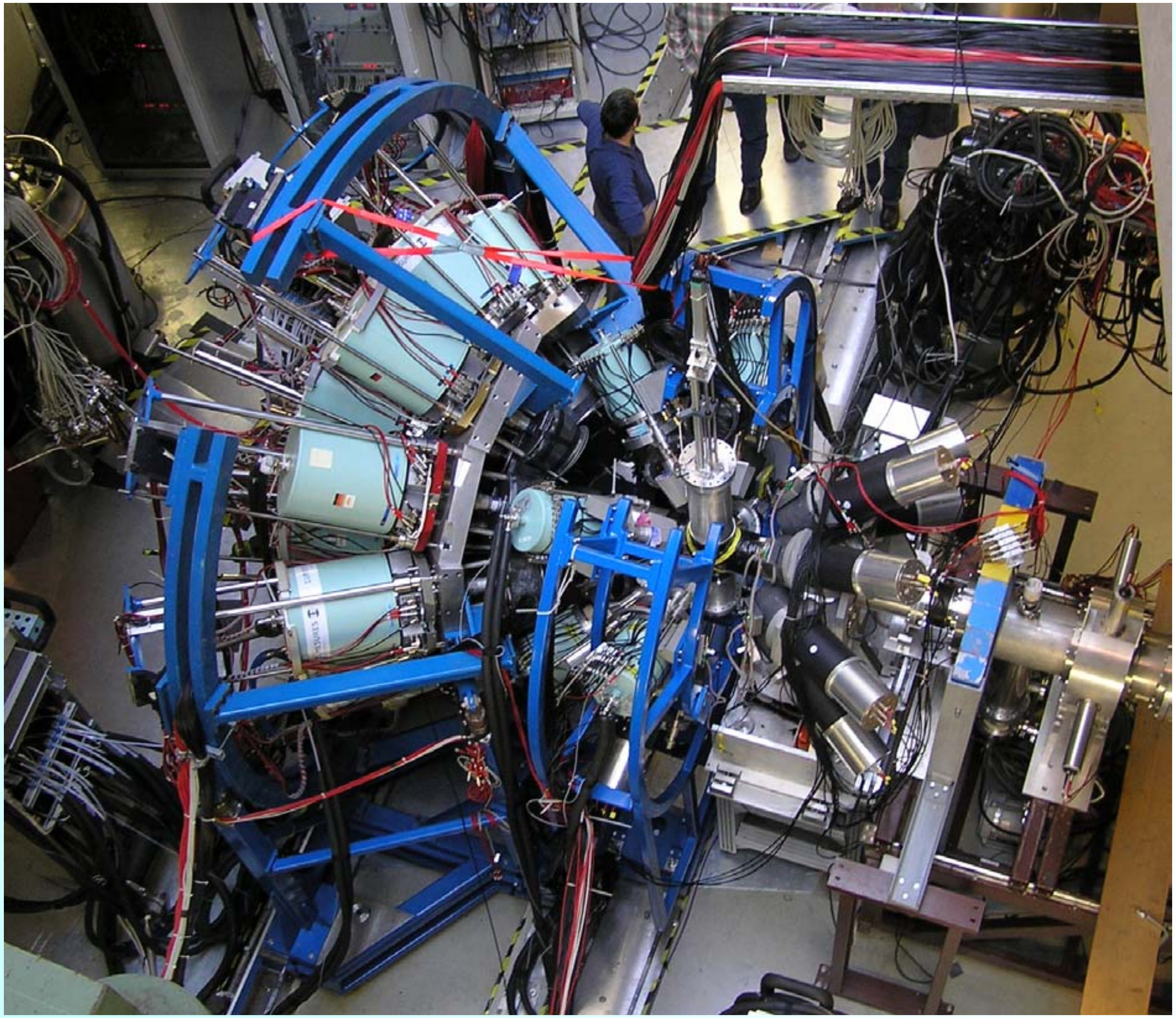
→ Apply autocorrelation analysis to fold back statistics from the full 15 μs range into 3 μs range

detectors at ±45° and ±135°:

$$R_i(t) = \frac{I_i(t,+B) - I_i(t,-B)}{I_i(t,+B) + I_i(t,-B)}$$



Gamma spectroscopy with RISING

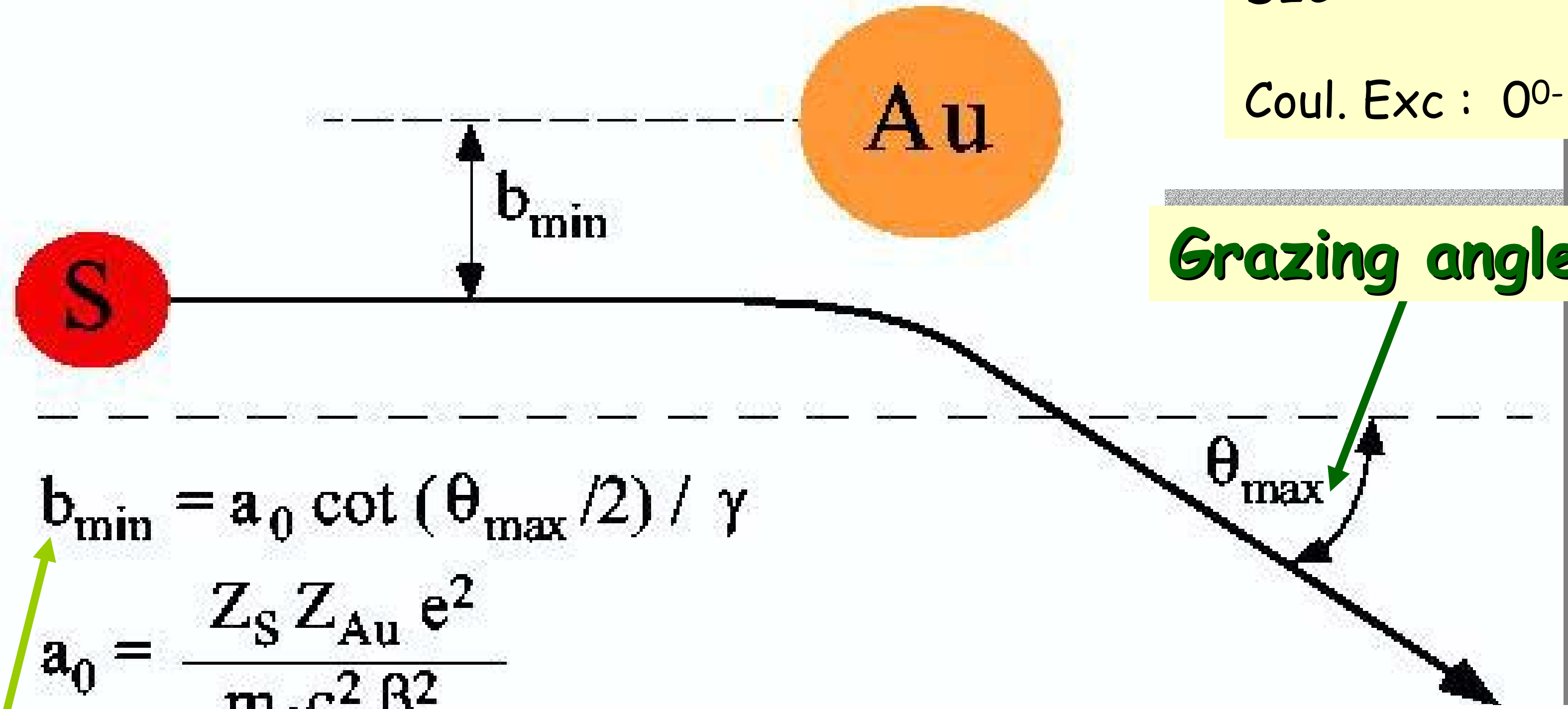


Eccitazione Coulombiana

At angles >than grazing DIC

Coul. Exc : 0^0- grazing

Grazing angle



$$b_{min} = a_0 \cot(\theta_{max}/2) / \gamma$$

$$a_0 = \frac{Z_S Z_{Au} e^2}{m_0 c^2 \beta^2}$$

$$\vartheta \simeq \frac{2Z_p Z_t e^2}{m_0 c^2 \gamma \beta^2 b} = \frac{2.88 Z_p Z_t [931.5 + T_{lab}]}{A_p [T_{lab}^2 + 1863 T_{lab}]} \frac{1}{b} \quad \text{(rad)}$$

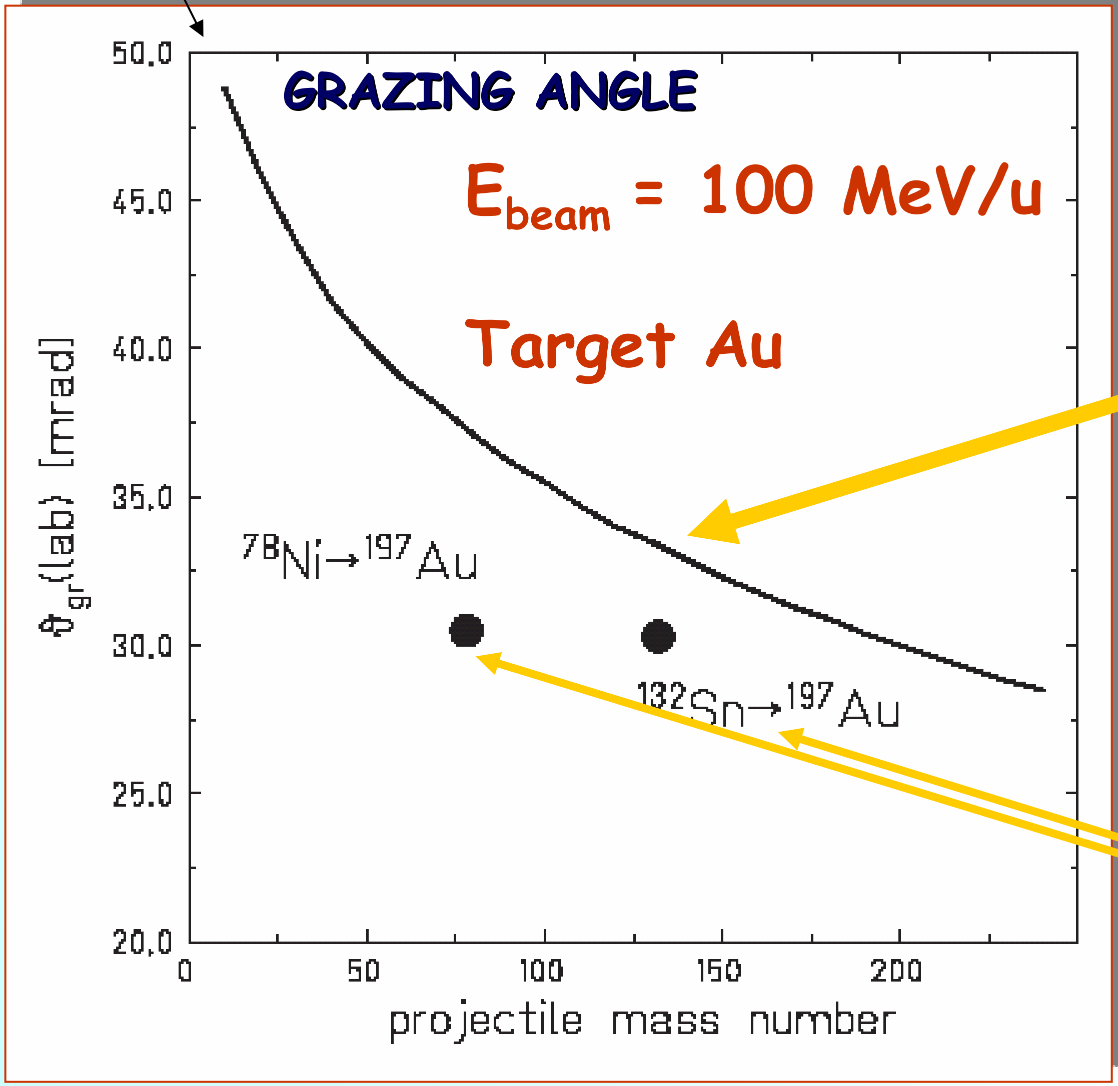
$$R_{int} = C_p + C_t + 4.49 - \frac{C_p + C_t}{6.35} \quad \text{(fm)}$$

$$C = R(1 - 1/R^2)$$

$$R = 1.28 A^{1/3} - 0.76 + 0.8 A^{-1/3}$$

Angular range for detecting reaction products in Coulomb excitation

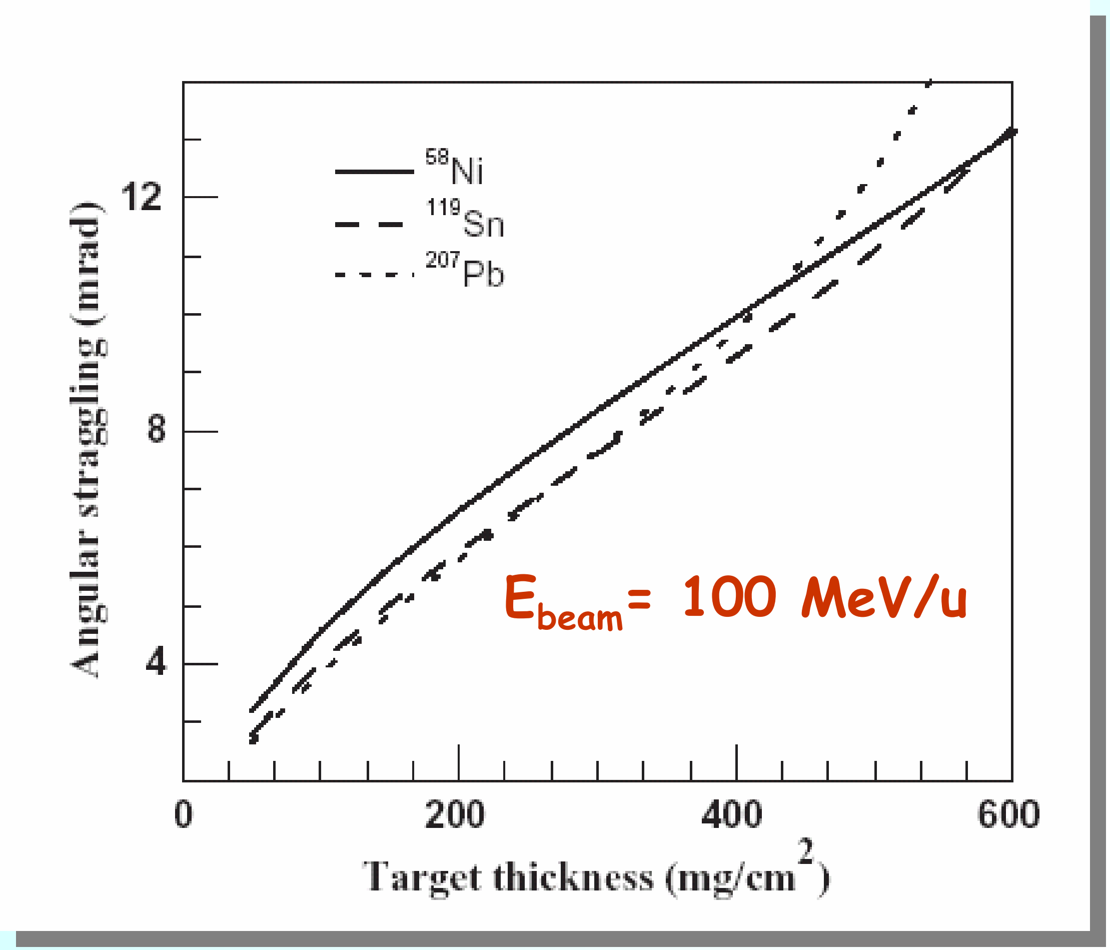
$\approx 3^0$



Nuclei on stability line

Neutron rich nuclei have larger radius

How thick can I take my target?

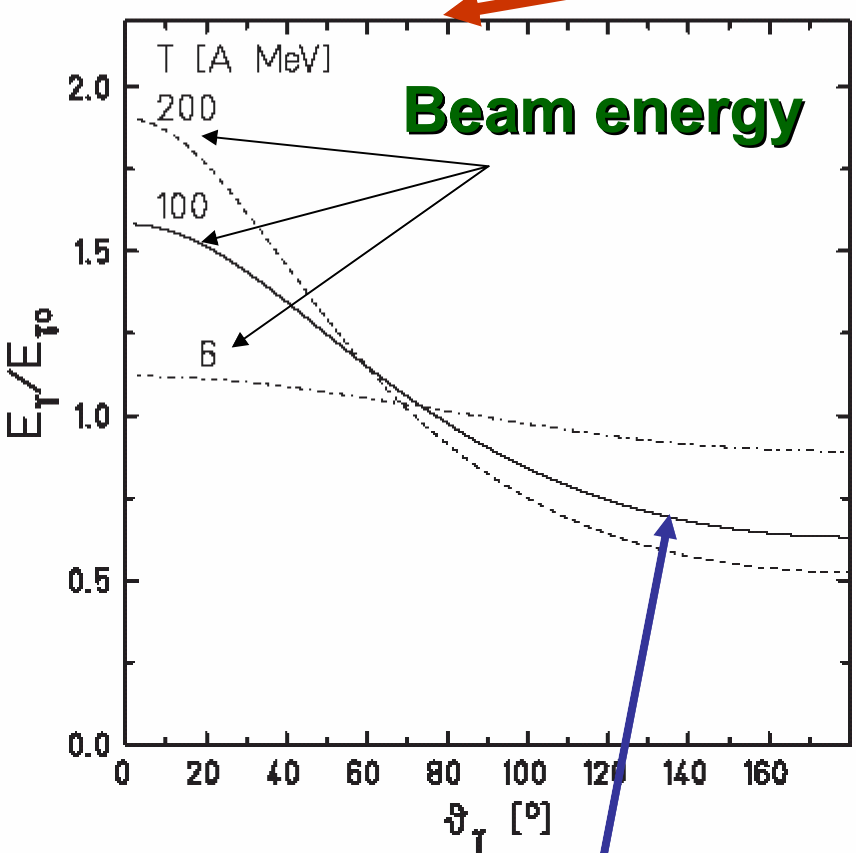


Effect of the angular Straggling of the Beam after passing through the target

Energy-loss straggling at relativistic energies is <1%
with 600 mg/cm^2 target

The angular straggling depends strongly on target thickness
which limits the impact parameter measurement for peripheral collisions

Ratio of the energy measured
in the laboratory
to the corresponding
energy in the rest frame



- Doppler shift
- (factor of 1.5 for β ~ 40%)

$$\frac{E_\gamma}{E_{\gamma 0}} = \frac{\sqrt{1-\beta^2}}{1-\beta\cos\vartheta_\gamma}$$

with

$$\beta = \frac{\sqrt{(T_{\text{lab}}/A_{\text{p}})^2 + 1863(T_{\text{lab}}/A_{\text{p}})}}{931.5 + T_{\text{lab}}/A_{\text{p}}}.$$

γ- spectroscopy at relativistic energies

Lorentz boost of γ-rays

- Gain in geometrical efficiency

  at forward angles in lab. System (factor of 2 for b ~ 40%)

$$\phi_\gamma^{\text{rest}} = \varphi_\gamma^{\text{lab}}$$

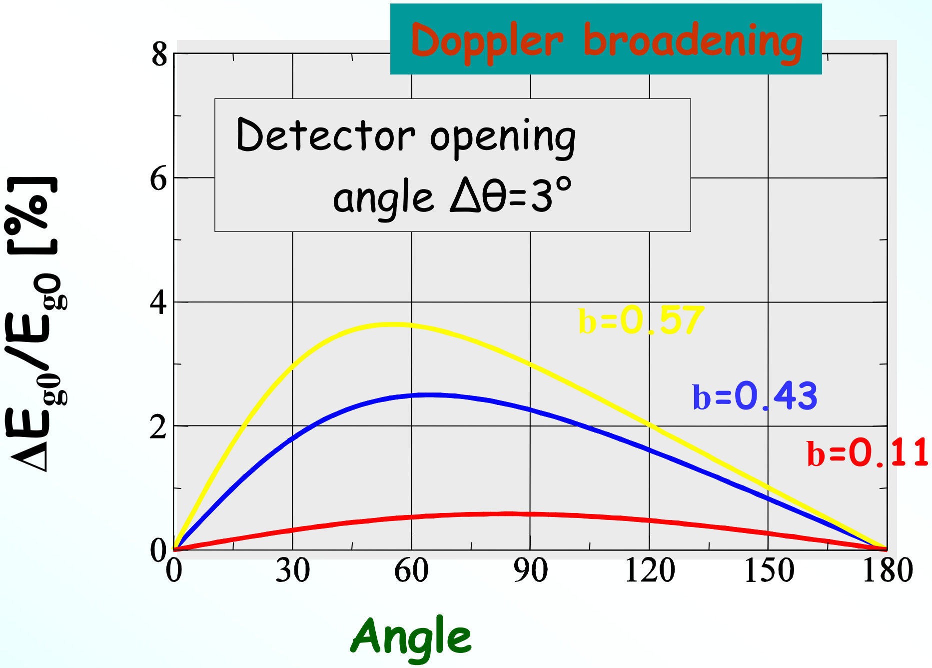
$$\cos\theta_\gamma^{\text{rest}} = \frac{\cos\vartheta_\gamma - \beta}{1 - \beta\cos\vartheta_\gamma}$$

$$\frac{d\Omega_{\text{rest}}}{d\Omega} = \left(\frac{E_\gamma}{E_{\gamma 0}}\right)^2 = \frac{1-\beta^2}{(1-\beta\cos\vartheta_\gamma)^2}.$$

Doppler broadening

$$\frac{\Delta E_{\gamma 0}}{E_{\gamma 0}} = \frac{\beta - \cos\vartheta_\gamma}{(1-\beta^2)(1-\beta\cos\vartheta_\gamma)}\Delta\beta.$$

6% due to velocity spread

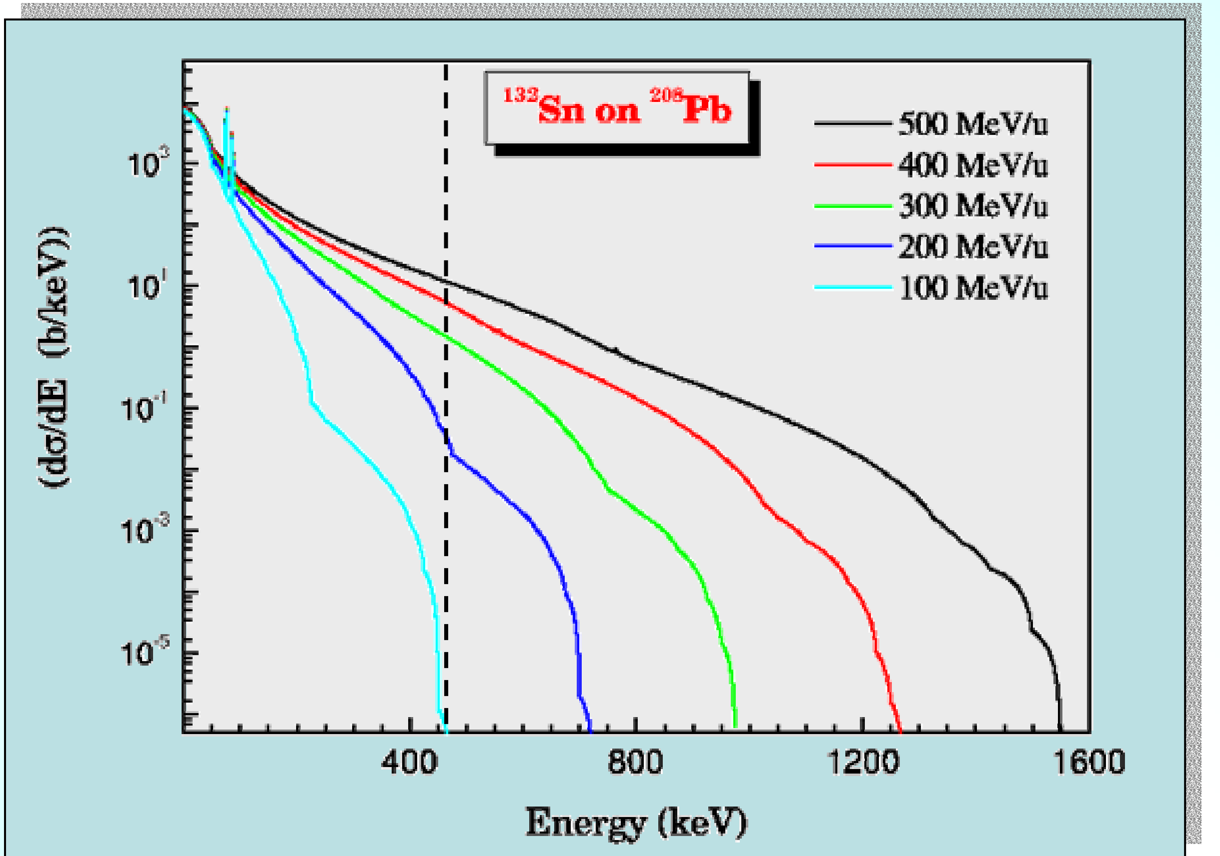


Atomic background,

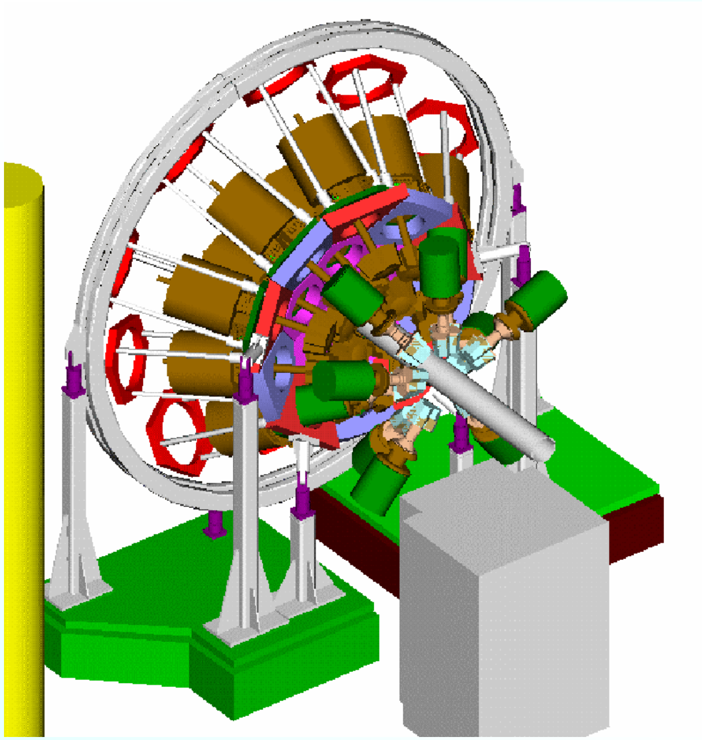
a limiting factor

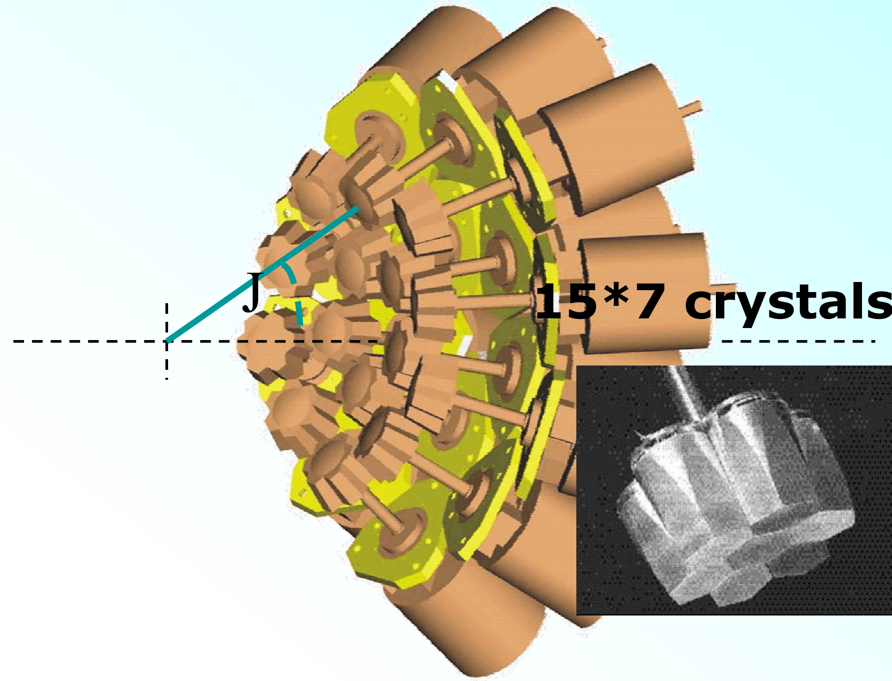
- X-rays from target atoms
- Radiative electron capture
- Primary Bremsstrahlung
- Secondary Bremsstrahlung
- s (atomic) ~ 10000 * s (nuclear)

- There is also a dependence on the target material



RISING Ge-array





15 EUROBALL cluster detectors
Clusters at forward angle

- Large Lorentz boost (b~0.4 up to 0.8)
- Optimum Doppler shift correction
- Minimizing Doppler broadening
  - Ring1 at 15.9° 70 cm
  - Ring2 at 33.0° 70 - 140 cm

Design (100MeV/u, 1.3MeV γ-ray)

energy resolution (FWHM):
Total efficiency: 2.88%
No anti-Compton
suppression shields

NIM A 537 (2005) 637

RISING ARRAY

Euroball 15 Clusters

Located at 16.5°, 33°, 36° degrees
Energetic threshold ~ 100 keV

Hector BaF_2

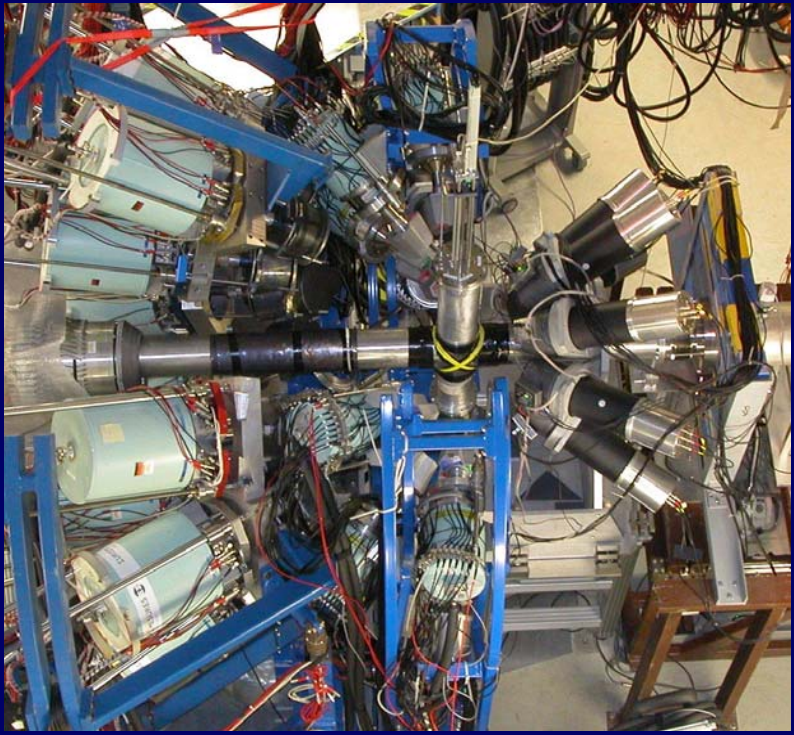
Located at 142° and 90° degrees
Energetic threshold ~ 1.5 MeV

Miniball segmented detectors

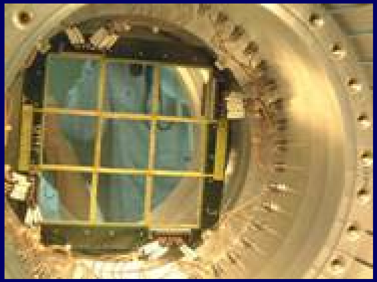
Located at 46°, 60°, 80°, 90° degrees
Energetic threshold ~ 100 keV

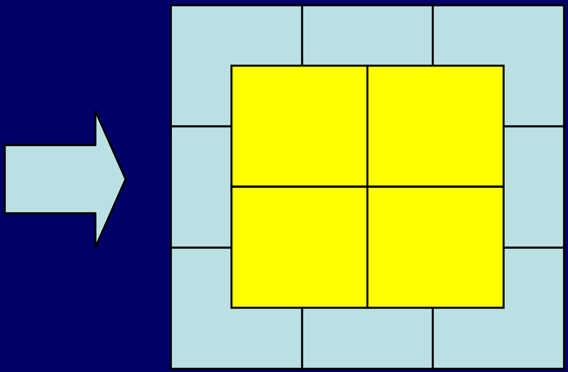
Beam identification and tracking detectors

Before and after the target



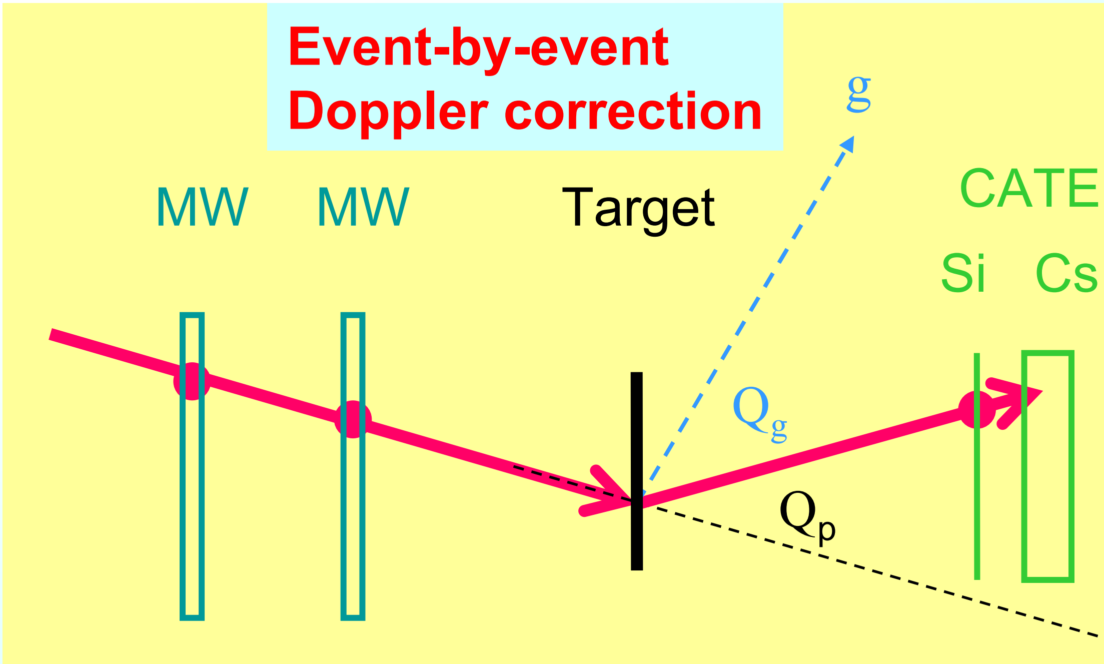
Calorimeter
Telescope
for beam identification
(CATE)





4 CsI
9 Si

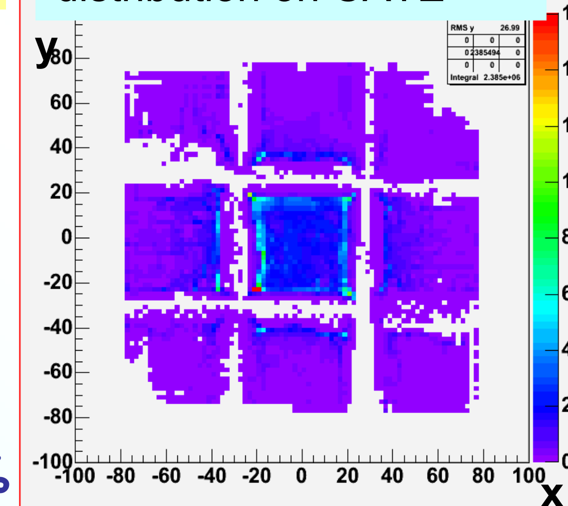
Tracking of outgoing particles



MW
pos. res. ~ 1 mm

CATE-Si
pos. res. ~ 5 mm
opening angle ± 3°

Outgoing particle distribution on CATE

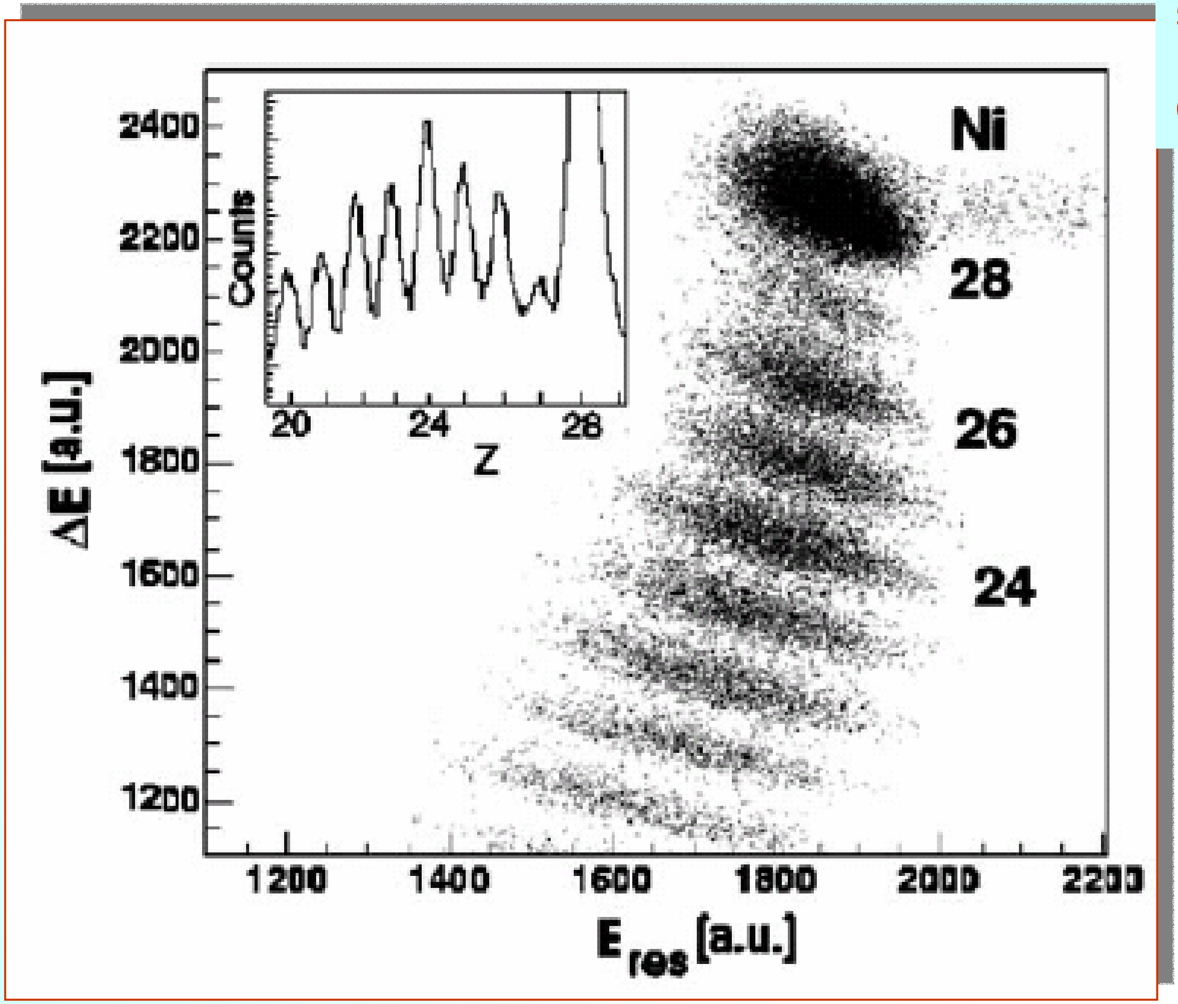


Calorimeter Telescope

It covers 58 mrad
1426 mm from the taget   mounted in vacuum
9 Si detectors each 50x50 mm^2
Si detectors are position sensitive

Cs(I) detectors have an energy resolution of 0.5%

^{55}Ni on ^{9}Be target at 100 MeV/u

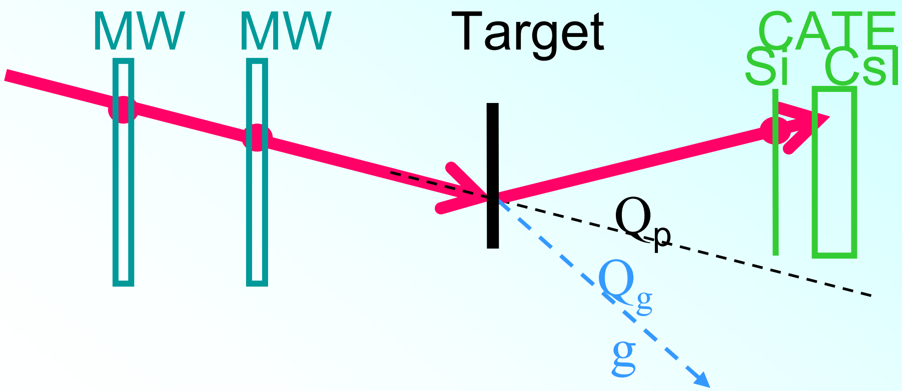


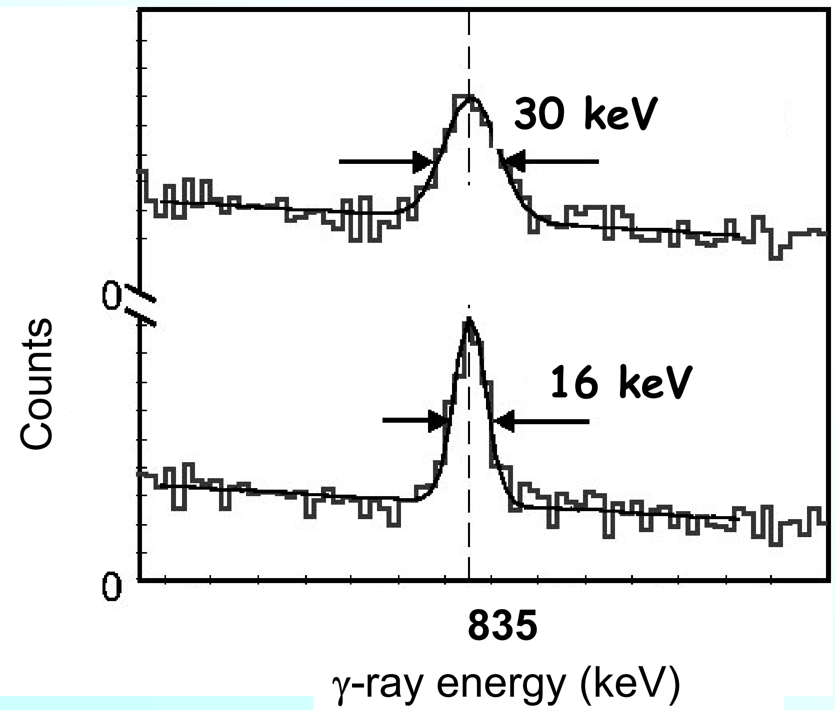
Z resolution of the calorimeter CATE is ΔZ= 0.7 (FWHM)

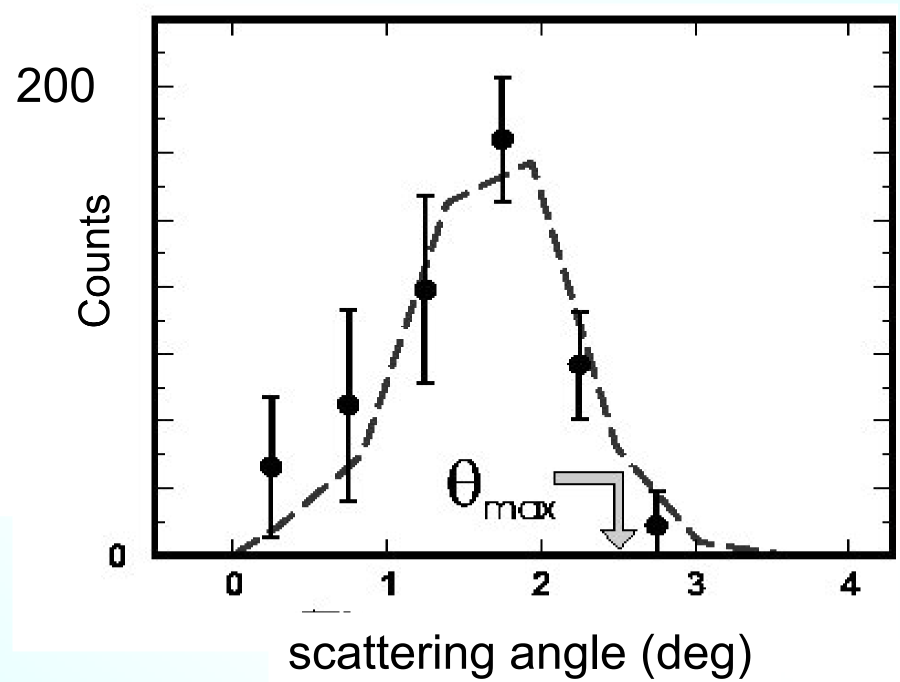
- velocity v/c from TOF (event-by-event)
- tracking Cr ions: g-ray emission angle

γ-ray energy resolution

scattering angle







Coulomb excitation of the primary beam - ^{84}Kr

Fragment identification:

before the target (FRS detectors)

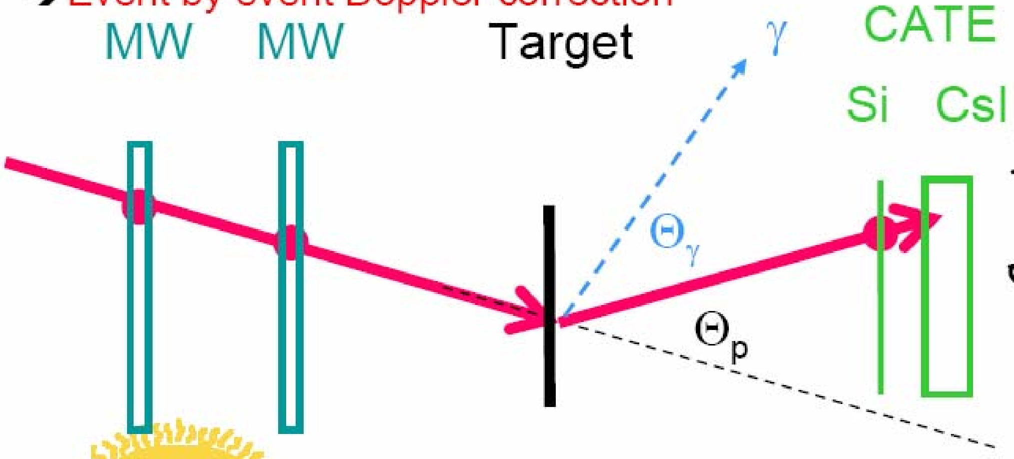
after the target (CAlorimeter TElescope)

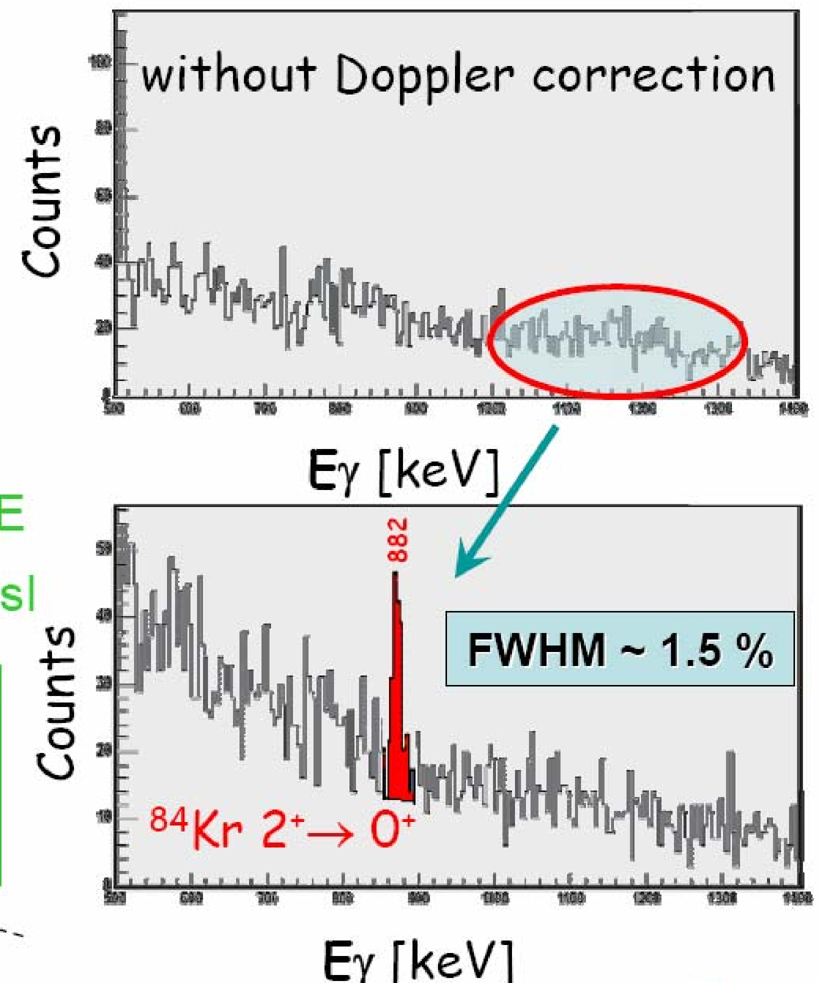
Tracking of the particles:

before the target (MW)

after the target (Si detector)

→ Event by event Doppler correction





RISING

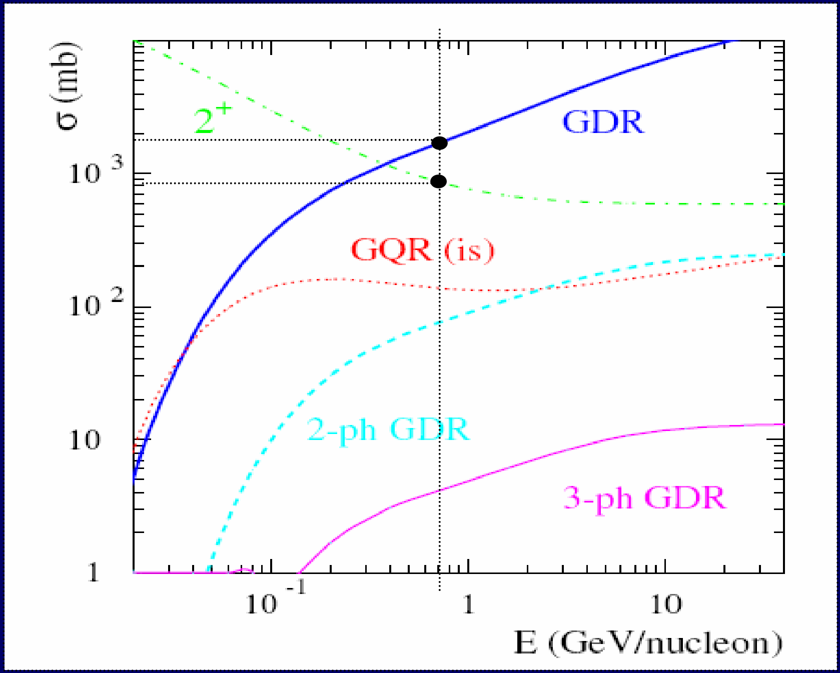
Virtual photon scattering technique first experiment with a relativistic beam

GDR - PYGMY Excitation

600 MeV/u $^{68}Ni + ^{197}Au$ (April 2005)

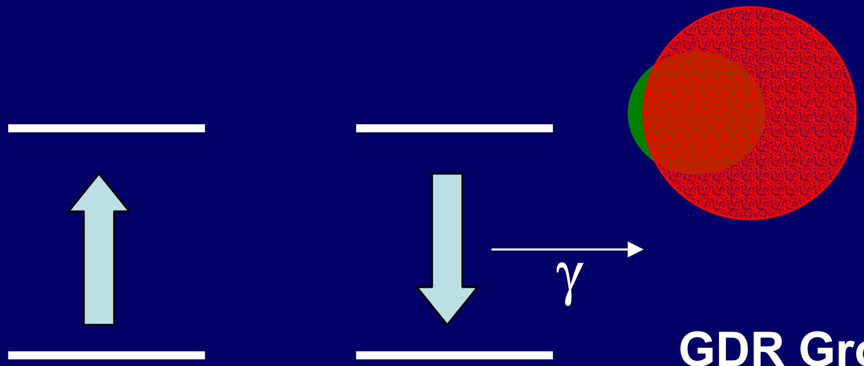
- High selectivity for dipole excitation

$$\frac{\sigma(GDR)}{\sigma(2+)+\sigma(GQR)} \approx 3$$



T.Aumann et al EPJ 26(2005)441

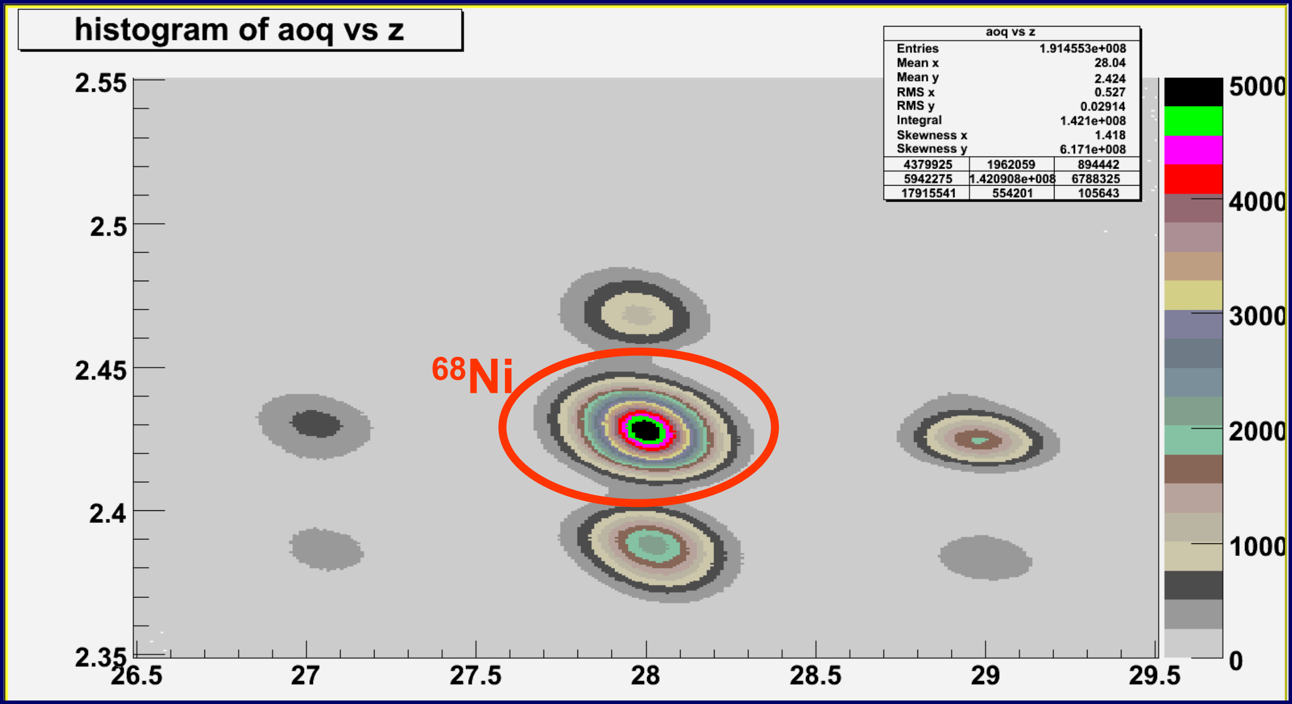
GDR - PYGMY Decay



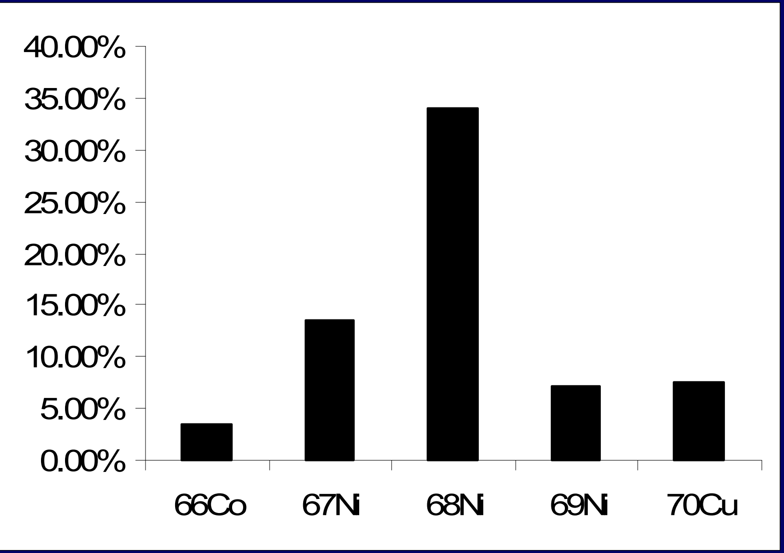
GDR Ground state decay branching ratio ~ 2% measured on ^{208}Pb

J.Beene et al PRC 41(1990)920

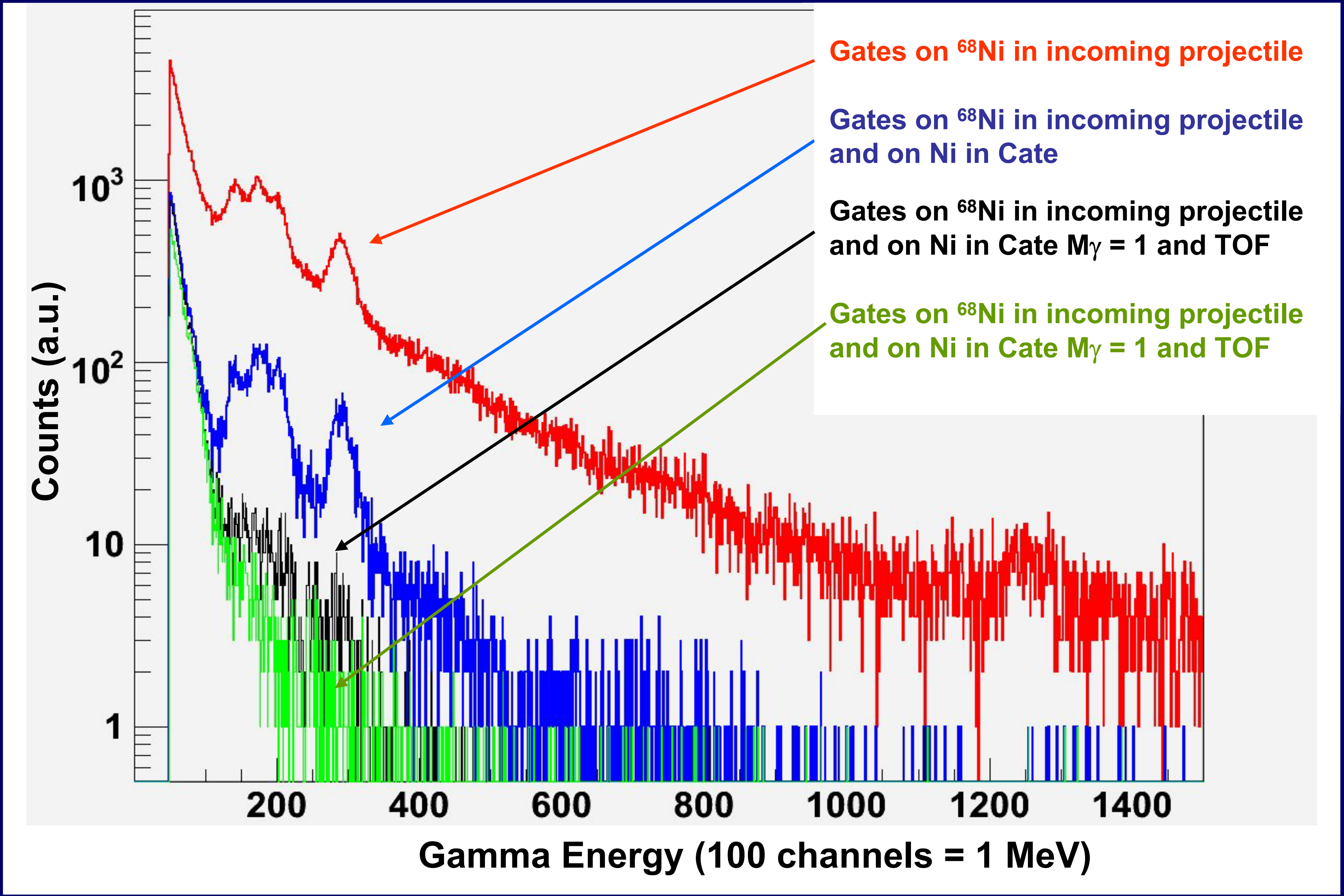
Incident Beam



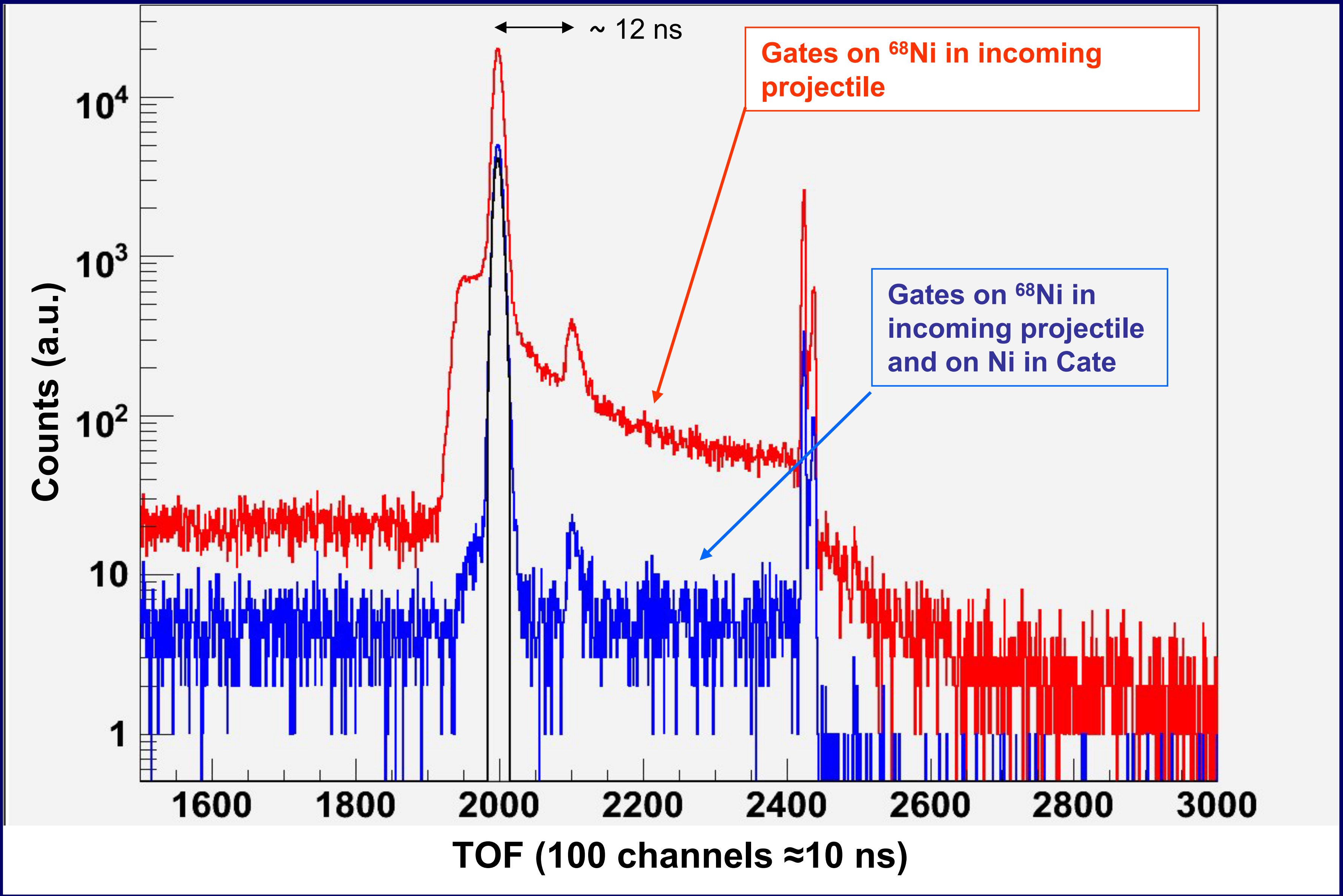
- ~ 6 Days of effective beam time
- ~ 400 GB of data recorded
- ~ 3 10^8 Events recorded
- ~ 1 10^8 ^{68}Ni recorded
- ~ 3 10^7 ‘ good ^{68}Ni events ‘ recorded



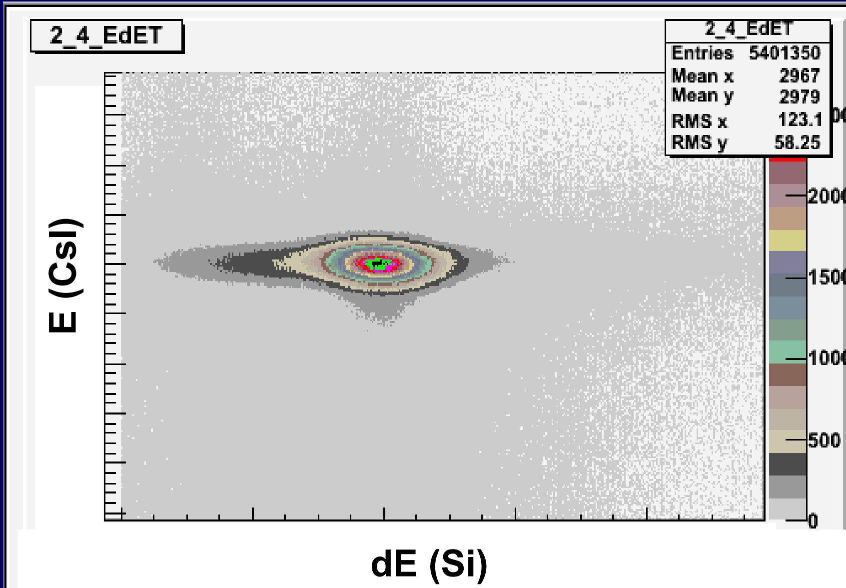
BaF_2 Energy Spectra

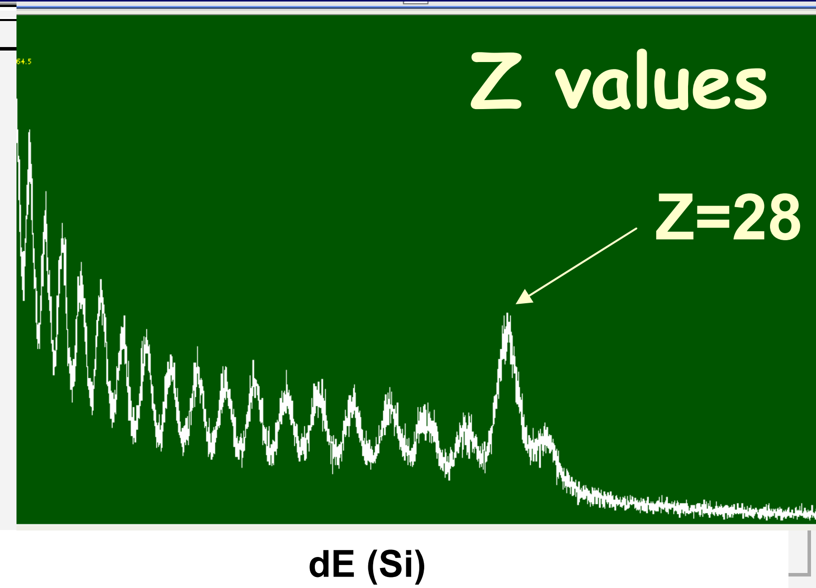


BaF_2 Time of Flight Spectra



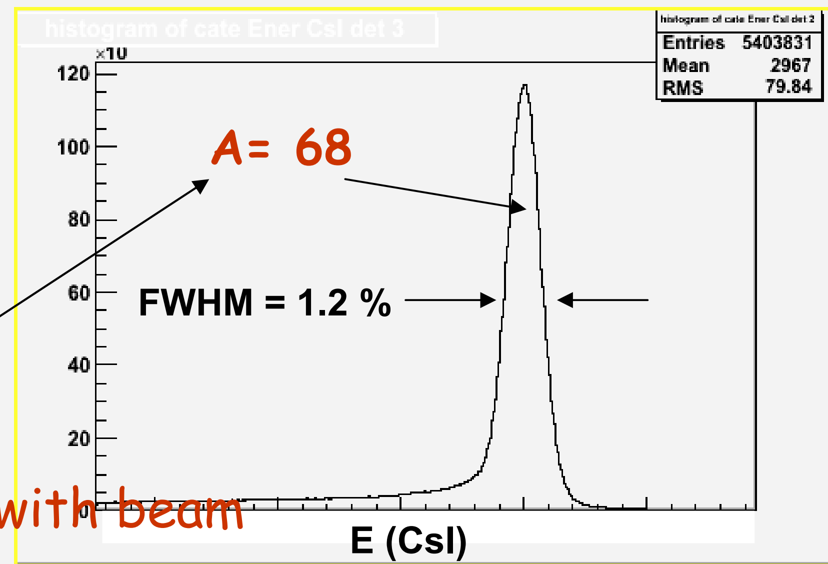
Beam Identification after the target





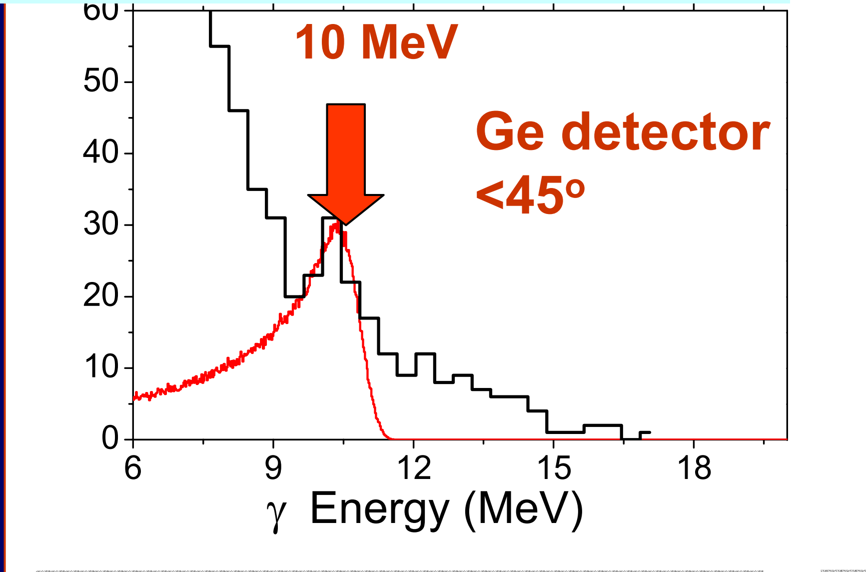
CATE spectra have been corrected

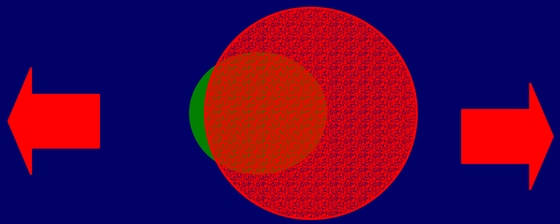
- **Drifts in energy with Time.**
- **Interaction positions.**
- **Beam velocity profile.**



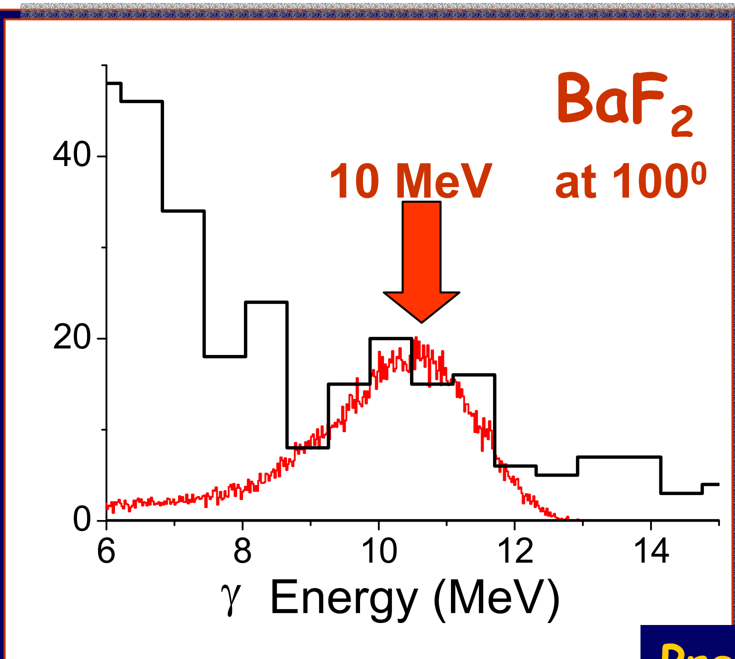
From Calibration with beam

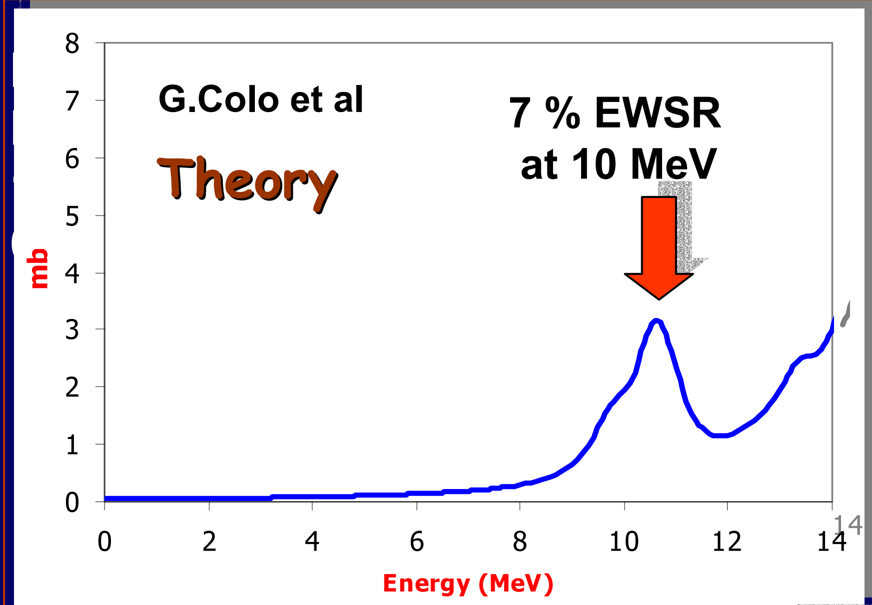
^{68}Ni beam at 600 MeV/u





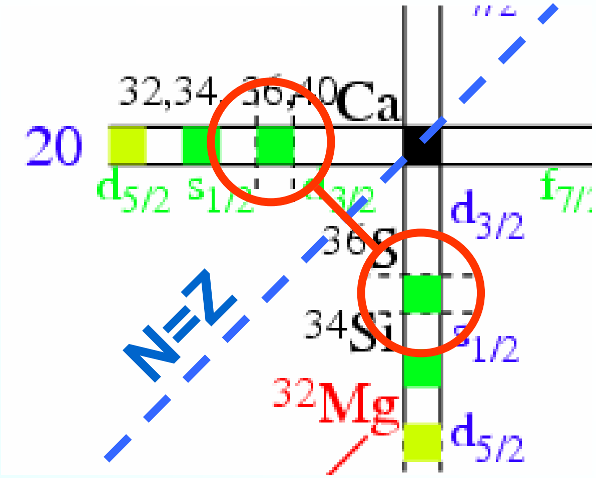
Pygmy Resonance
Collective oscillation of neutron skin against the core:
First measurement !

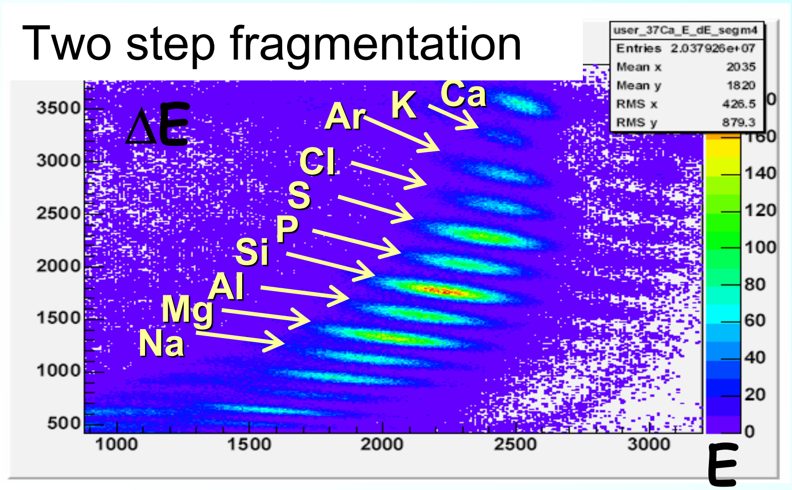


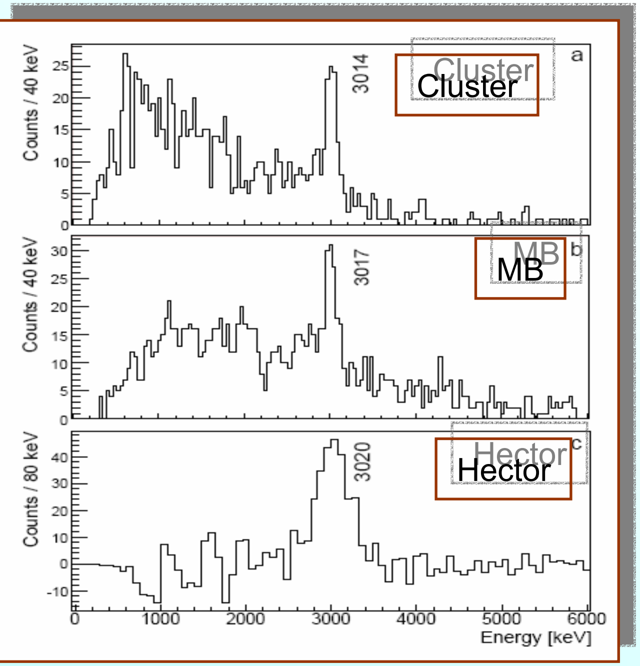


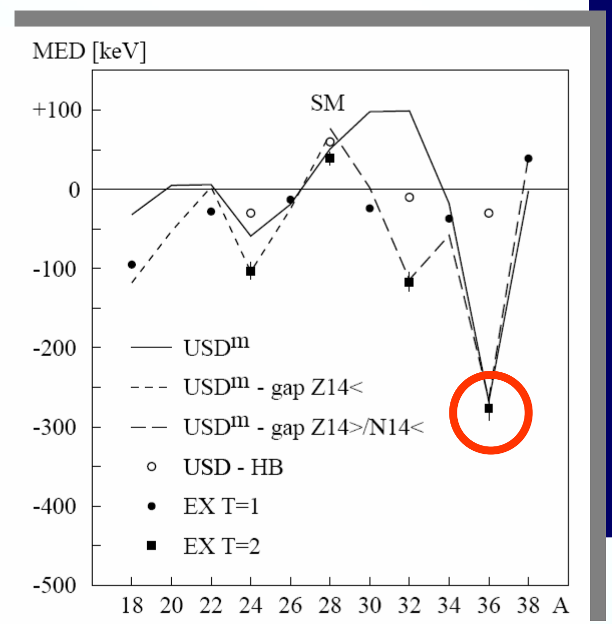
Preliminary results. Other data under analysis- First measurement

Multiframmentazione del ^{37}Ca $\Rightarrow$ T = 2 mirrors ^{36}Ca and ^{36}S:





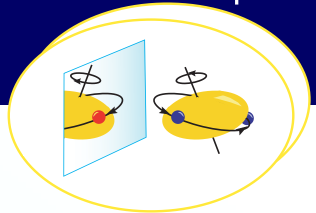




$\Delta E_M = E(^{36}Ca) - E(^{36}S) = -276$ keV
The second highest measured

The monopole part of the two body interaction drives the shell structure scenario

Probably an "island of inversion" similar as in the A=20 cases is developed in N < 16 Ca isotopes



First excited state in ^{36}Ca seen for the first time

L'eccitazione Coulombiana e' uno strumento molto efficace per studiare la risposta elastica del sistema attraverso l'eccitazione delle risonanze giganti che sono ad alta frequenza

Cercare la risposta dipolare in nuclei esotici e' importante per studiare le caratteristiche del campo medio e della pelle di neutroni in nuclei vicino alla neutron drip line.
Interesse astrofisico perche' conoscere la E1 strength permette di valutare la competizione tra cattura neutronica e decadimento gamma nel processo r

Ma se voglio eccitare stati con configurazioni piu' complesse soprattutto ad alto spin mi servono altre reazioni che producono Molte righe negli spettri e quindi devo avere una risoluzione migliore

Le risoluzioni richieste (pochi KeV) nel caso di fasci relativistici si si hanno solo se si studia la spettroscopia dei fasci fermati e (decadimenti da stati isomerici)

Fasci RIB < 20 MeV/u e segmentazione nei rivelatori al Ge

FASCI radioattivi a Bassa energia : Perche' servono?

- Reazioni attorno alla barriera (trasferimento, deep-inelastic, fusione) per popolare gli stati eccitati dei nuclei esotici e studiare la loro struttura

- La velocita' del nucleo emettitore ha $\beta<0.2$ e quindi la spettroscopia γ e' piu' facile che con i fasci di Frammentazione on- flight

- **Caratterizzare le eccitazioni dei nuclei con misure ad alta risoluzione:**

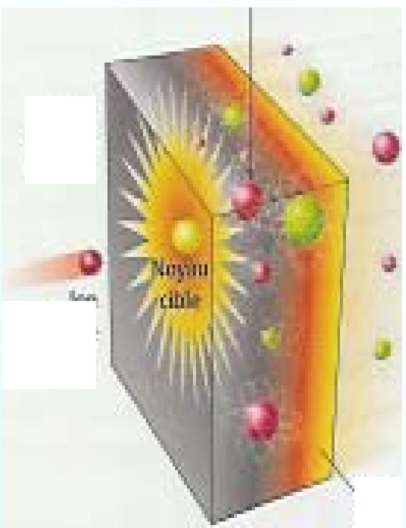
Spettroscopia gamma

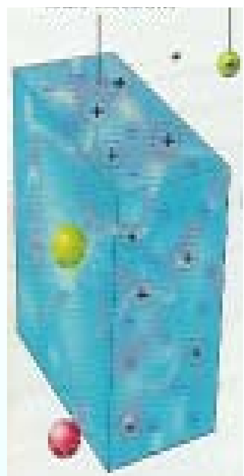
usare rivelatori piu' segmentati ed efficienti per identificare il punto d'interazione per la correzione Doppler (Progetto AGATA)

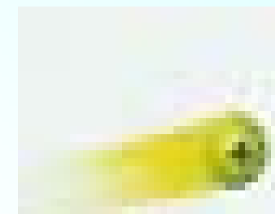
ISOL TECHNIQUE

Ion projectiles stopped
in a thick target
target heated and
the fragments
diffuse

Separation
of the fragments







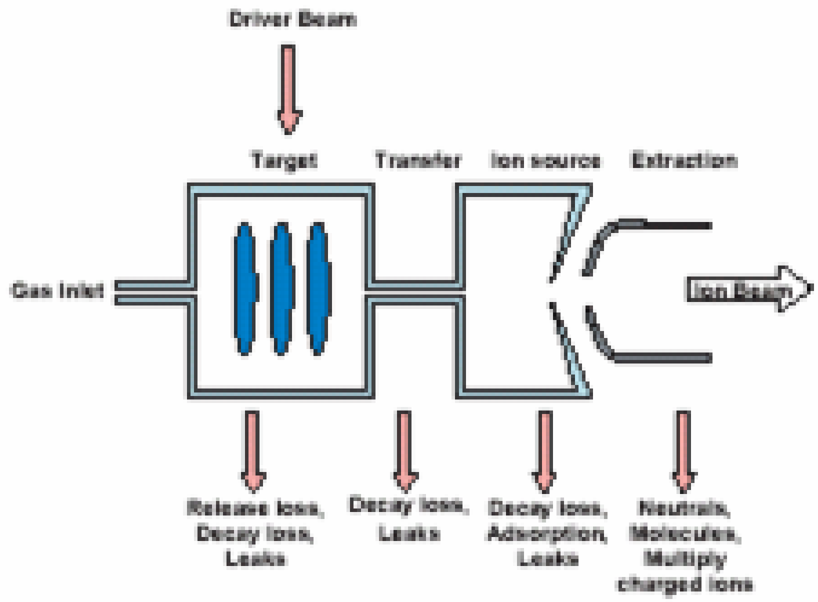
Post acceleration of the fragments

Ionization of the fragments
Charge breeder

Existing facilities
Oak-Ridge
Triumf
Rex-Isolde
SPIRAL
Excyt

Good beam quality (pure beam and well focussed) – ideal for beams up to 50 MeV/u

Limitation to nuclei with lifetimes larger than 1 ms



Metodo ISOL

sviluppato al Niels Bohr Institute negli anni 50

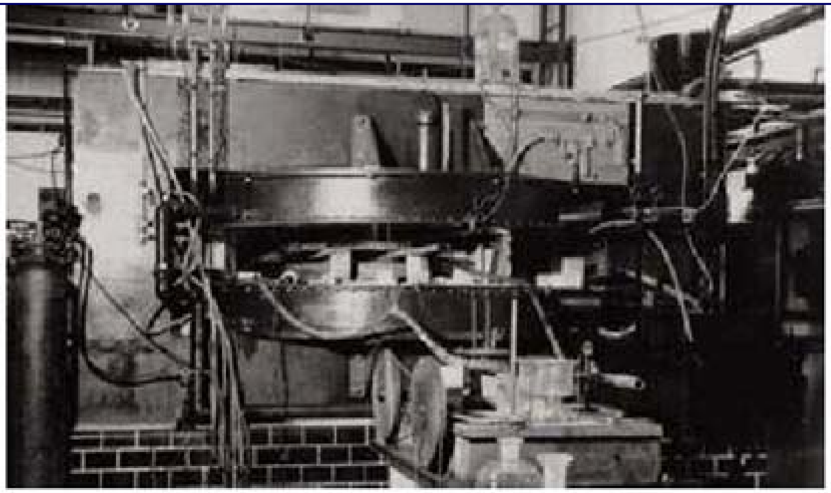
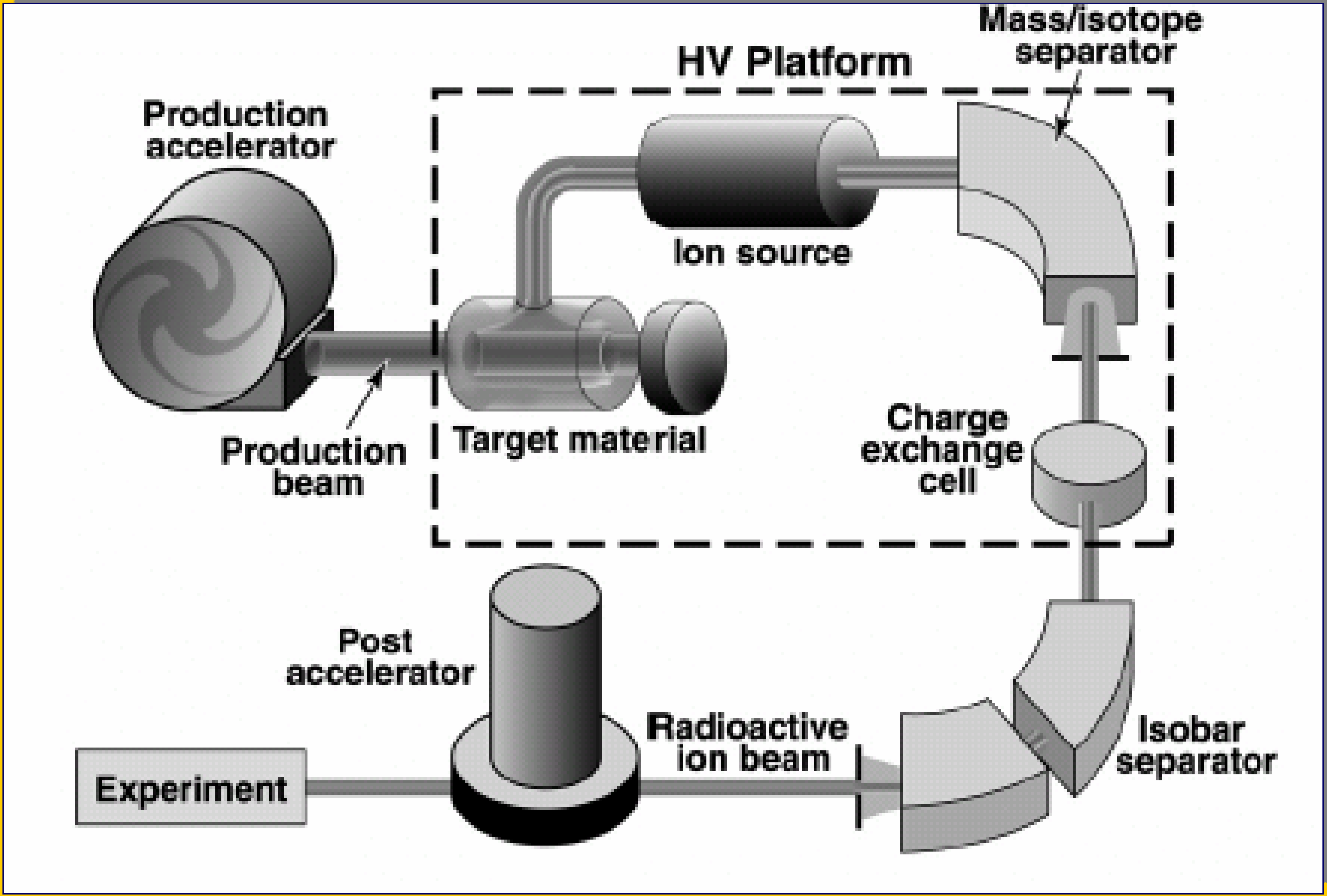


Figure 1: The Niels Bohr Institute cyclotron.

Produzione di ioni di Kr per studiare il decadimento beta

They were investigating beta-decay and neutrino emission from neutron-rich krypton isotopes, produced in uranium fission. Using a variant of the "converter" method – now enjoying renewed interest for the next generation of RIB facilities – they used deuterons from their cyclotron on an internal target to produce neutrons. These then struck a uranium oxide target (mixed with baking powder) from which gas flowed. The gas was then ionised, extracted from a high-voltage platform and passed through a mass-separator, which selected the krypton ions of interest.


Mass/isotope separator
HV Platform
Production accelerator
Ion source
Production beam
Target material
Charge exchange cell
Post accelerator
Radioactive ion beam
Isobar separator
Experiment

Intensità particelle prodotte

$$I = \sigma \times \Phi \times N \times \varepsilon_1 \times \varepsilon_2 \times \varepsilon_3 \times \varepsilon_4 \times \varepsilon_5$$

I = Intensità particelle prodotte

σ: cross-section,
Φ: primary-beam intensity,
N: target thickness,
ε_1: product release and transfer efficiency,
ε_2: ion-source efficiency,
ε_3: efficiency due to radioactive decay losses,
ε_4: efficiency of the spectrometer,
ε_5: post-accelerator efficiency.

$\Phi \times N$ = Luminosity

Metodo ISOL

Isotopes Separation On Line

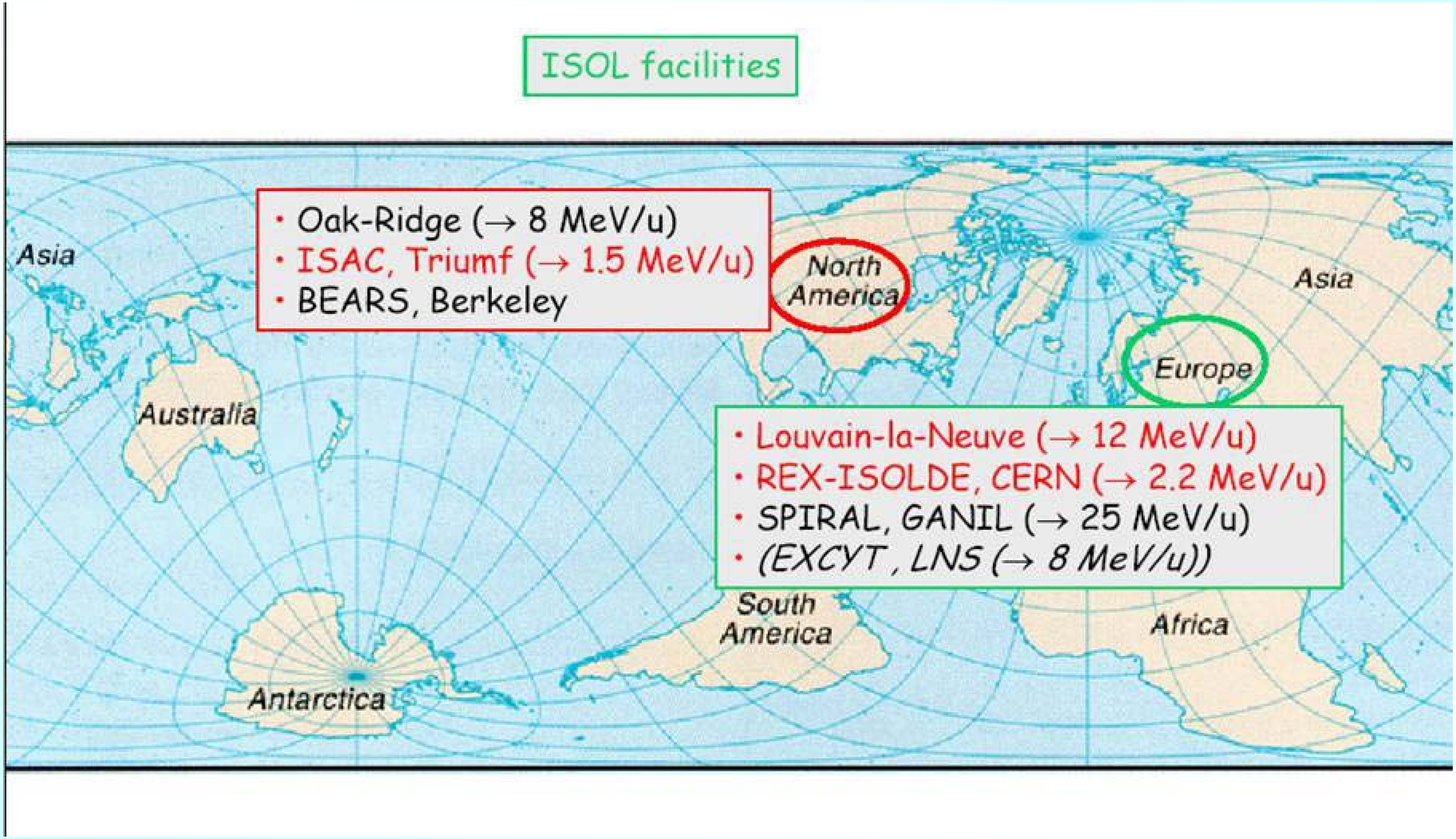
- Driver ad alta intensità (Dissipazione Calore)
- Targhette di produzione (Raffreddamento e Radioattività)
- Efficienza Selezione(20%)
- Efficienza di estrazione (30%)
- Efficienza di Trasmissione alla Sorgente(30%)

Potenza in gioco

Potenza (W)= I V = I (Energy/Charge state)

Es: I=1mA E=50 A MeV di O^{16} completamente strippato (O^{8+}) :
P = 1 10^{-3} (50 16/8) 10^{6} =100 kW

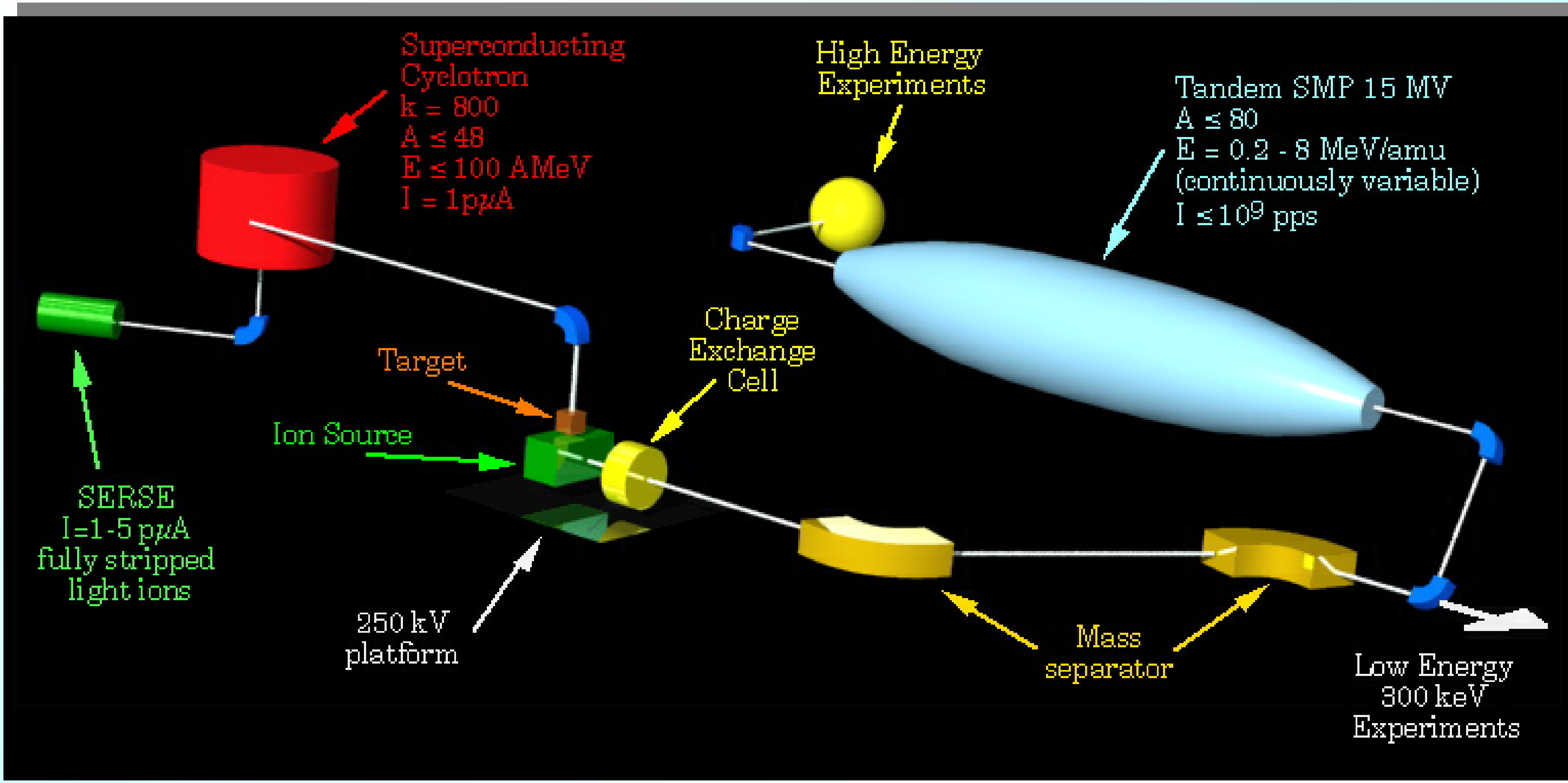
Facilities of the first generation



Potenze del fascio del driver primario di pochi kW

Location	Year	Driver	Post Accelerator
CRC, Louvain-la-Neuve, Belgium	1989	Cyclotron p, 30 MeV, 200μA	cyclotrons K = 44 and 110
SPIRAL, GANIL, Caen, France	2001	2 cyclotrons heavy ions up to 95 MeV/u 6 kW	cyclotron K = 265 2 - 25 MeV/u
REX-ISOLDE, CERN, Geneva, Switzerland	2001	PS booster p, 1.4 GeV, 2 μA	linac 0.8 - 2.2 MeV/u
HRIBF, Oak Ridge, USA Excyt (LNS)	1998 2006	cyclotron p, d, α, 50 -100 MeV 10 - 20 μA Cyclotron	25 MV tandem 15 MV Tandem
ISAC, TRIUMF, Vancouver, Canada	2000	synchrotron p, 500 MeV, 100 μA	linac 1.5 MeV/u

Facility Layout



Maximun Energy: 2.5 ÷ 150 MeV (***preacceleration energy up to 300 keV***)

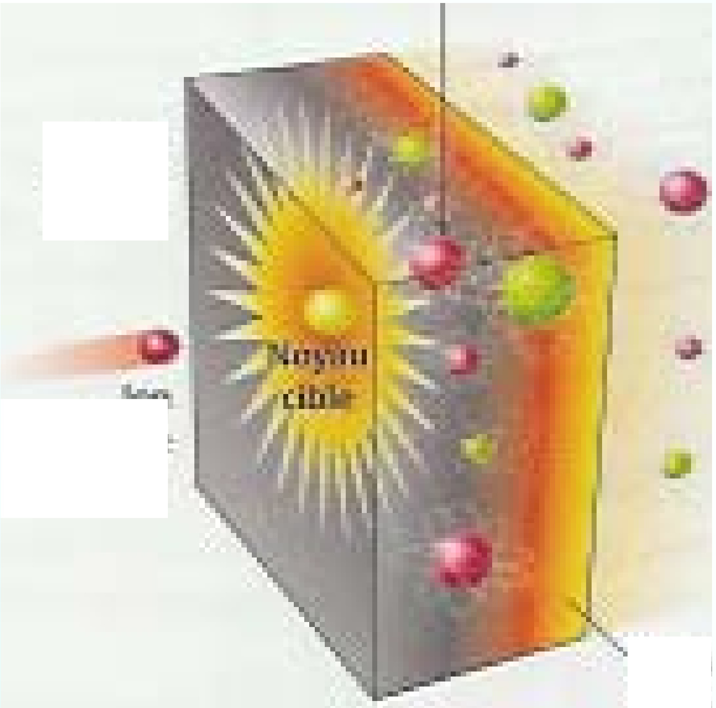
Low emittance (<0.5 π mm.mrad): clear-cut beam spot e low angular spread

Easy variable beam energy (excitation function study)

***Low energy spread*:** $\Delta E/E = 10^{-4}$.

Proprieta' del bersaglio di produzione

ISOL: I nuclei prodotti dalle reazioni sono fermati nel bersaglio di produzione



Per estrarli si sfrutta il processo di effusione-diffusione nei solidi

Diffusione : e' il processo attraverso il quale la materia e' trasportata da una parte all'altra come risultato del moto molecolare di tipo random

Serve un gradiente termico

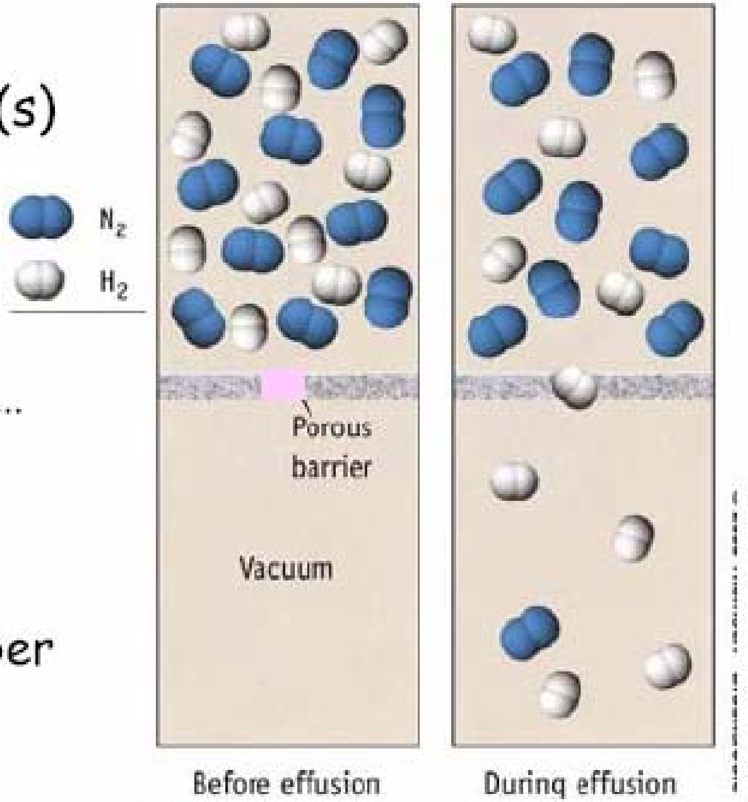
Indipendentempente dal meccanismo atomico responsabile della diffusione si descrive il coefficiente di diffusione macroscopico D (che dipende dalla temperatura, e dal materiale)

+ meccanismo di effusione per uscire dalla superficie

2. Effusion

= movement of a gas through tiny hole(s)

= faster for lighter molecules…



WHY DOES IT HAPPEN?

→ molecules collide with container walls…

→ but if "hit" the hole: go through!

BALLOONS:

- molecules effuse through holes in rubber
- rate (= moles/time) is:
  proportional to temperature
  inversely proportional to molar mass.

Thus: a He balloon deflates after a while…
He effuses out more rapidly than
N_2 & O_2 from air effuse in.

ISOL : SERVE UN BERSAGLIO CON BUONA POROSITA' !

Metodo ISOL

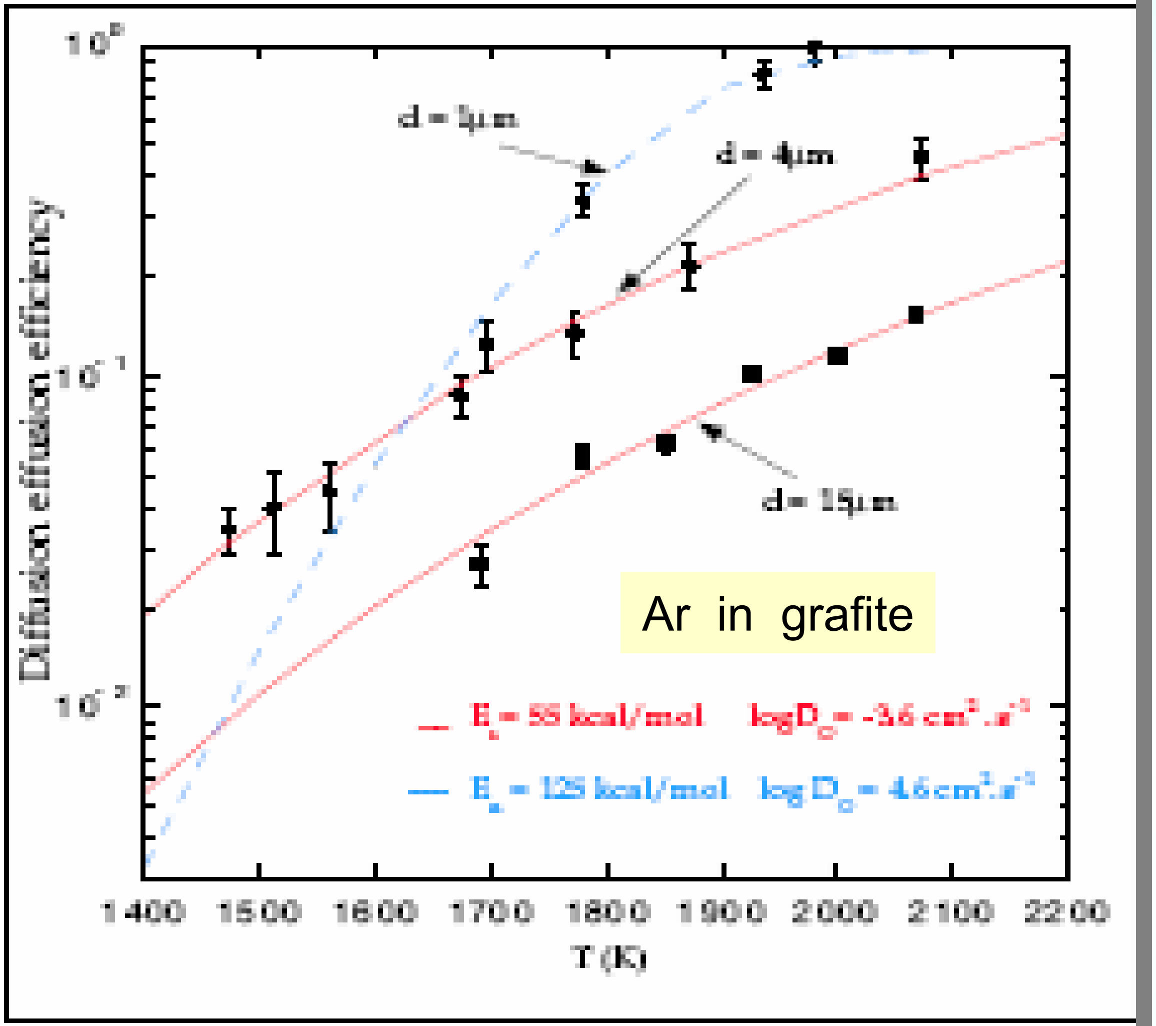


Figure 3 : The dependence of the diffusion-effusion efficiency on the target temperature [6, 7, 8].

d = dimensione del diffusore

E_A = energia di attivazione che dipende dalla composizione chimica del materiale (polvere lastre etc..) e dall'elemento che diffonde

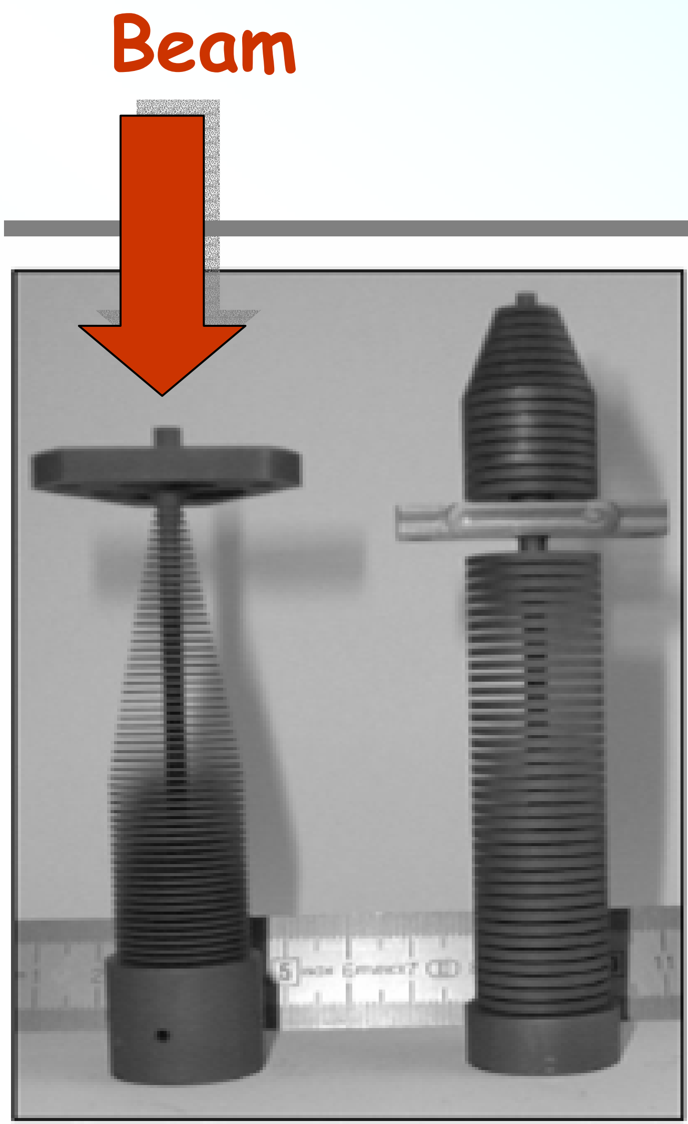


Figure 4 : Picture of the carbon targets : (left) the target dedicated to Ar and Ne production; (right) the target dedicated to He production.

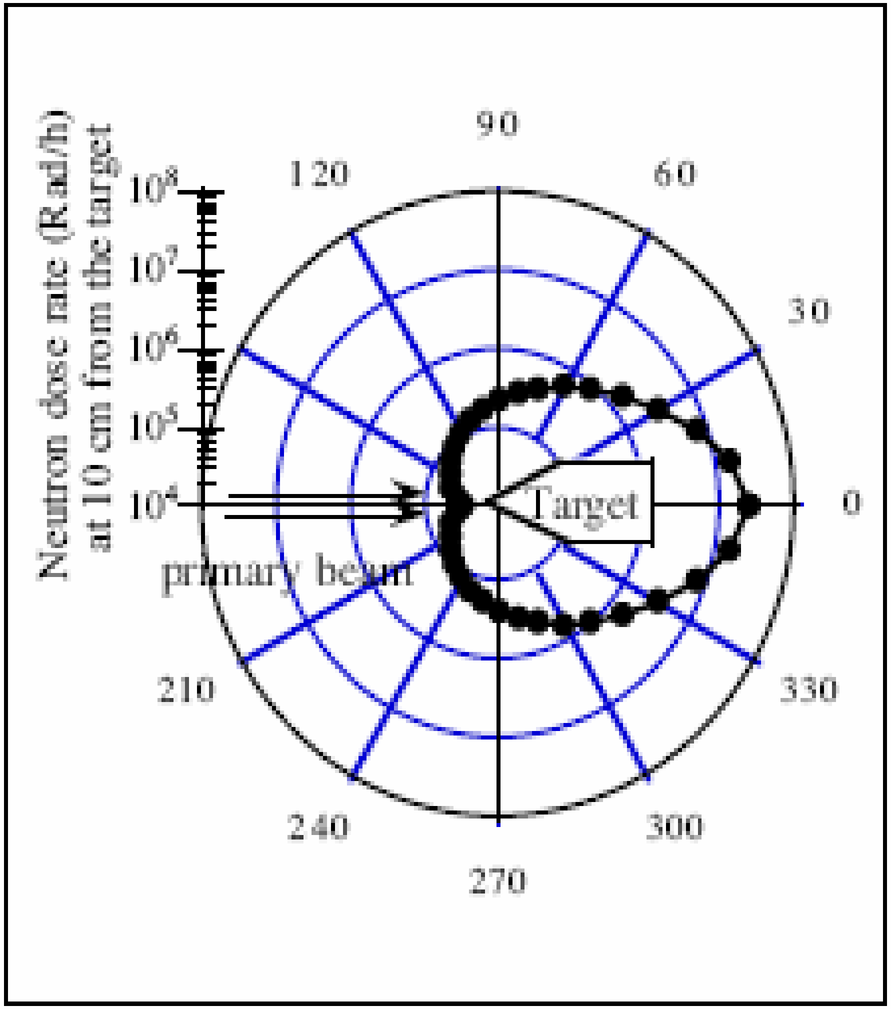
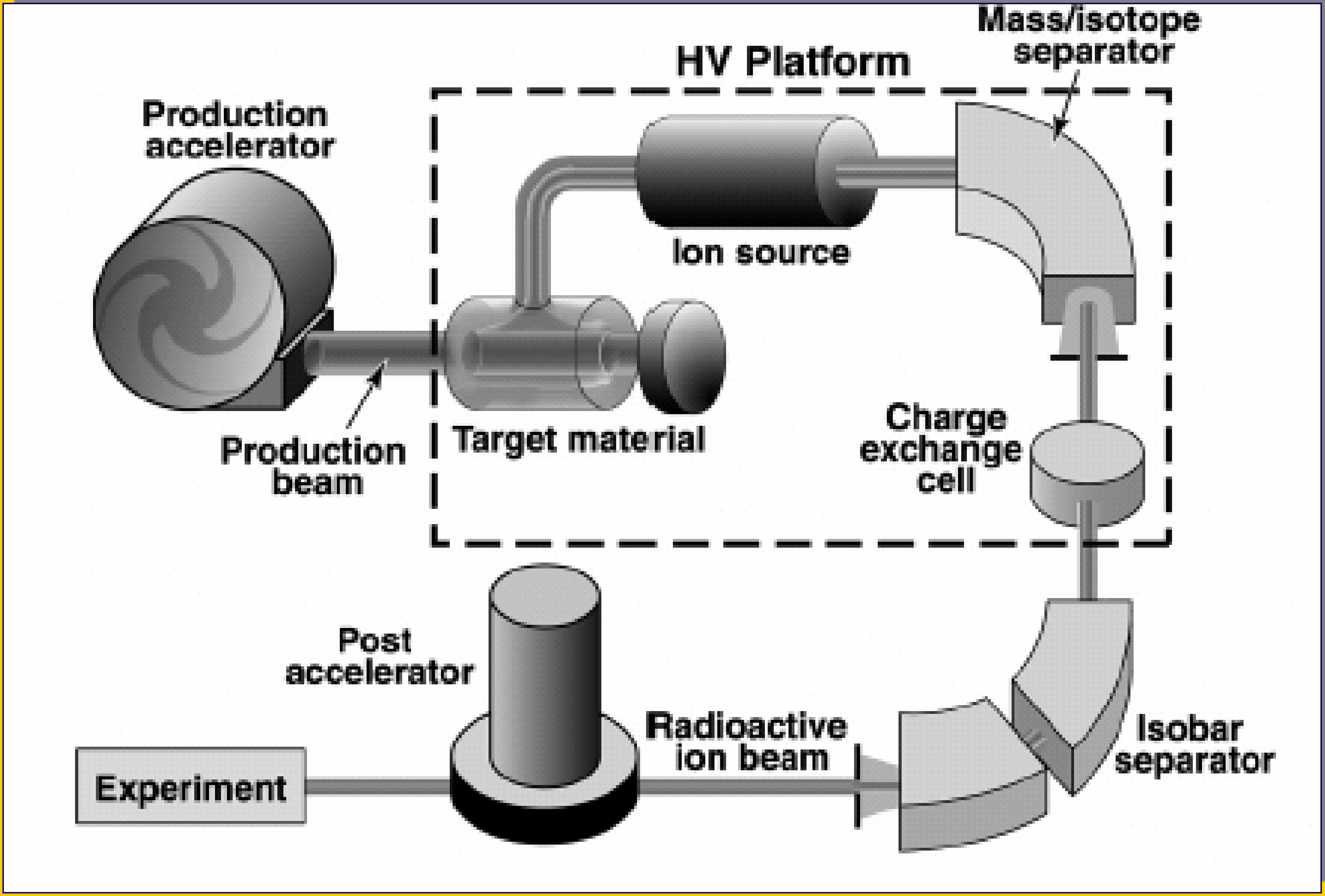
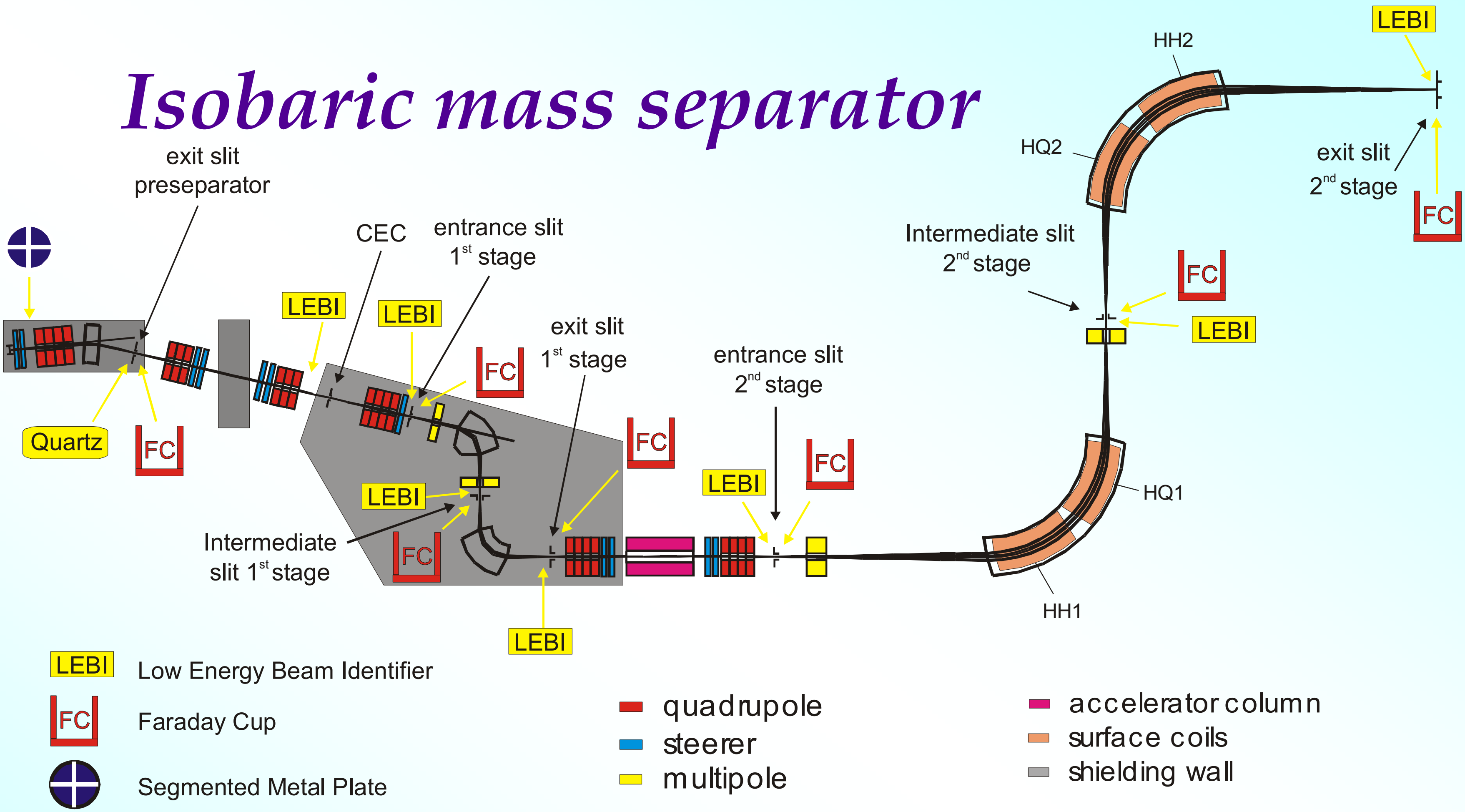


Figure 6 : Predicted angular distribution of the neutron dose for a 6 kW ³²S primary beam.


HV Platform
Mass/isotope separator
Production accelerator
Ion source
Production beam
Target material
Charge exchange cell
Post accelerator
Radioactive ion beam
Isobar separator
Experiment

Isobaric mass separator



The mass separator system consists on 2 stages, the first stage on two platforms at High Voltage (up to 250 kV).

The design transmision efficiency is ~ 100% with a beam of $\varepsilon_x=\varepsilon_y=4\pi$ mm mrad ($x_0=y_0= \pm 0.2$ mm, $a_0=b_0= \pm 0.2$ mm).

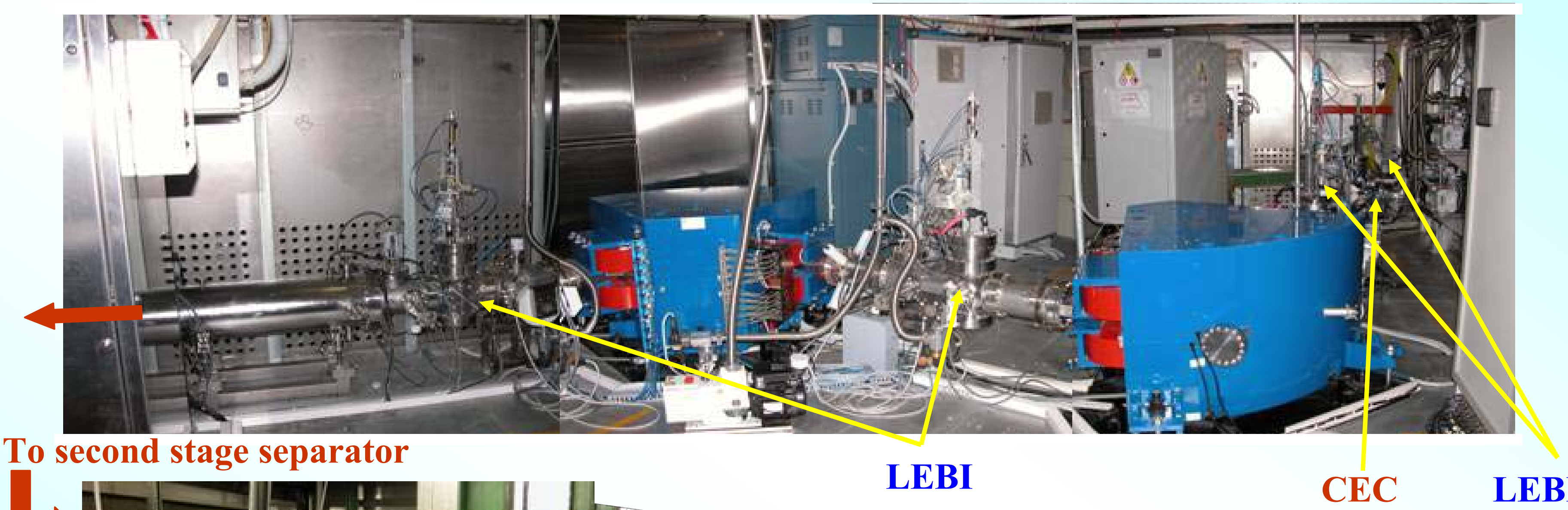
The mass resolution of each step is:

$(\Delta M/M)_{Pre} \approx 180$ (**Pre-separator** : 18° magnet and a set of 4 electrostatic quadrupoles)

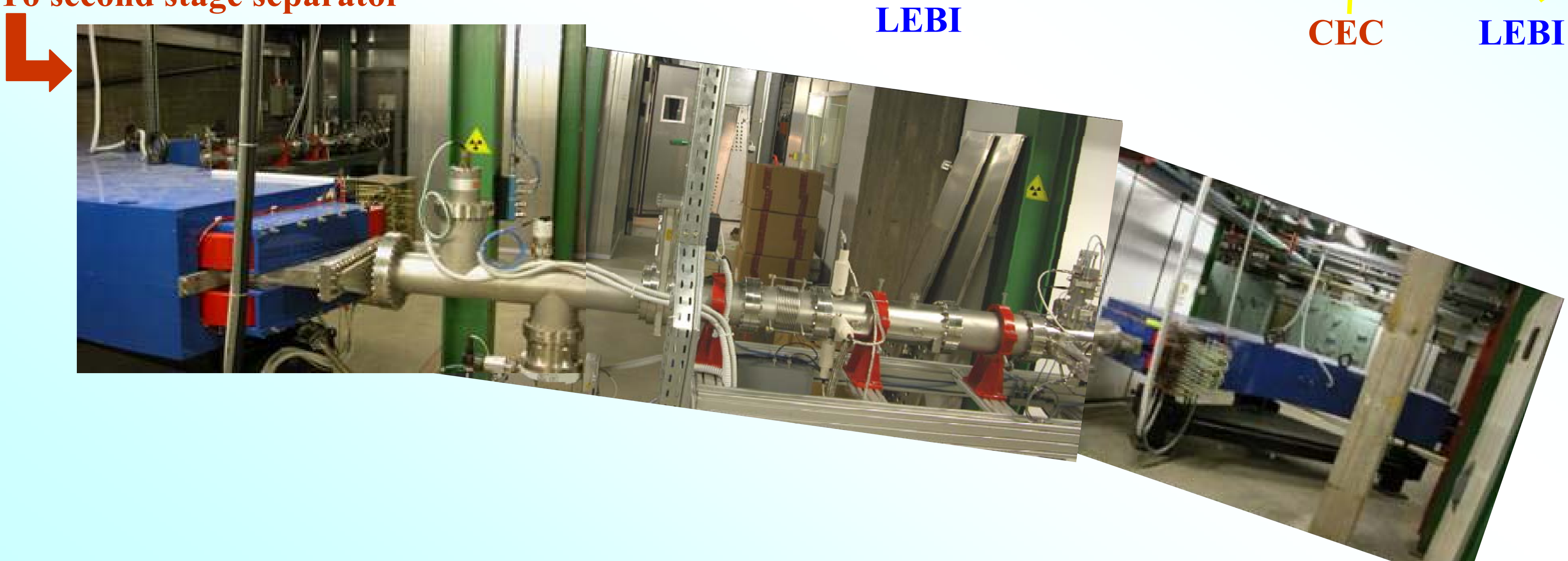
$(\Delta M/M)_{1st} \approx 2000$ (**I stage**: 2 magnets (77° e 90°) and 2 sets of 4 electrostatic quadrupoles)

$(\Delta M/M)_{2nd} \approx 20000$ (**II stage**: 2 magnets (90°, ρ=2.6 m) and a set of 4 electrostatic quadrupoles)

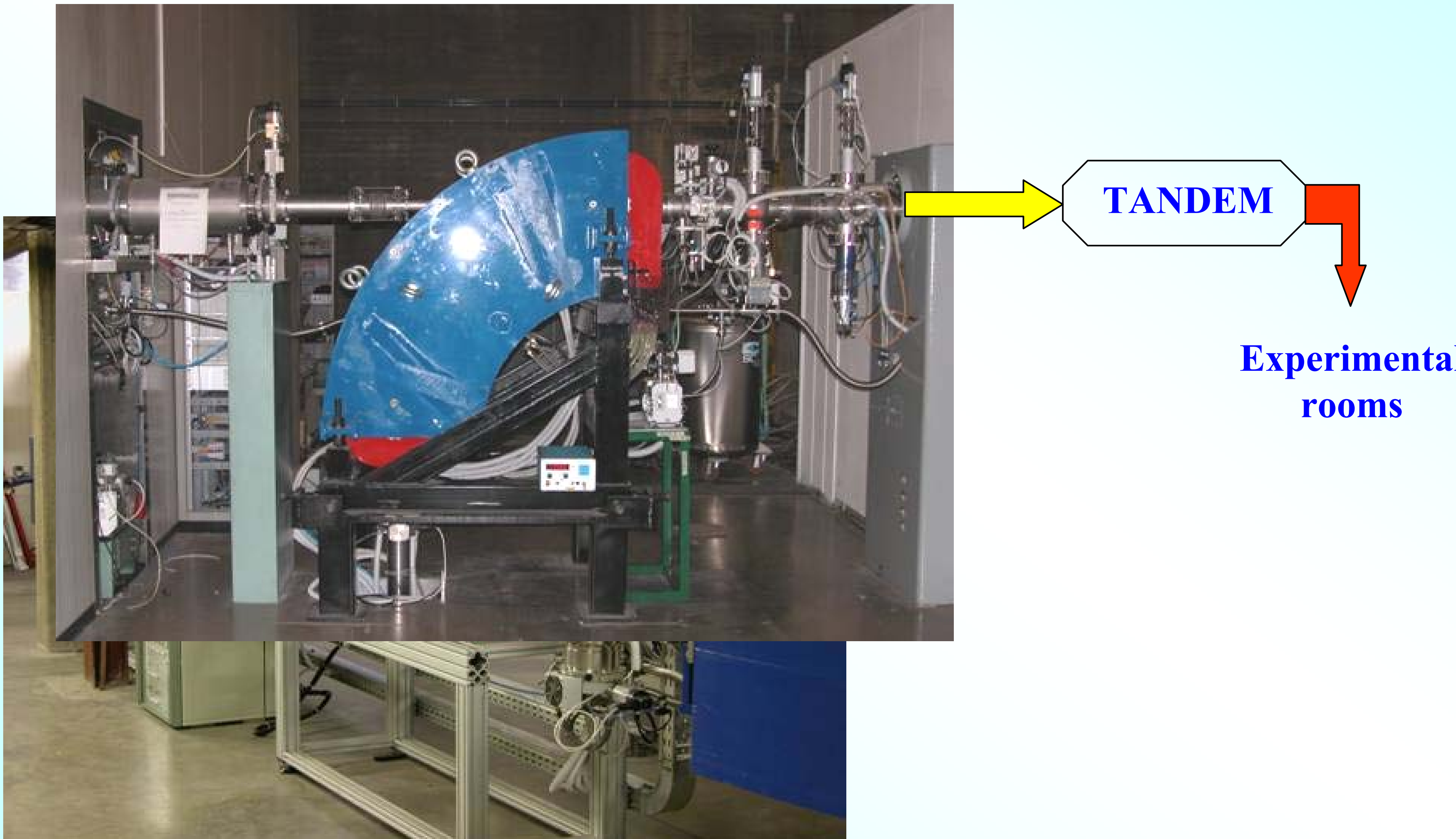
First and Second stage of the isobaric mass separator



To second stage separator



Beam lines to the Tandem



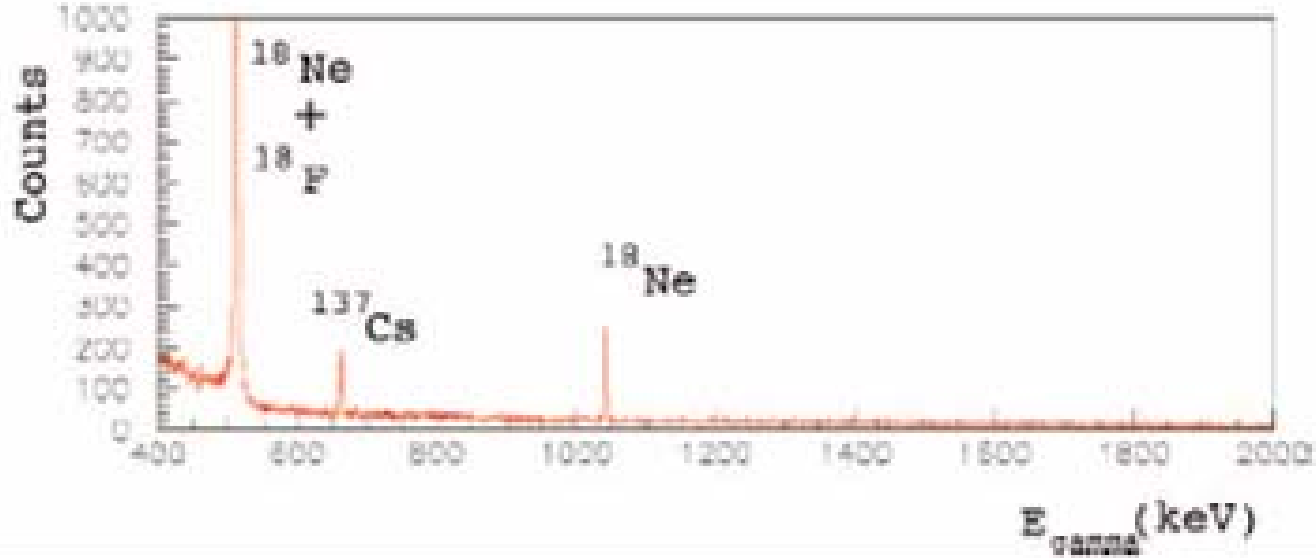


Figure 3 : Energy spectrum of the germanium detector during the first experiment at SPIRAL. The ^{18}Ne is clearly identified with the 1041 keV gamma ray. The 671 keV is emitted by the ^{137}Cs of the calibration source used.

Check beam purity with gamma spectroscopy!

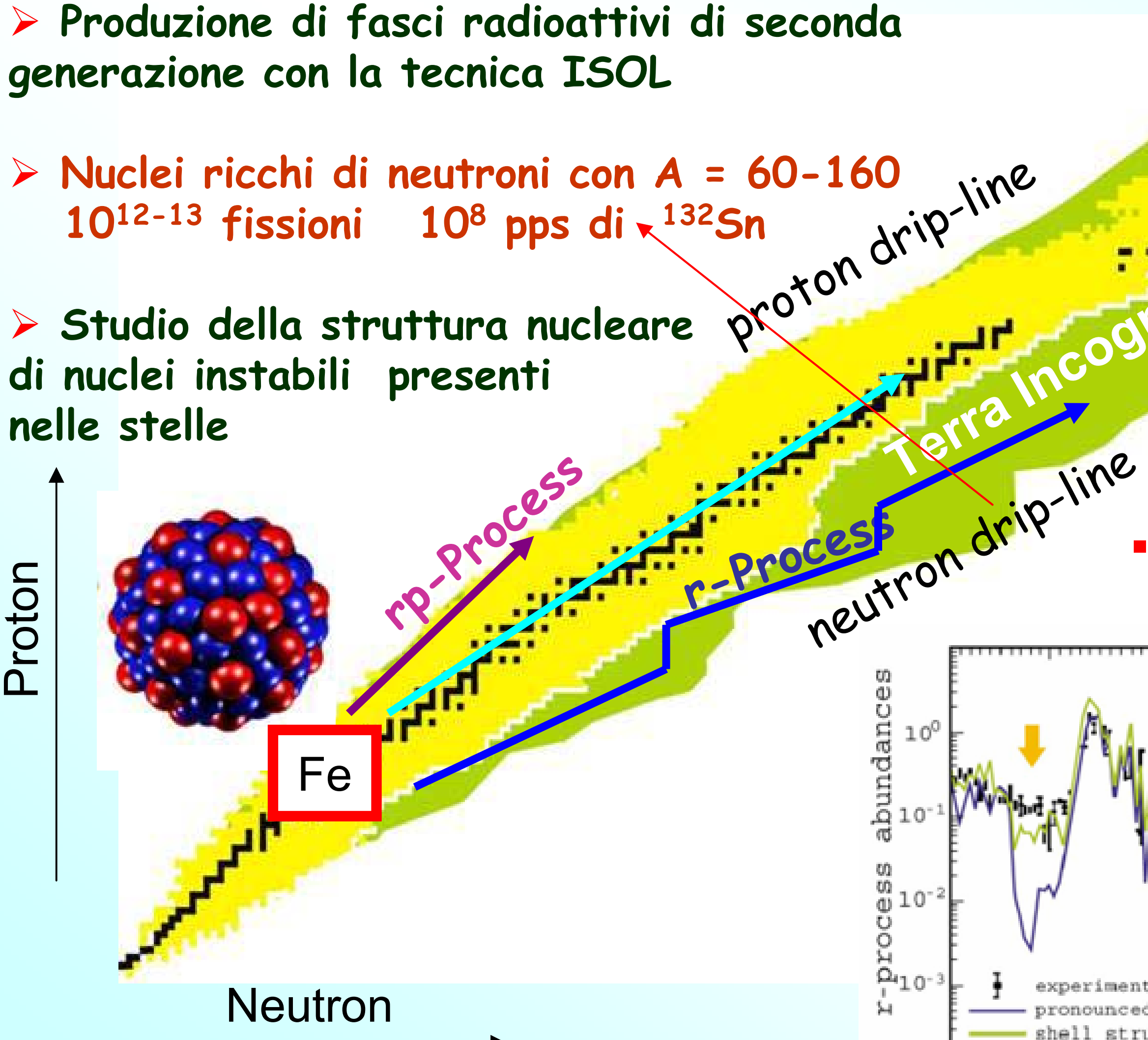
SPES

A Mid-term RNB Facility Based on a 40 MeV Proton Driver and on the Multi-Slice Direct Target Concept

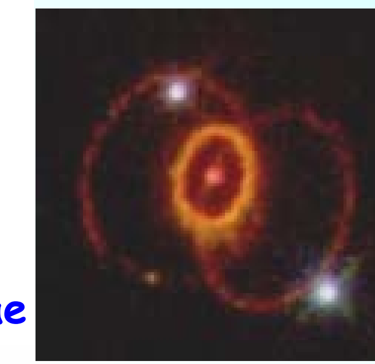
La frontiera in struttura nucleare:
Il limite della stabilita' Nucleare

SPES a LNL

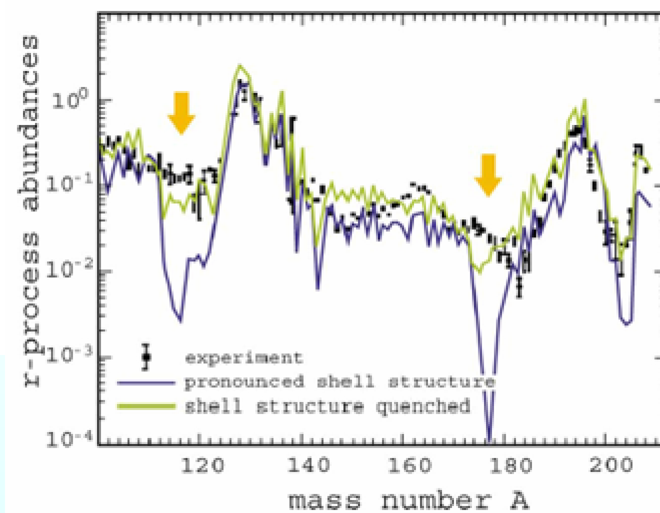
- Produzione di fasci radioattivi di seconda generazione con la tecnica ISOL
- Nuclei ricchi di neutroni con A = 60-160
  10^{12-13} fissioni 10^{8} pps di ^{132}Sn
- Studio della struttura nucleare di nuclei instabili presenti nelle stelle



Implicazioni Astrofisiche



- nucleosintesi nelle supernovae



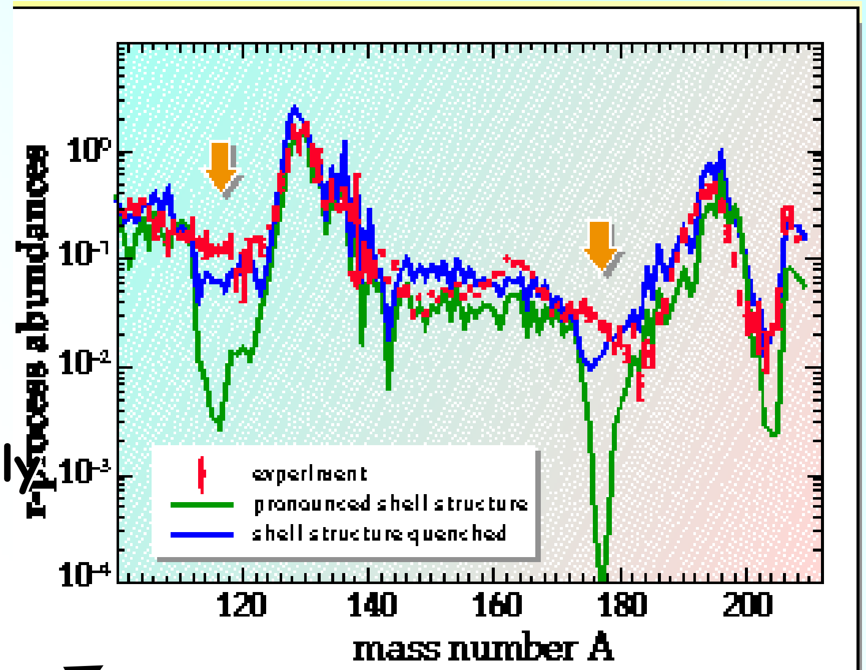
- abbondanze r-process
- waiting points nuclei

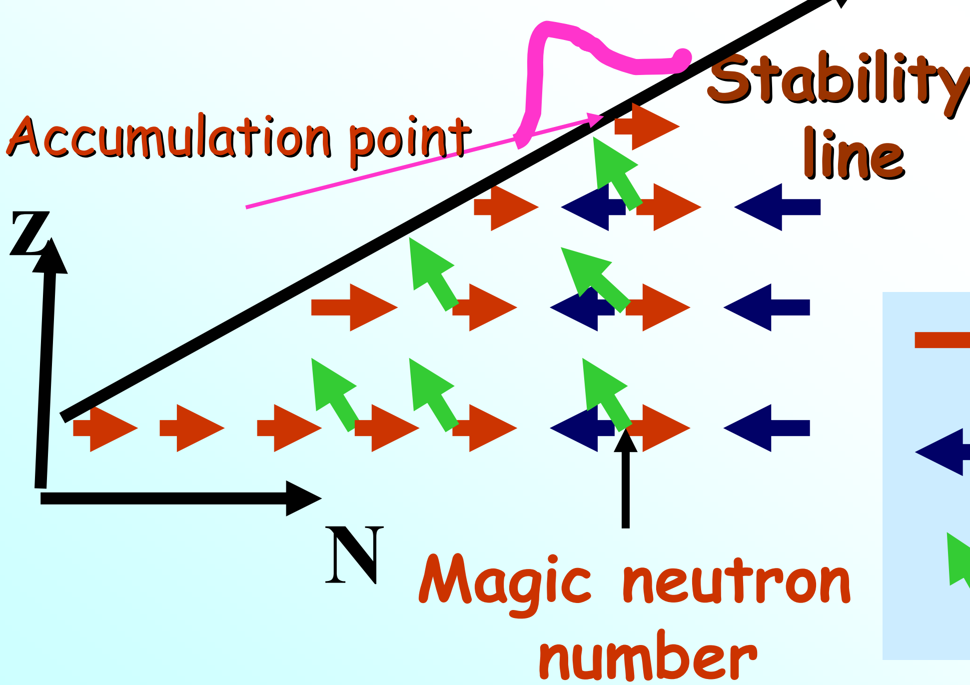
The r-process

Abundance peak in the r-nuclei distribution

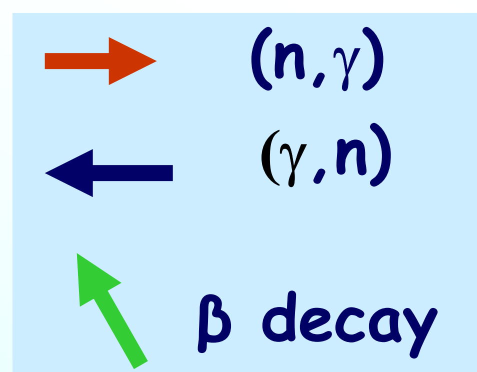
Decrease of Sn

→ Photodisintegration competes with neutron capture and eventually Equilibrium is reached and then neutron capture is stopped





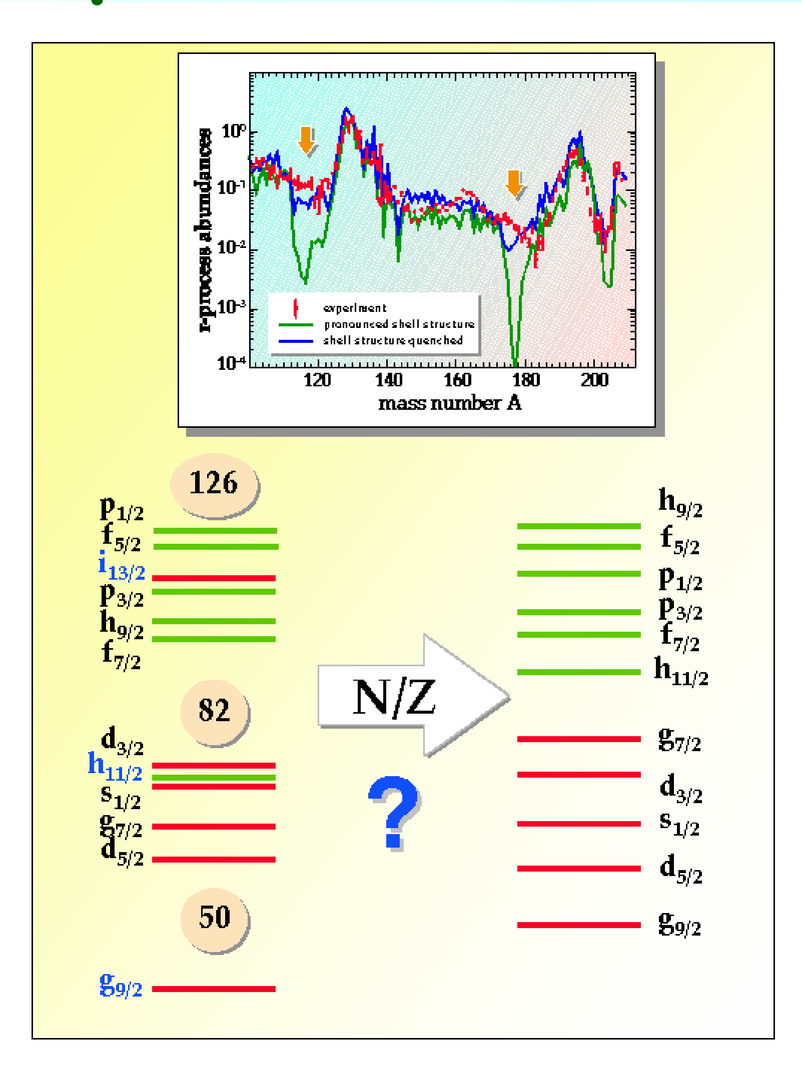
r-process is characterized by neutron densities and temperature so that (n,γ) Is faster than β decay



Nuclear physics in r-process

R-process involves many unstable exotic nuclei and their properties needsto be known:

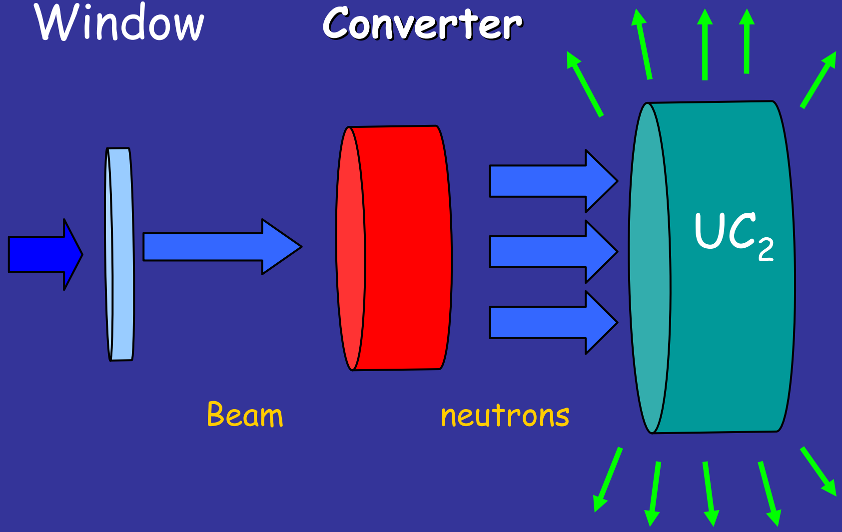
- Ground state properties
- Optical potential
- Level densities
- Gamma-ray strength function
- Reaction rates
- Beta-decay rates
- Shell structure and its evolution with N/Z

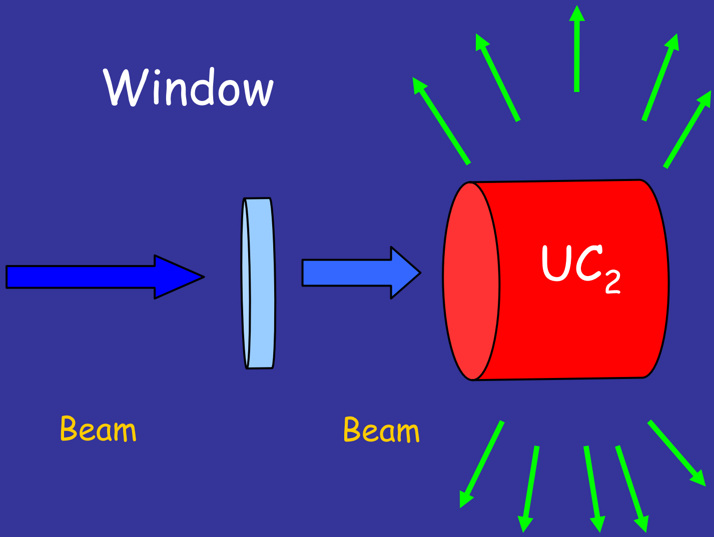


Produce and accelerate RIB to undertake this program

Bersaglio di produzione di nuclei instabili

Possible Target Configurations:





2 STEP:

Use of neutron converter

Better beam: deuteron

Beam Power send to the Converter

1 STEP:

Direct beam on target

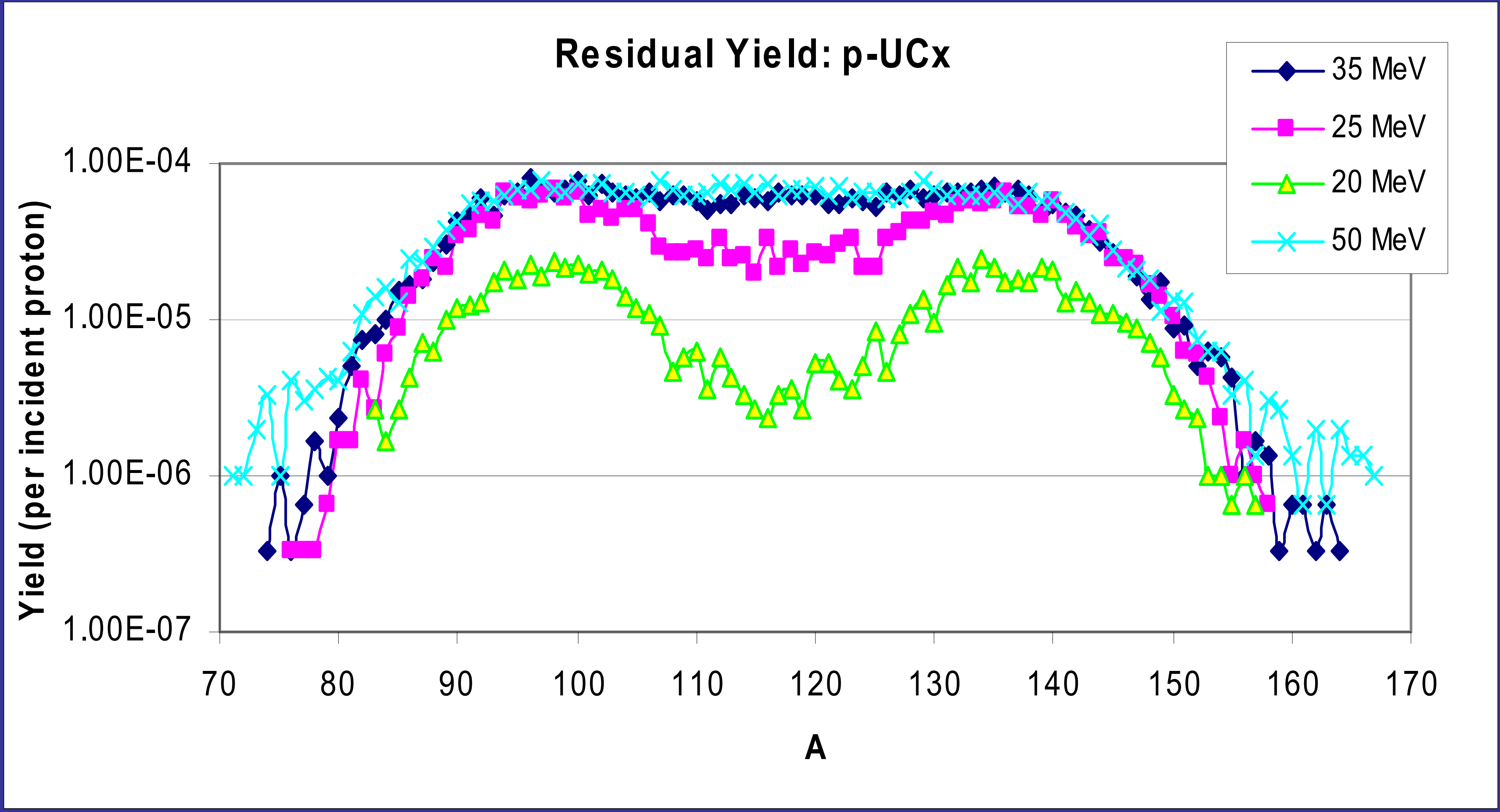
Better beam: proton

Beam Power send to the Target

A. Andrighetto, Napoli November 2004

Fission Mass Spectra: p-> UC_2

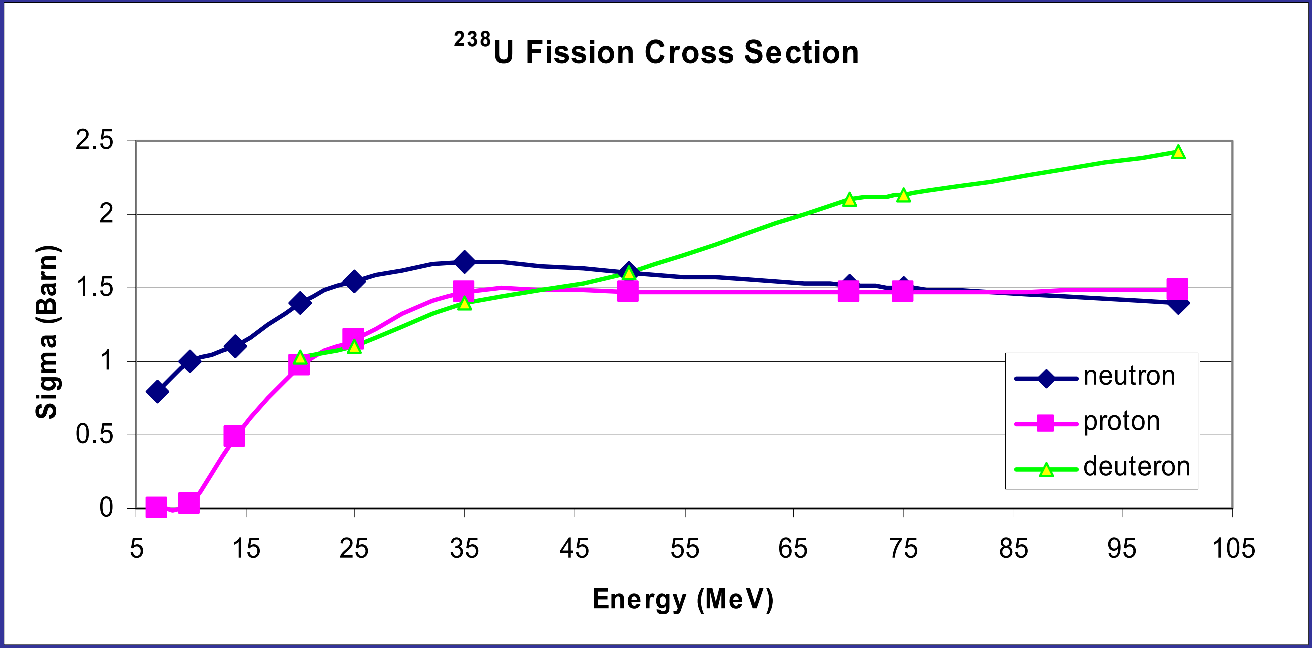
Using MCNPX code: Single Target 2 mm thin, ρ=2.5 g/cm3



Fission Cross Sections

Experimental Fission Cross Sections of ^{238}U -> (UC_2 is a ^{238}U compound)

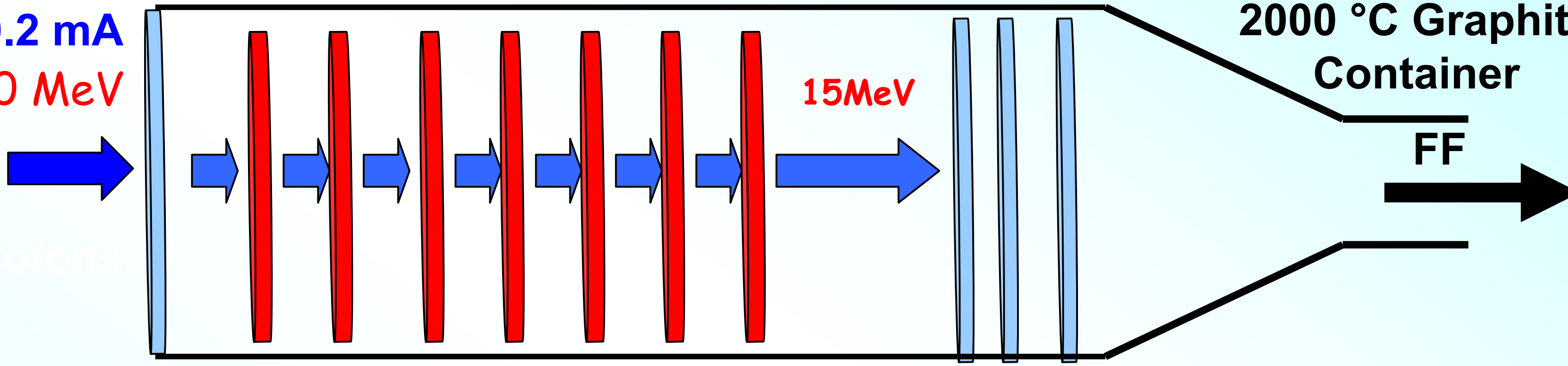
- Phys Rev 111(1958) 886;
- Nucl Phys A175(1971) 177;
- Nucle. Sci. Eng. 136 (2000) 340



→ Almost flat for neutrons and protons energies higher than 30 MeV (~ 1.5 Barn)

→ Around 35 MeV the same for p,n,d

The Multi-Slice Direct Target Concept



C Window

UCx Targets
(s= **1.5→1 mm)**
2.5 g/cm^3, 4.5 kW
600 W/disc (100 W/g)

Dump (graphite slices)
1.75 g/cm3, 3 kW

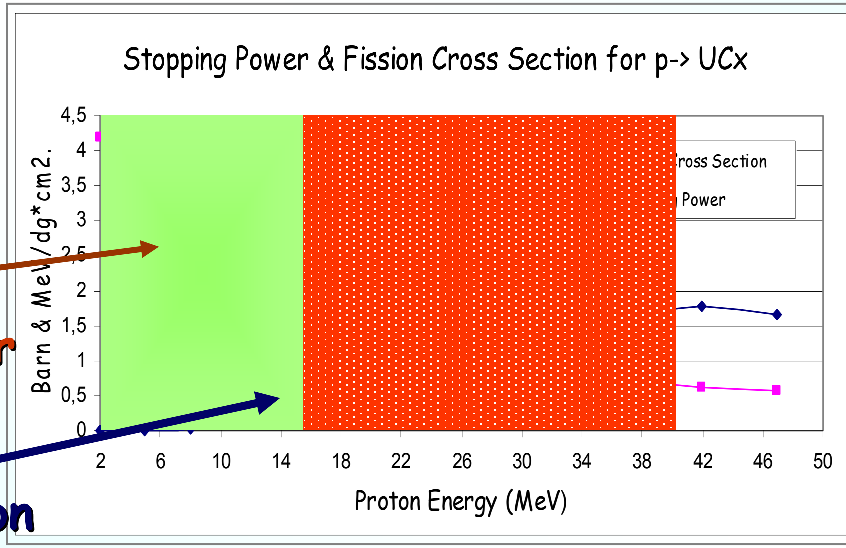
ΔE Targ ≈ 2.5 MeV

ΔE Window = 1.4 MeV

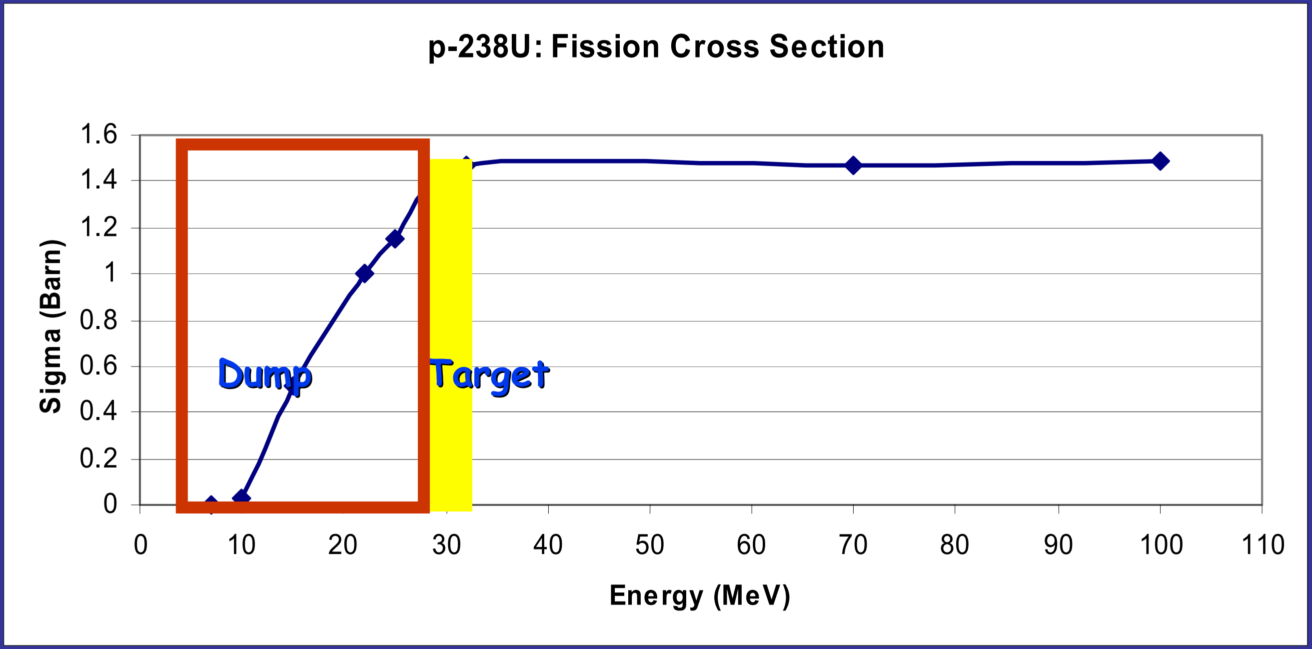
700 W in each slide

Stopping power

Fission cross section



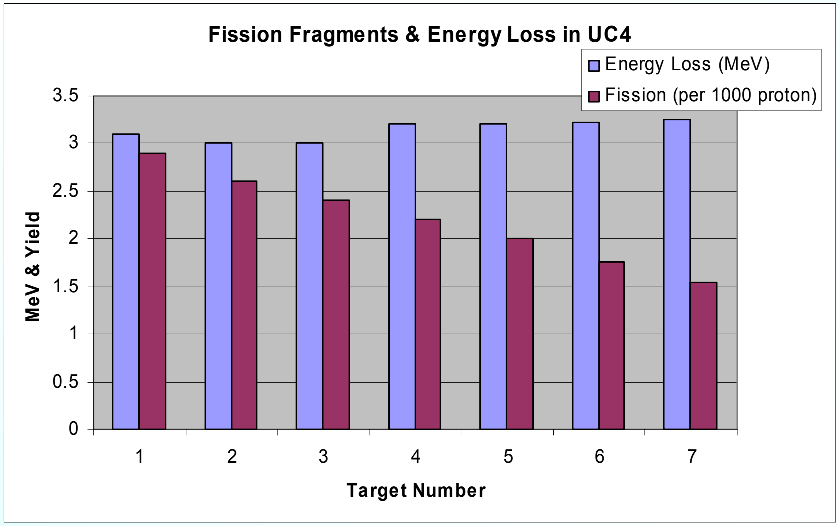
Proposal for 1 Step Thin Target:



Use a Thin UC_2 Target ->

To transfer a huge amount of Power to the Dump!

40 MeV Multiple Target #2



Fission efficiency →

100p per 1.5 fission Fragments

~ 200 μA → 10^{13} fissions/sec

Beam power = 40 MeV p x 200 μA

= 8 KW

Power distribution:

Direct target→ **7 disks 6 cm φ** ~1 mm thick

Energy loss UCx (60gr) **23 MeV** → 4.2 KW

(**600 W each disk, ~70 W/gr**)

Window energy loss → 200 W

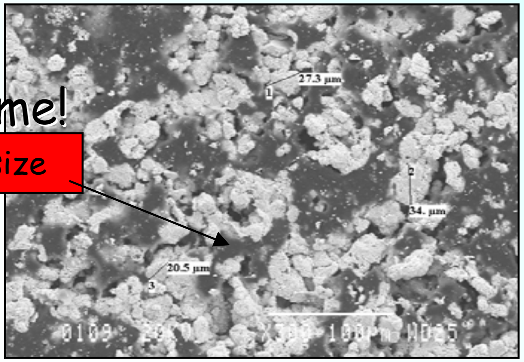
beam-dump → 3.5 KW

(HRIBF target: 100 W/gr)
OAK RIDGE

Diffusion process with RIBO

- Diffusor Grain Size: d=10 µm (very conservative number)
- T= 2000 °C
- Diffusion coefficient = 9E-9 cm^2/s (input parameter - estimate)

- **Diffusion time = 1.6 s** -> 95% of total time!
- *Average flight path: 15 µm*

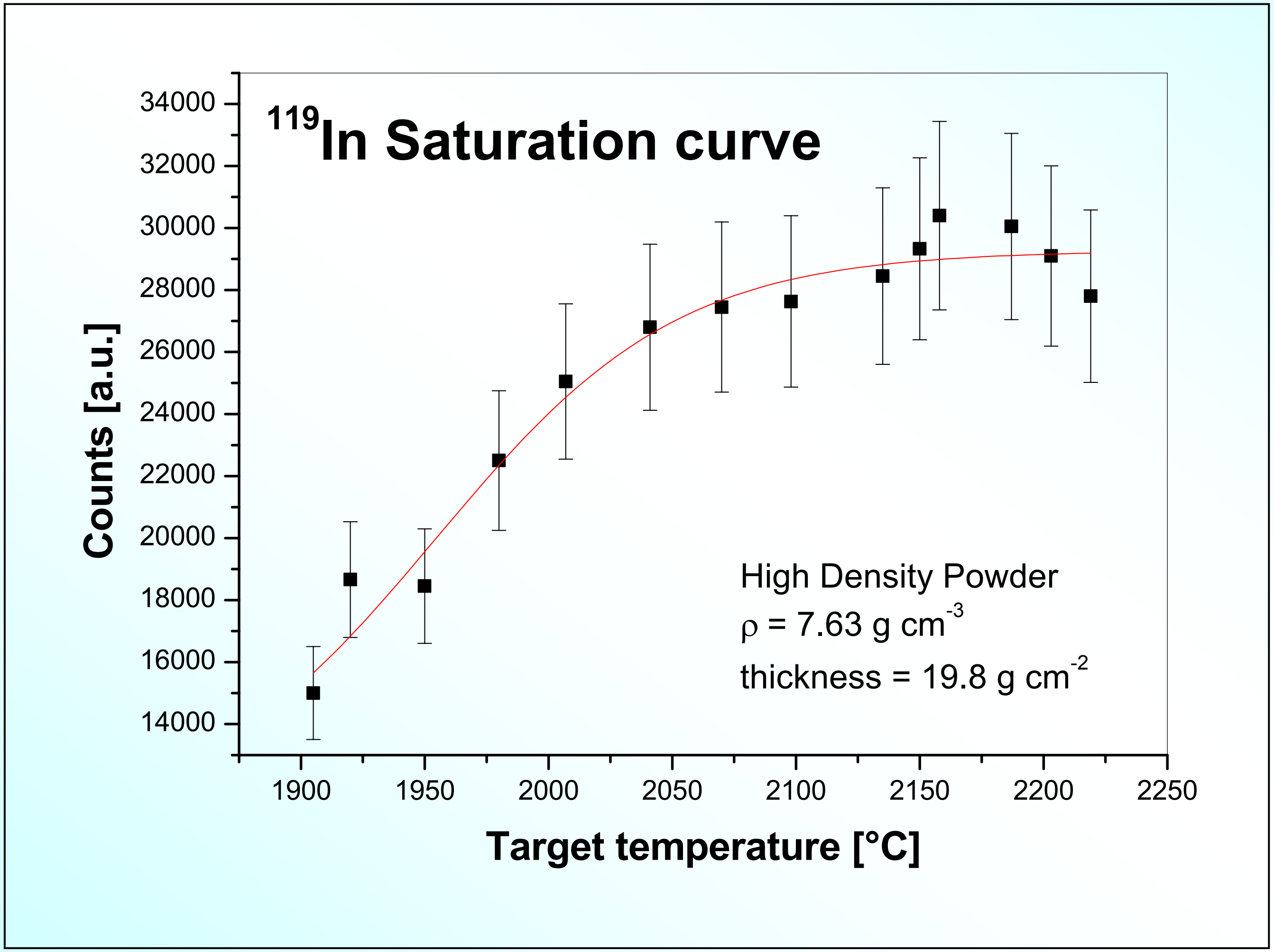


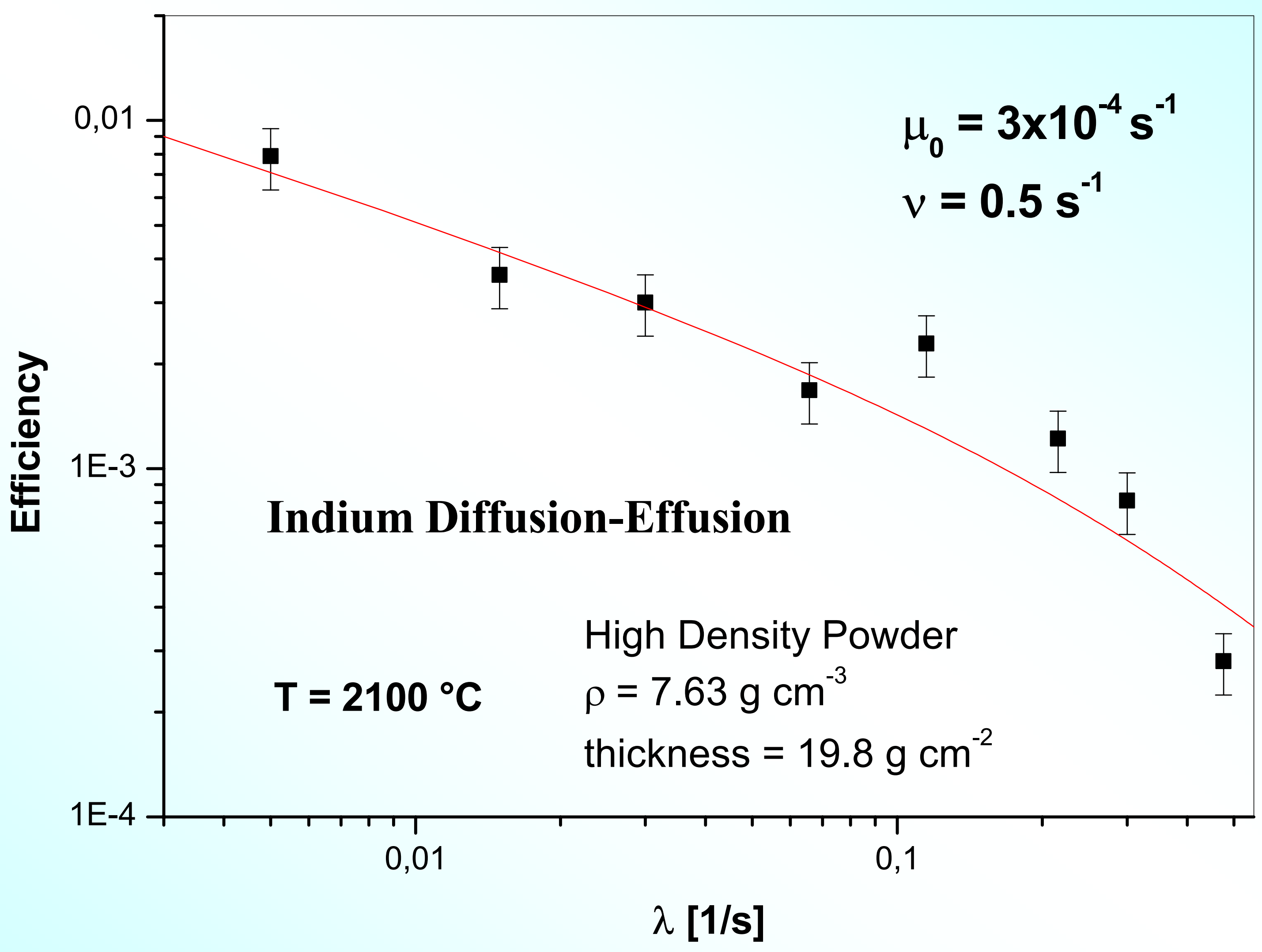
- Grain Size Parametrization :

d = 5 µm -> Diffusion Time = 0.4 s !
d = 3 µm -> Diffusion Time = 0.1 s !!

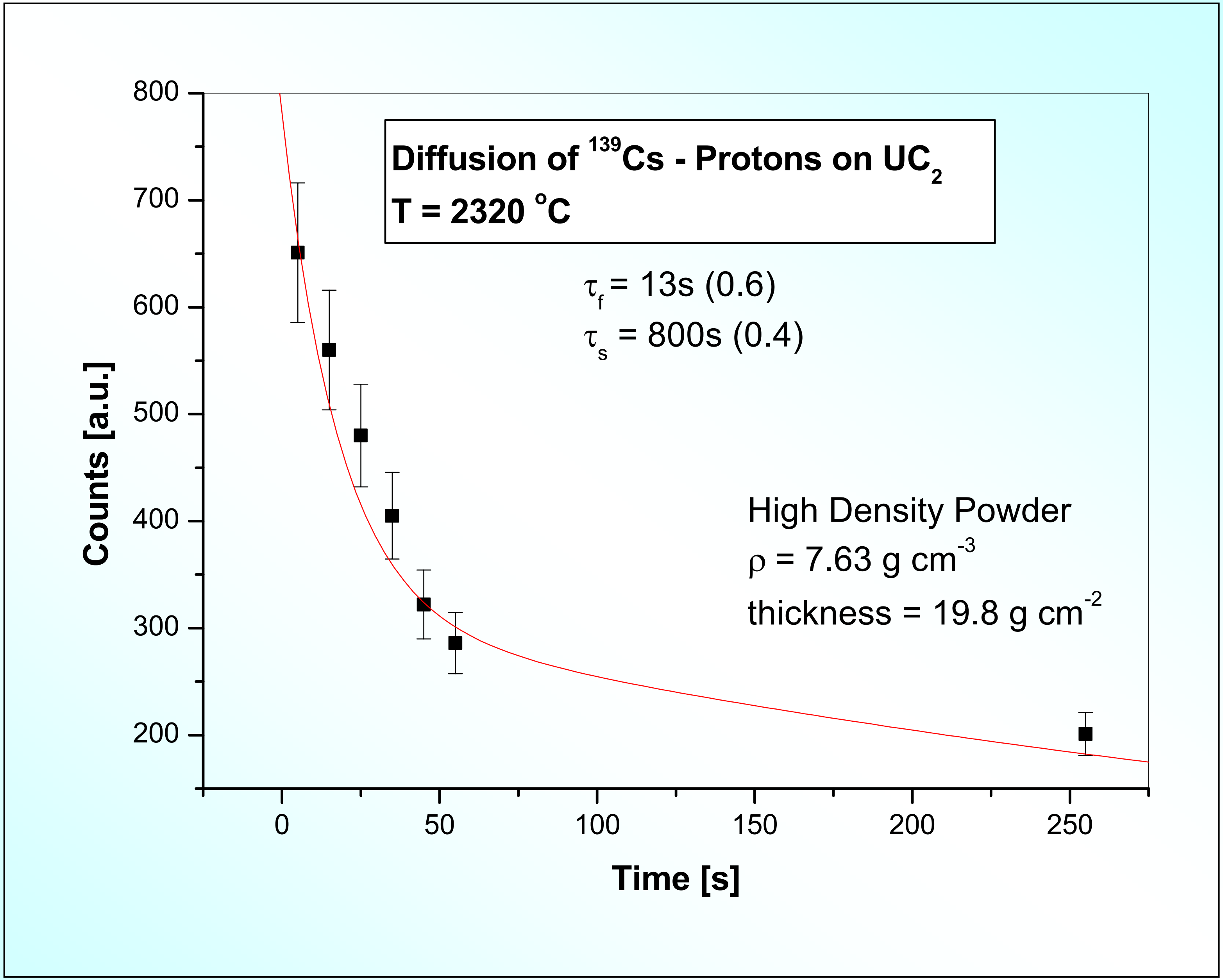
-Diffusion Strogly dependent of diffusor Grain Size!

Trovare la temperatura ottimale





Efficiency
0,01
1E-3
1E-4
0,01
0,1
λ [1/s]
μ0 = 3x10-4 s-1
ν = 0.5 s-1
Indium Diffusion-Effusion
T = 2100 °C
High Density Powder
ρ = 7.63 g cm-3
thickness = 19.8 g cm-2



Diffusion of 139Cs - Protons on UC2
T = 2320 °C
τf = 13s (0.6)
τs = 800s (0.4)
High Density Powder
ρ = 7.63 g cm-3
thickness = 19.8 g cm-2
Counts [a.u.]
Time [s]
800
700
600
500
400
300
200
0
50
100
150
200
250

Preliminary Results with RIBO

^{132}Sn ($T_{1/2}$=40 s)	No Sticking Time	Sticking Time on Ta = 0.1 ms
$T_{effusion}$ (s)	0.25	0.61
Average free path (m)	144	139
Average number of collisions	3770	3640

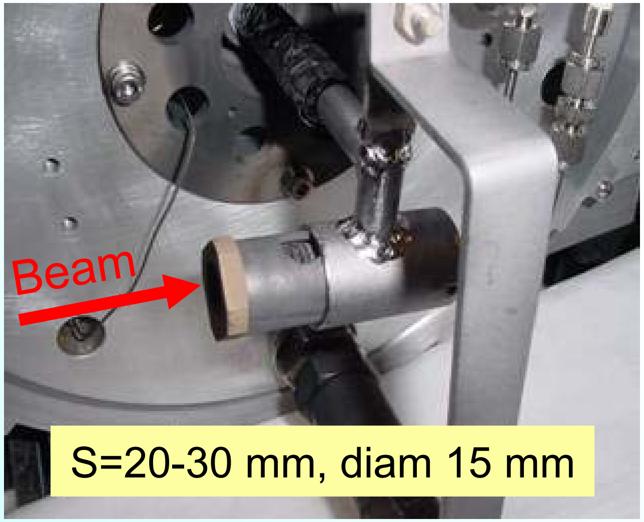
Results in accord with GEANT4 calculation →

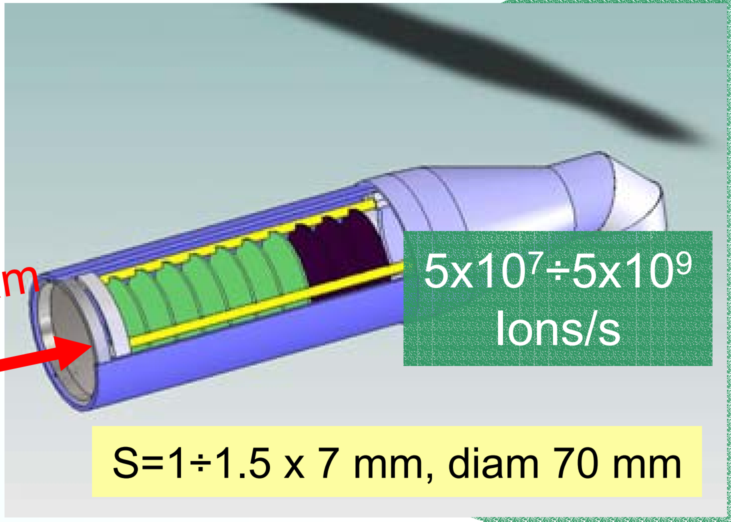
Effusion Less than 1 s !

Evolution of the DT Approach

ORNL	p, 42 MeV, 10÷12 μA
LNL	p, 40 MeV, 200 μA

→ ^{238}U (UC_x) → FF ~ $4x10^{11}$ / ~10^{13}



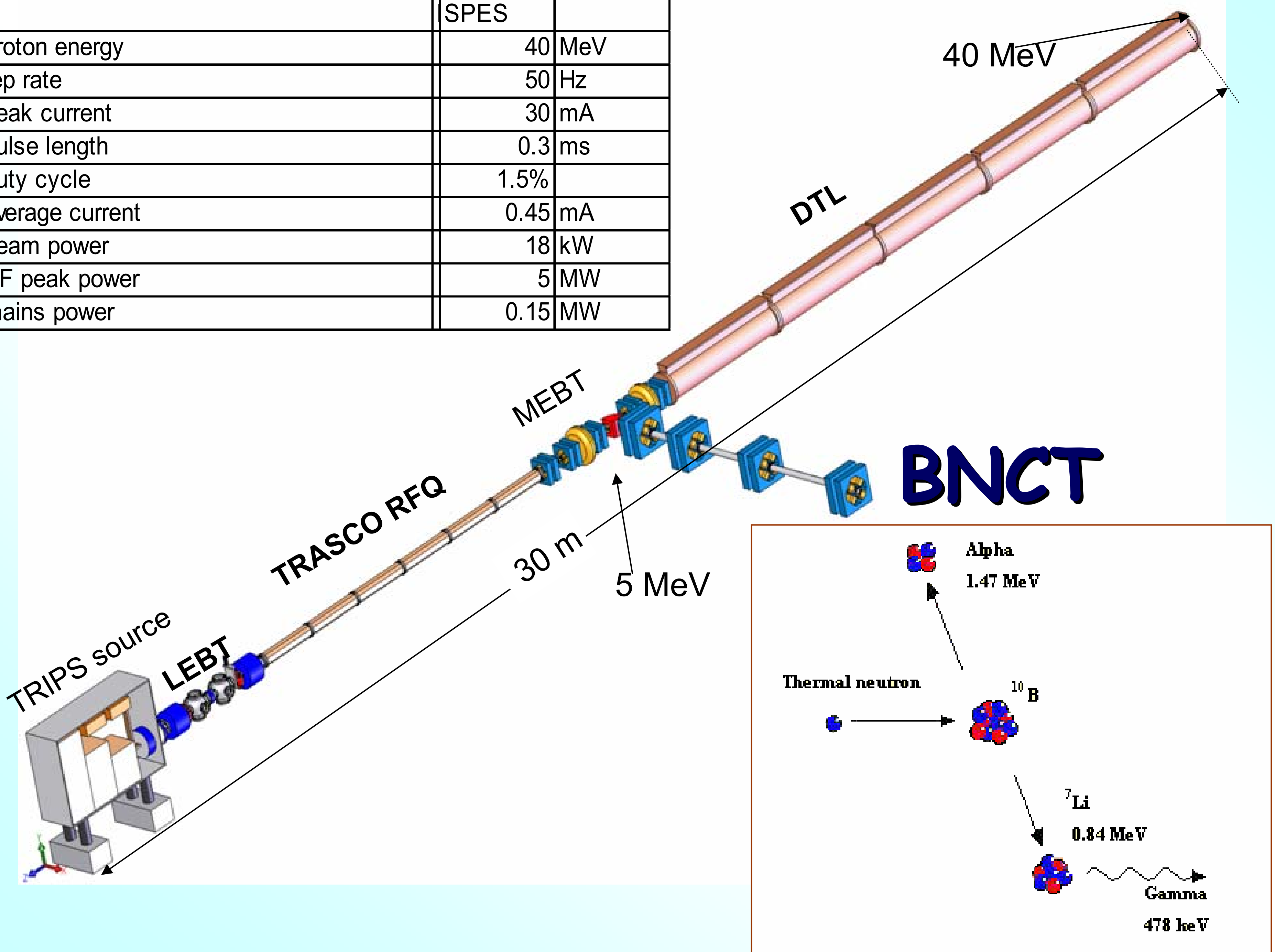


Ga	67÷84
Ge	75÷85
As	69÷85
Se	81÷88
Br	83÷91
Kr	86÷92
Rb	88÷94
Sr	90÷97
Y	91÷95
Ag	112÷121
Cd	117÷121
In	117÷127
Sn	123÷136
Sb	126÷134
Te	129÷136
I	130÷139
Xe	135÷139
Cs	138÷143
Ba	139÷142
La	142÷144

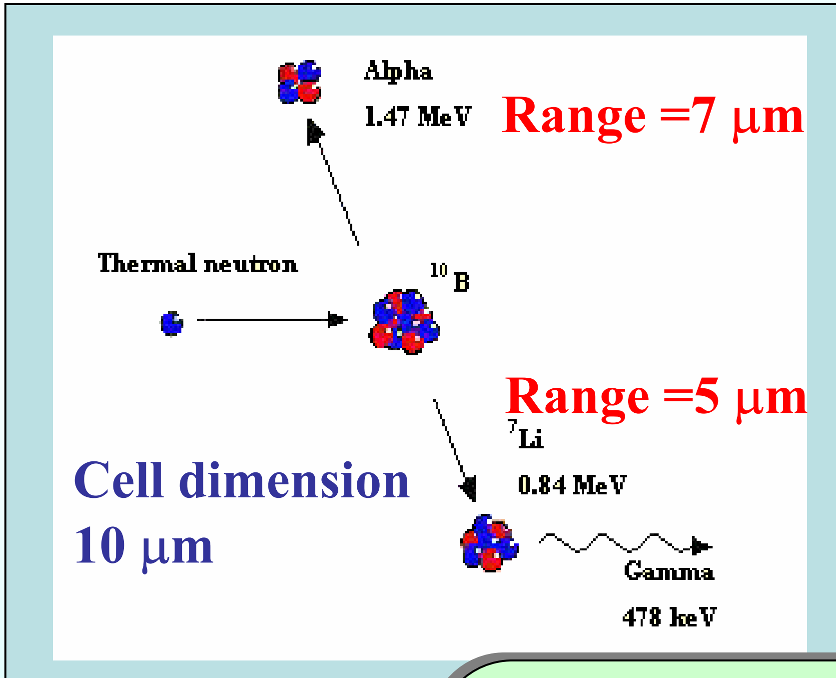
- Total of 1200 hours operation with 10-12 μA of 42 MeV protons
- More than 120 different radioactive beams extracted
- 400 W deposited in target (power density is 97 W/g, as LNL-project)

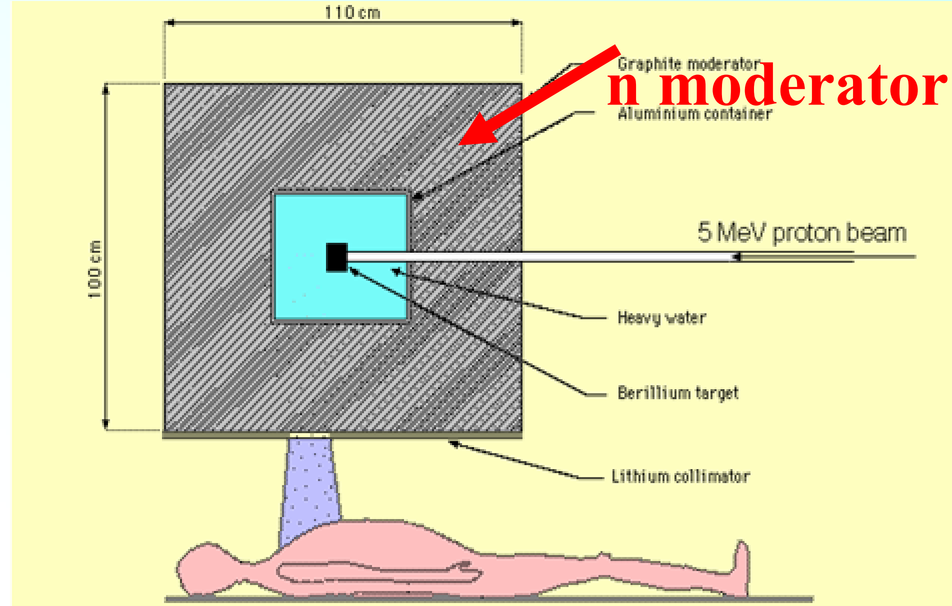
INFN

DTL Parameters		
	SPES	
proton energy	40	MeV
rep rate	50	Hz
peak current	30	mA
pulse length	0.3	ms
duty cycle	1.5%	
average current	0.45	mA
beam power	18	kW
RF peak power	5	MW
mains power	0.15	MW



How BNCT Work?





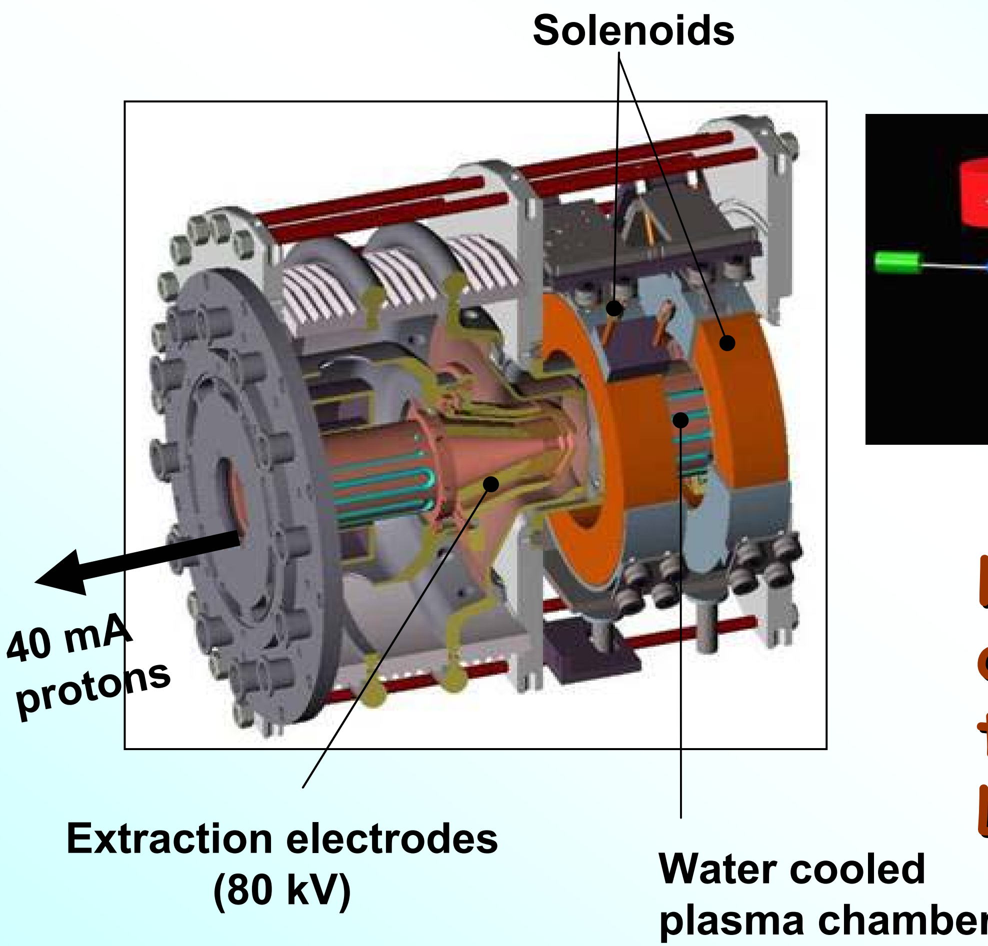
- ϕ_{th} ($\leq \sim 0.5$ eV)	[$n/cm^2 s$]	$\geq 1 \cdot 10^9$
- ϕ_{th}/ϕ_{total}		$\geq \sim 0.9$
- $D_{n,fast} + D_{n,epi} + D_{\gamma}$ (cumulative dose)	[Gy]	$\leq \sim 2$ (for a B10 tumour dose of ~20 Gy)
- $(D_{n,fast} + D_{n,epi} + D_{\gamma})/\phi_{th}$	[$Gy \cdot cm^2 \cdot n^{-1}$]	$\leq \sim 4 \cdot 10^{-13}$

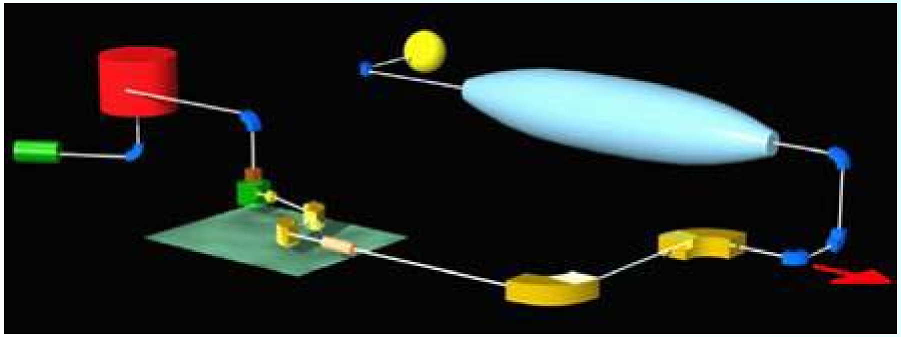
- Fast energy group — E > 10 keV
- Epithermal energy group — 10 keV > E > 0.5 eV
- Thermal energy group — E< ~ 0.5 eV

Neutron energy distribution at different angles:

5 MeV protons
Be and ^{13}C targets
Liquid scintillator, time of flight, CN measurements

The TRASCO Ion Source TRIPS (built by INFN-LNS)

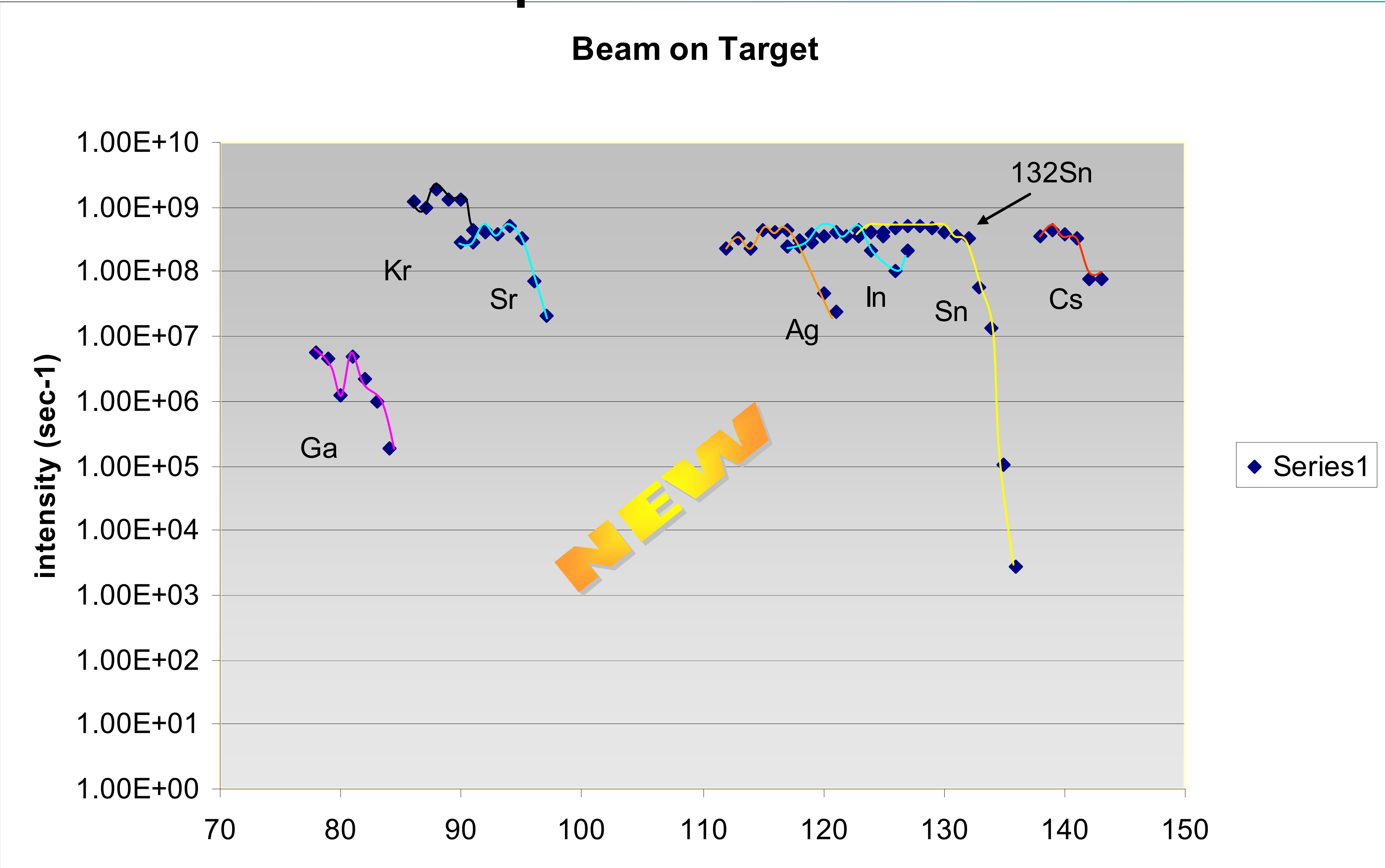




Know how for target development also from the EXCYT project at LNS

Nominal current (**40 mA**) at low emittance (~ 0.1 mm mrad rms) has been measured (LNS)

SPES production rates



Evaluated with SPIRAL2 efficiencies

Schedule

	2006	2007	2008	2009	2010	2011	2012
Target prototypes							
Authorization to construction							
Facility Design							
Building Construction							
Completion of driver (1st part-RFQ)							
Installation and commissioning of SPES-1							
Construction of driver (2nd part-DTL)							
Installation and comm. of the full driver							
Installation and comm of the target system							
Alpi preparation for post acceleration							
Installation of RIBs transfer lines and spectrom.							
Complete commissioning							

Instrumentation

Gamma spectroscopy connected to an instrument to identify and characterize the:

- nucleus produced in the reaction and
- emitting the gamma-rays

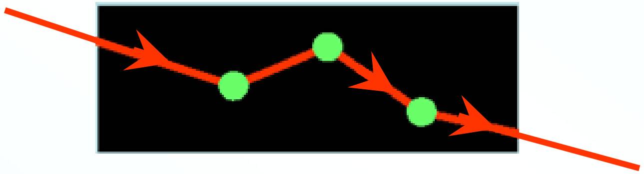
Simultaneuos information on

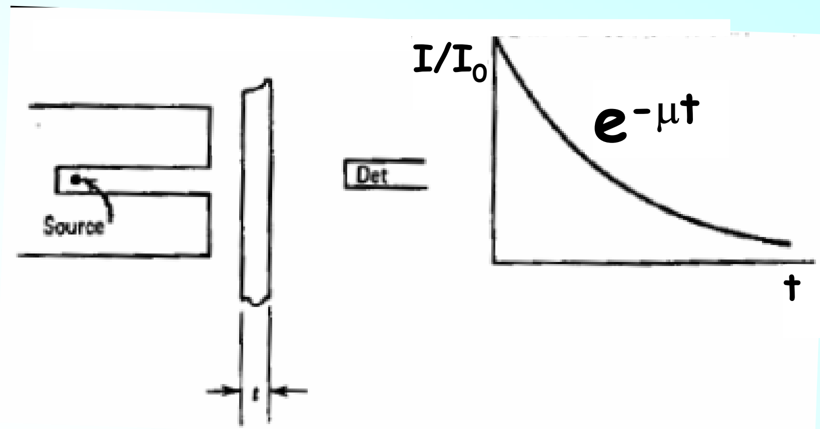
- **the reaction mechanisms**
- **the nuclear structure**

γ-ray interaction

$$I = I_0\, e^{-\mu x}$$

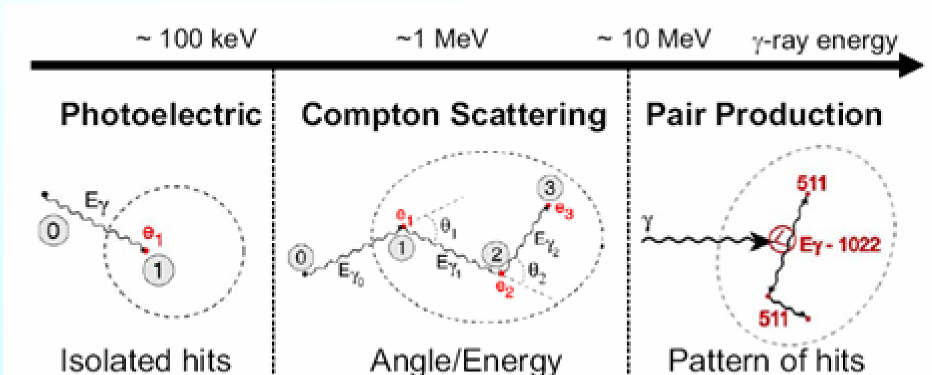
ionization occurs
in limited regions of the absorber





Linear attenuation coefficient
(probability per unit path)

$$\mu = \sigma_{ph} + \sigma_C + \sigma_{pp}$$



$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1-\cos\theta)}$$

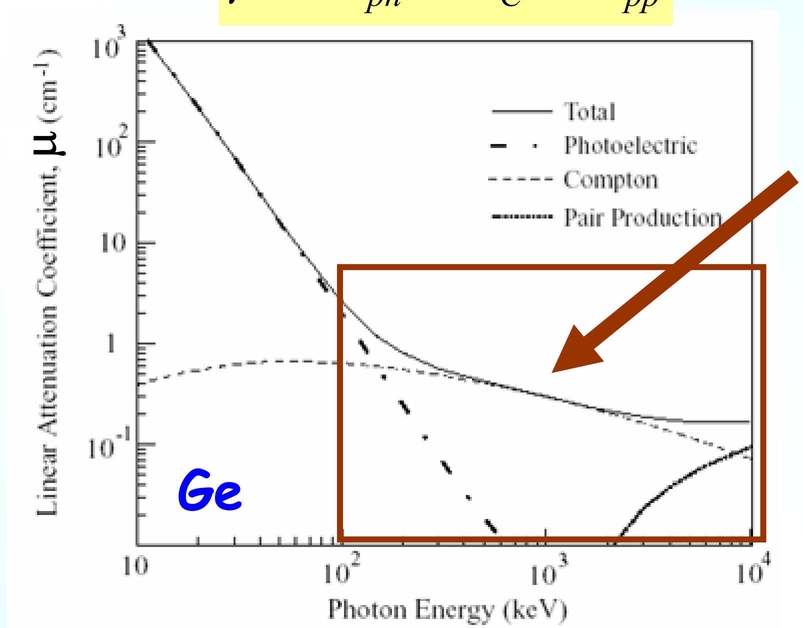
$$E_{1st} = E_\gamma - 2\,mc^2$$

$$\sigma_{ph} \approx \frac{Z^n}{E_\gamma^{3.5}}$$

$$n = 4-5$$

$$\sigma_C \approx Z\frac{\ln E_\gamma}{E_\gamma}$$

$$\sigma_{pp} \approx Z^2 \ln E_\gamma$$

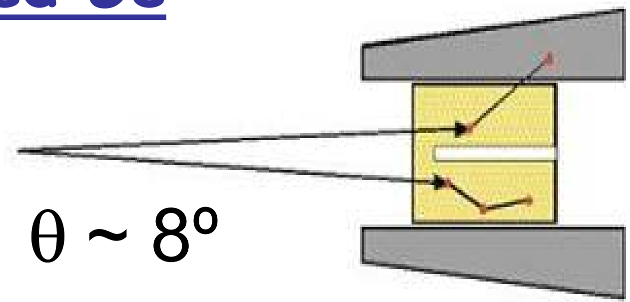


From conventional arrays to γ-ray tracking

Compton Shielded Ge

ε_{ph}	~ 10%
N_{det}	~ 100

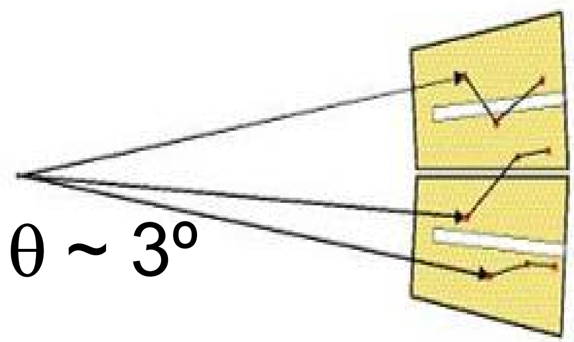
Ω ~40%



Efficiency is lost due to the solid angle covered by the shield; poor energy resolution at high recoil velocity because of the large opening angle

Ge Shell

ε_{ph}	~ 50%
N_{det}	~ 1000

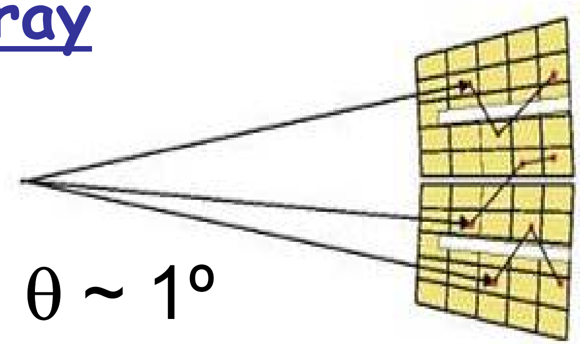


Using only conventional Ge detectors, too many detectors are needed to avoid summing effects and keep the resolution to good values

Ge Tracking Array

ε_{ph}	~ 50%
N_{det}	~ 100

Ω ~80%



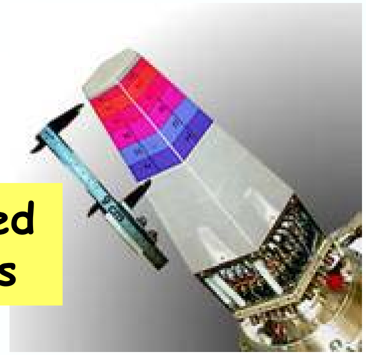
The proposed solution:
Use the detectors in a non-conventional way!

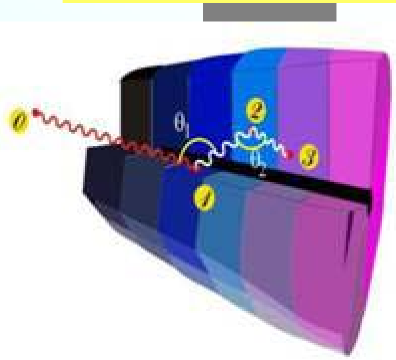
→ AGATA and GRETA

Basic ingredients of AGATA

1

Highly segmented HPGe detectors





2

Digital electronics to record and process segment signals

3

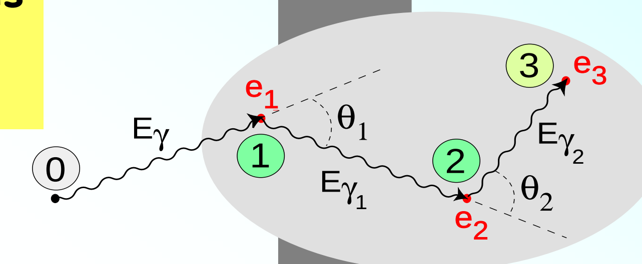
Pulse Shape Analysis to decompose recorded waves

Identified interaction points

$(x,y,z,E,t)_i$

4

Reconstruction of tracks evaluating permutations of interaction points



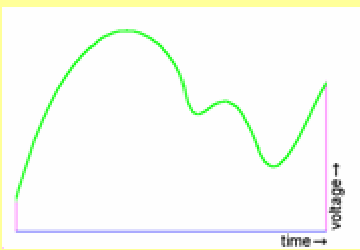
Reconstructed gamma-rays

Digitization of electronic signals

digitizing, or **digitization**, is the process of turning an analog (continous) signal into a digital representation of that signal (sequence of integers)

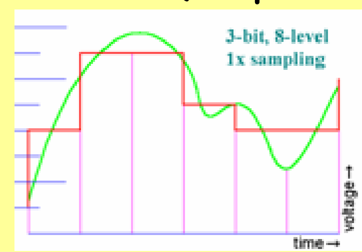
<u>way of storing signals in a form suitable for transmission and computer processing</u>

Analog signal:
continous variable

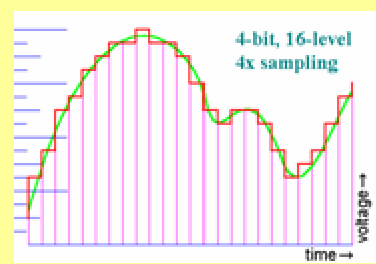


Digital signal:
discrete variable (sequence if integers)

Analog to digital conversion



low sample frequency

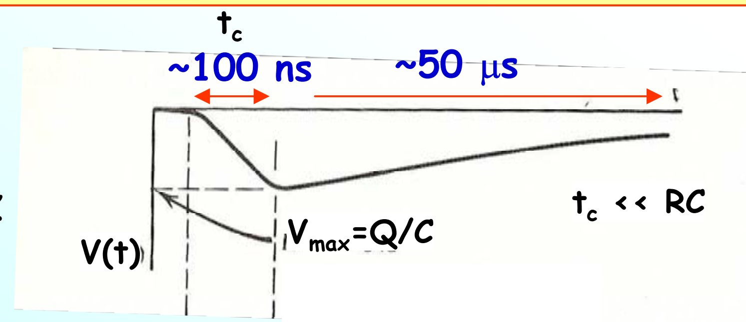


high sample frequency

Precision in digitization:
- sample frequency
- bits used to represent the integer

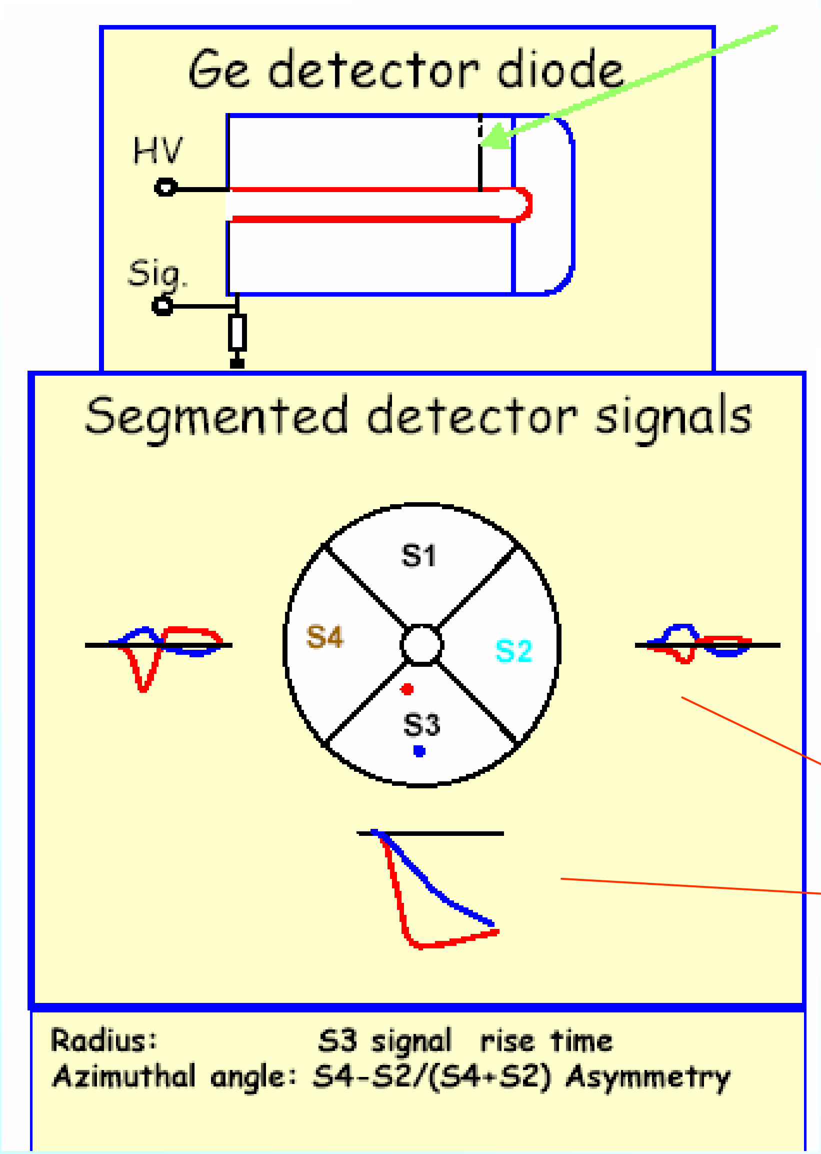
t_c = 100 ns = 10^{-7}s

Sample frequency ~ 100 MHz
14 Bits = 2^{14} = 16384



Analog signal
from **Ge** detector pre-amplifier

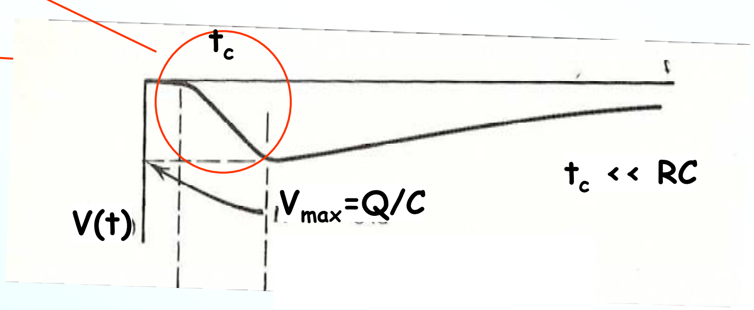
Pulse Shape Analysis (PSA)



The charge collection process induces signals with **Shapes & Amplitude** depending on the interaction point

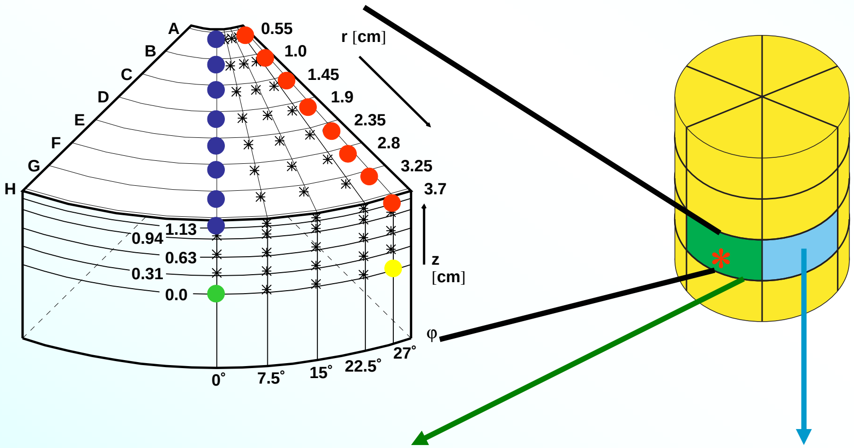
detailed study of **preamplifier signals**

particularly the **leading edge**, which carries information on the charge collection time



Pulse Shape Analysis (PSA)

Analysis of **amplitude & shape** of recorded signals in each segment allows to determine the **3-dimentional position** of interaction point

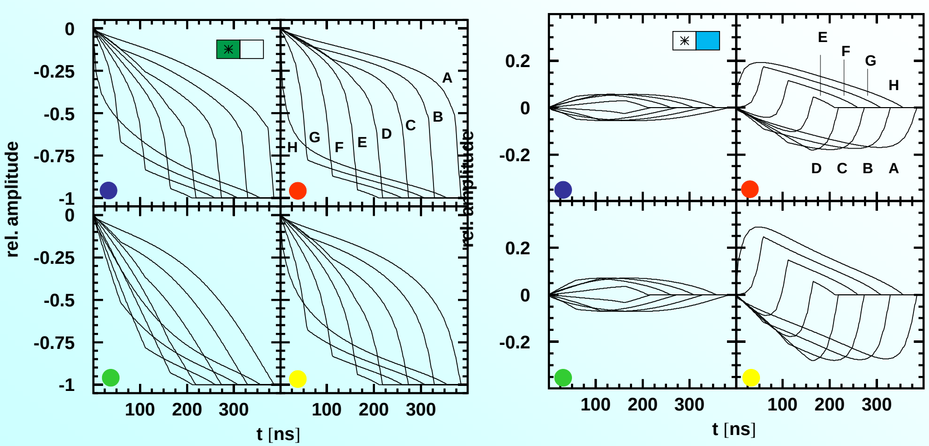


Procedure:

1. The charge collection process induces signals with **Shapes & Amplitude** depending on the interaction point
2. **Shapes & Amplitudes** can be calculated rather well using finite elements analysis
3. ***Genetic algorithms*** are used to determine points of interactions with ~2 mm precision

net charge signals ($Q \neq 0$)

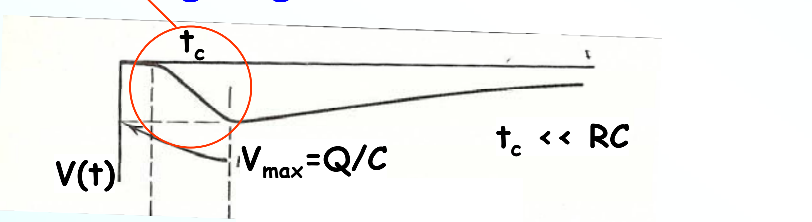
transient signals ($Q=0$)



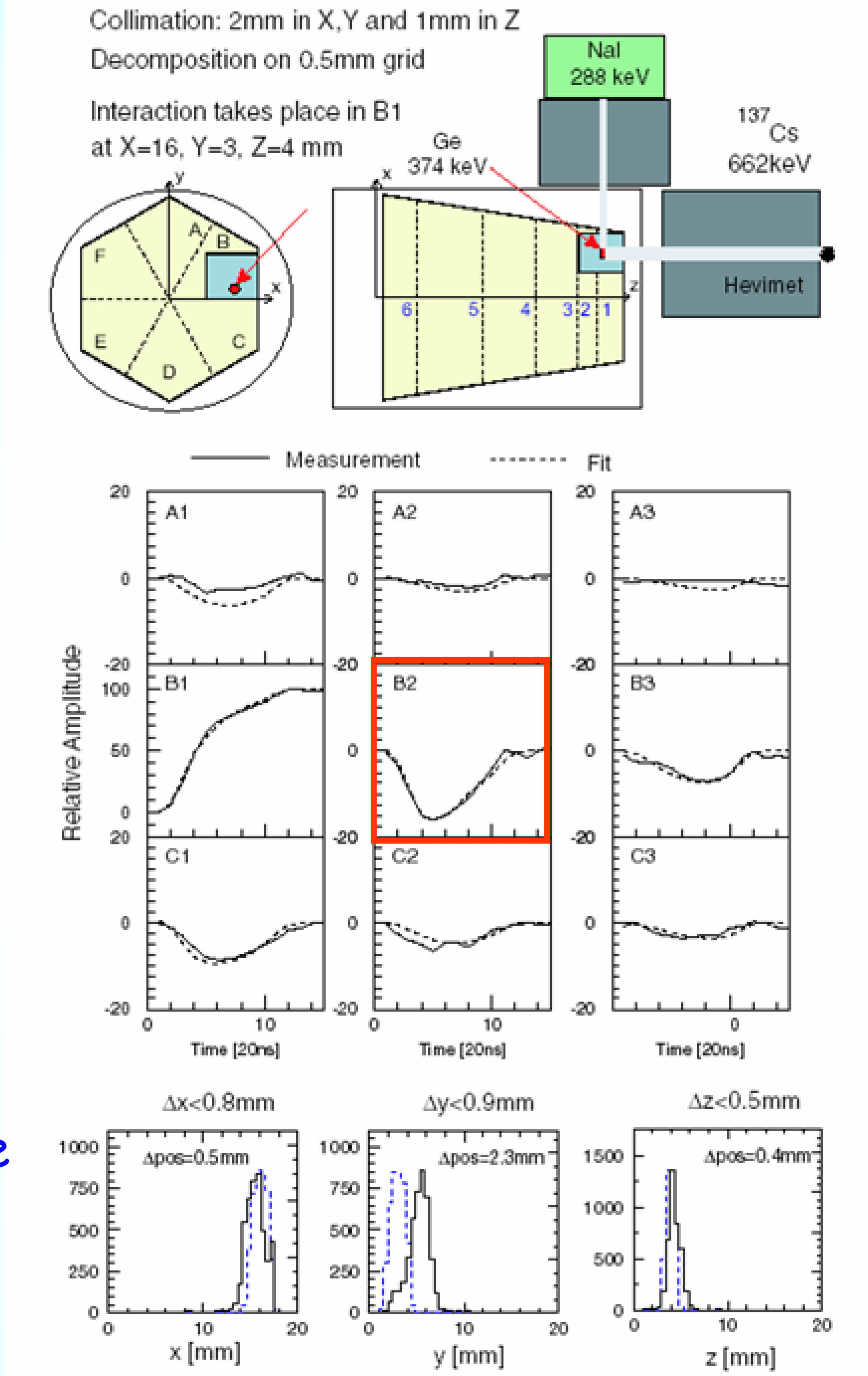
leading edge signals from PREAMP

Digital electronics is needed to sample preamplifiers signals with fast ADC (100 MHz, 14 bits)

Only the subset of samples relative to the **leading edge** is transferred to ACQ



AGATA detector scanning



Full scan in 1 mm^3 grid almost impossible

→ define characteristic points to calibrate calculations

Tracking Principle

*determination of **individual γ-rays interactions***
*and **scattering sequence** in time order*

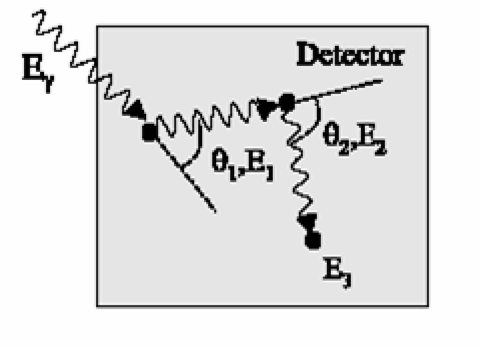
NOT possible with timing measurements:

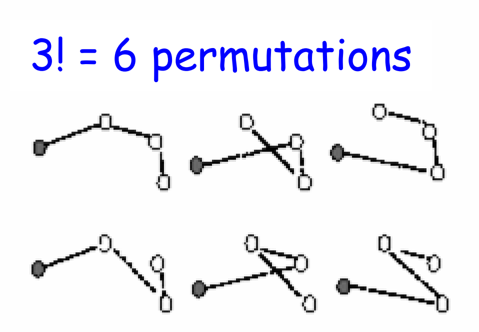
interaction distance: $d \sim 1$ mm-1 cm
interval between interactions: $t = d/(c/\sqrt{\varepsilon_r \mu_r}) \sim (10^{-2}\text{-}10^{-3} m)/(3\times10^8/(\sqrt{16\times100})\, m/s)$
$= 0.1\text{-}1.2$ ns

Ge time resolution: $\tau \sim 5$ ns $\gg t$

$\Rightarrow$ *individual interactions are seen in coincidence*

Solution: reconstruction of interaction path via **tracking algorithms** based on **i)** Compton scattering (dominant process), **ii)** pair production and **iii)** photoelectric interaction.

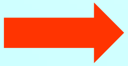




exact sequence is determined by Compton scattering laws

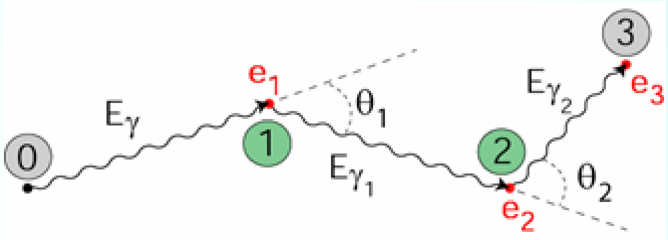
$$E'_\gamma = \frac{E_\gamma}{1 + (E_\gamma / m_0 c^2)(1 - \cos\theta)}$$

Required position resolution: 1-2 mm & Required energy resolution : 2-3 keV

 Position resolution is achieved with Pulse Shape Analysis

γ-ray tracking

Given the interaction points (PSA) one has to identify the sequence of interactions points belonging to each individual photon

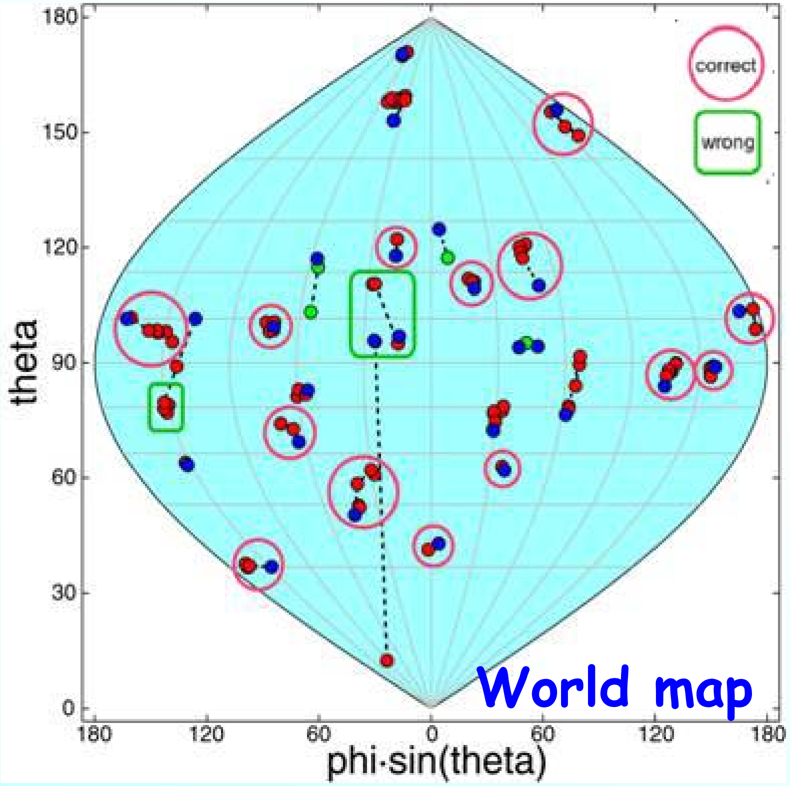


Basic formula is Compton scattering

A high multiplicity event

E_γ=1.33MeV, M_γ=30

in ideal Ge shell



Tough problem!

especially for high-multiplicity events

Tracking methods

1 – Cluster (forward) tracking

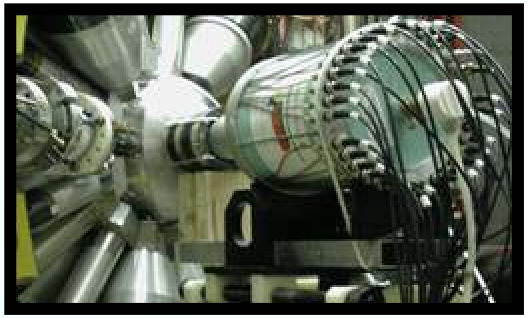
2 – Backtracking

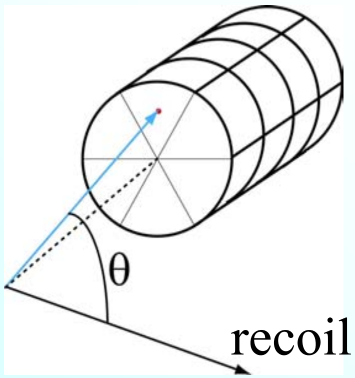
3 – Other approaches

(fuzzy tracking, etc.)

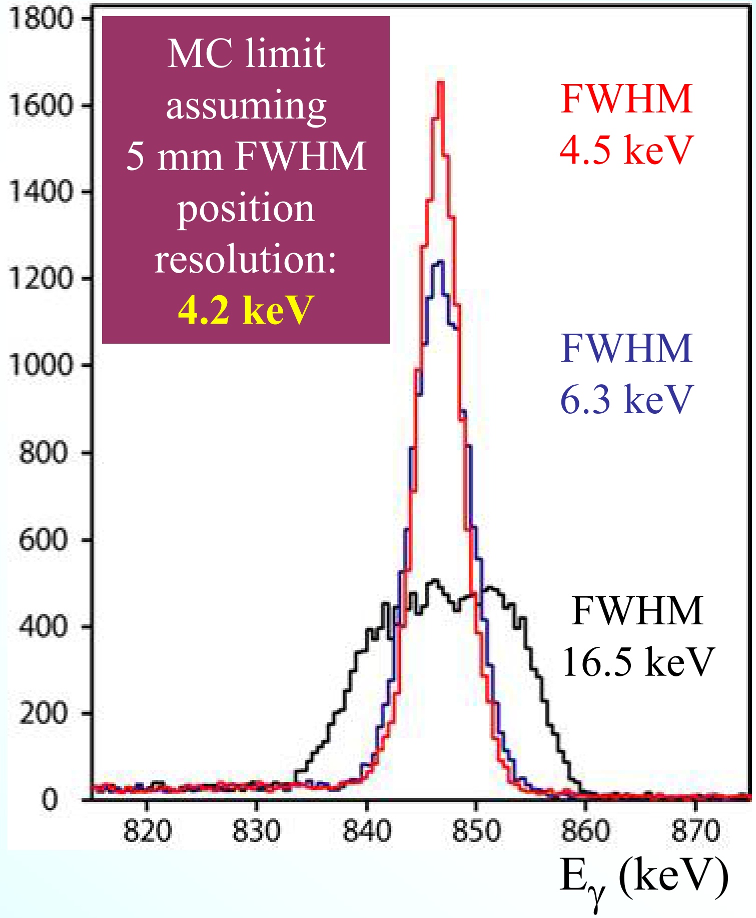
In-beam test of PSA: MARS detector (6x4+1) segments

Coulex. of ^{56}Fe at 240 MeV on ^{208}Pb, **v = 0.08c**





$$E_\gamma^{CM} = E_\gamma^{Lab} \frac{1-\beta\cos(\theta)}{\sqrt{1-\beta^2}}$$



Corrected using points determined with a Genetic Algorithm

Corrected using center of segments → 24 detectors with Δθ ≈ **9°**

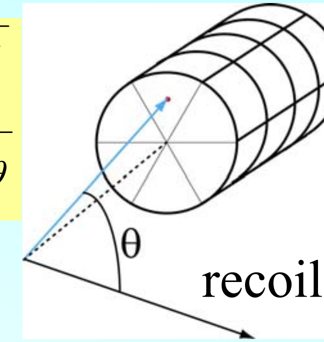
Corrected using center of crystal → one detector with Δθ ≈ **22°**

Position resolution → 5 mm FWHM

Similar result from an experiment done with the GRETA detector

Benefits of γ-ray tracking
(Doppler Correction)

$$E_{\gamma} = E_{\gamma 0} \frac{\sqrt{1-\left(\frac{v}{c}\right)^2}}{1-\frac{v}{c}\cos\theta}$$

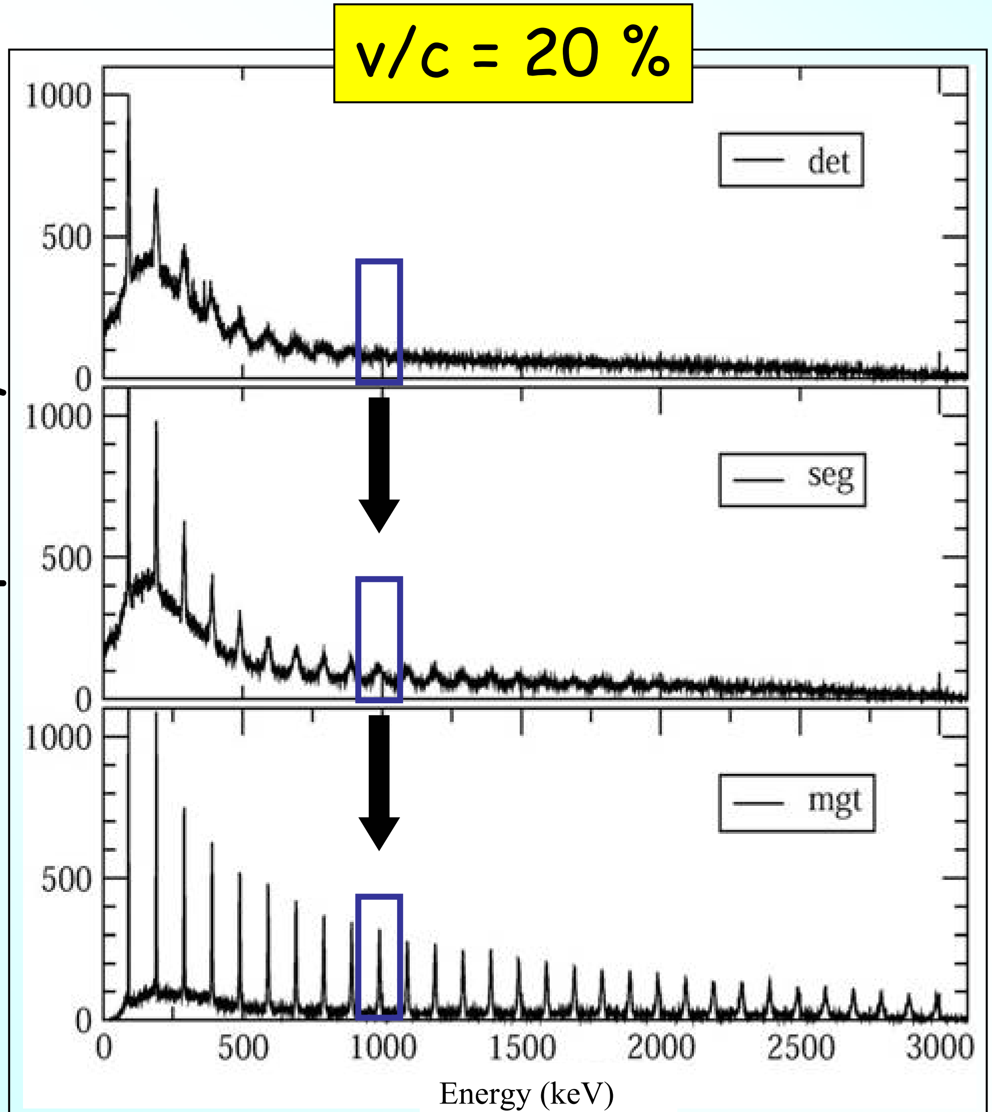


scarce

Definition of the photon direction

Doppler correction capability

good



Detector

↓

Segment

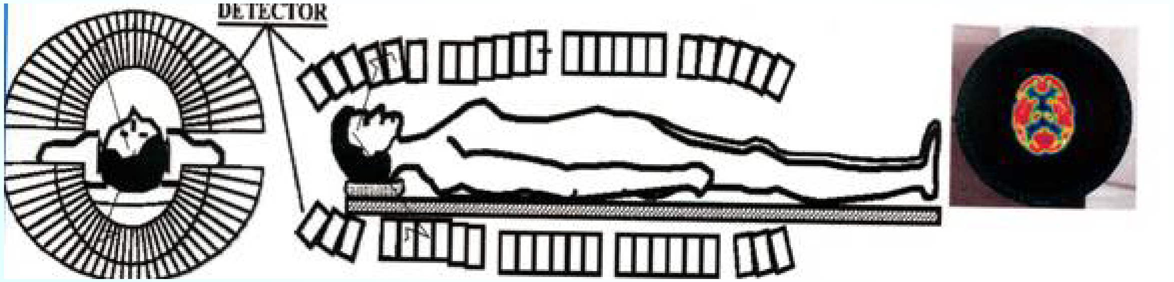
↓

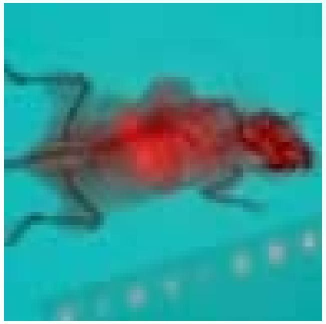
Pulse shape analysis
+
tracking γ

Impact on applied research

- High Energy Astrophysics
- Biomedical Research
- National Security
- Industrial non destructive asessments

Medicine: ultra-low radiation (full body scan)



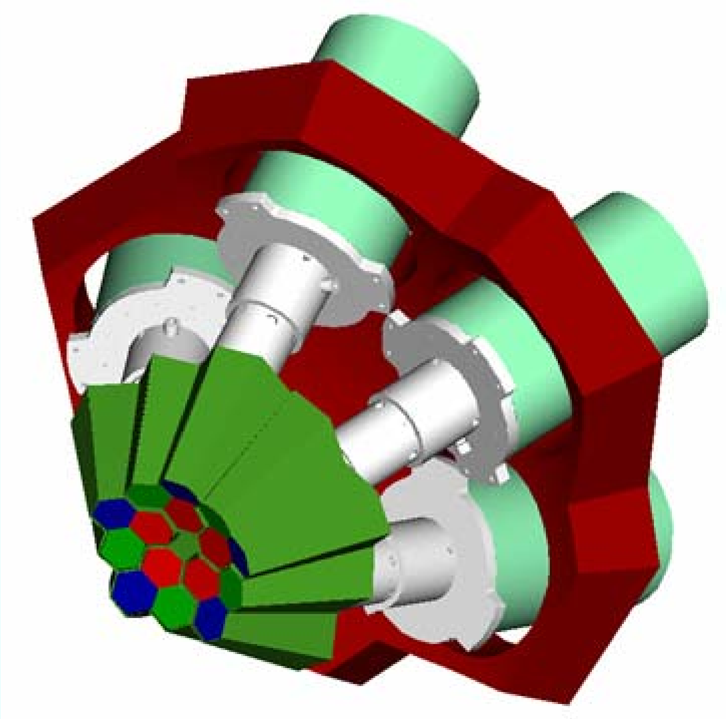


γ-ray source loalization

The First Step:

The AGATA Demonstrator

Objective of the final R&D phase 2008



$\Omega \sim 1/3\ \pi - 2/3\pi$

1 symmetric triple-cluster

5 asymmetric triple-clusters

36-fold segmented crystals

540 segments

555 digital-channels

Eff. 3 – 8 % @ M_γ = 1

Eff. 2 – 4 % @ M_γ = 30

Full ACQ

with on line PSA and γ-ray tracking

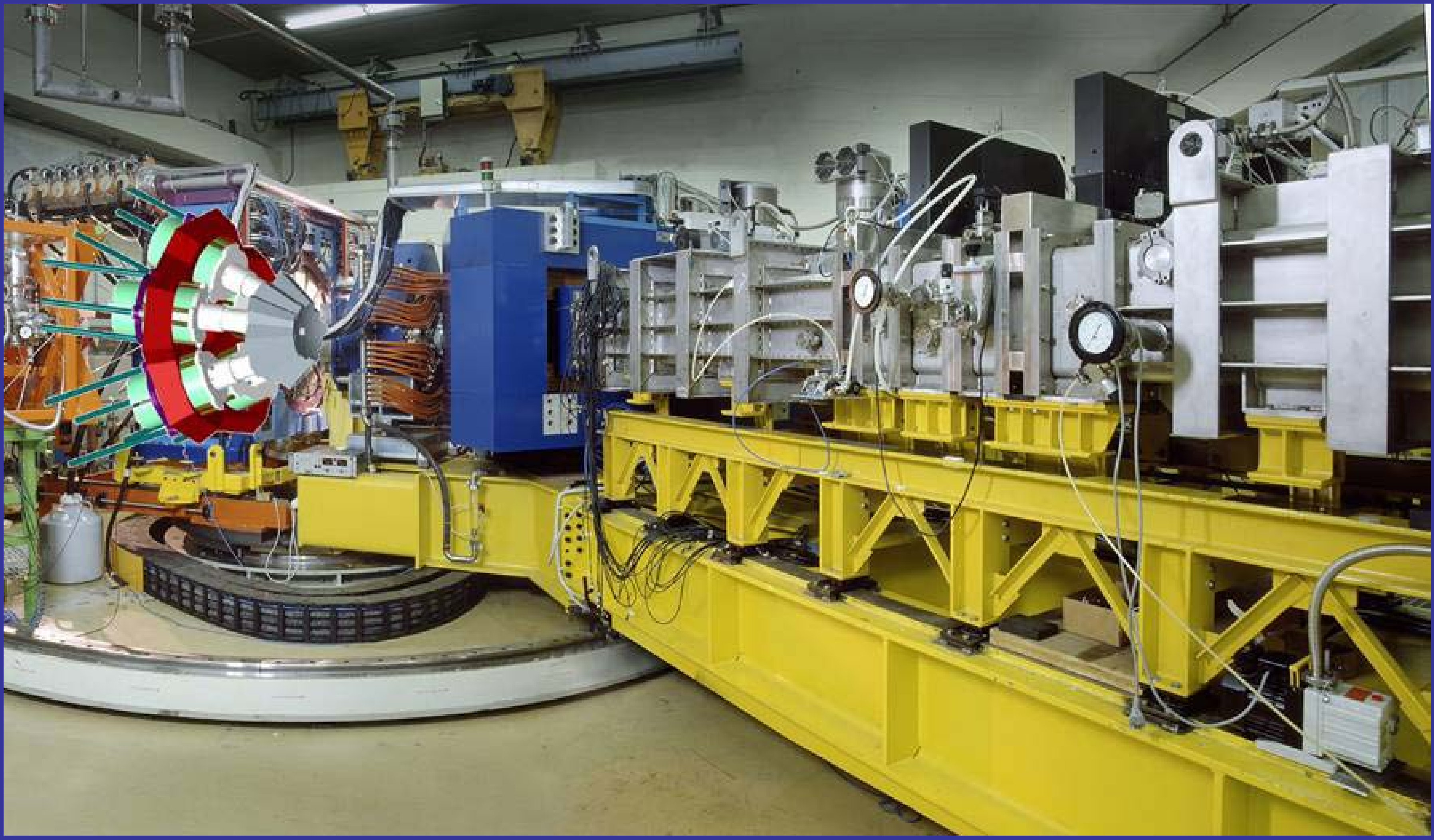
Test Sites:

LNL, GANIL, GSI, Jyväskylä, Köln

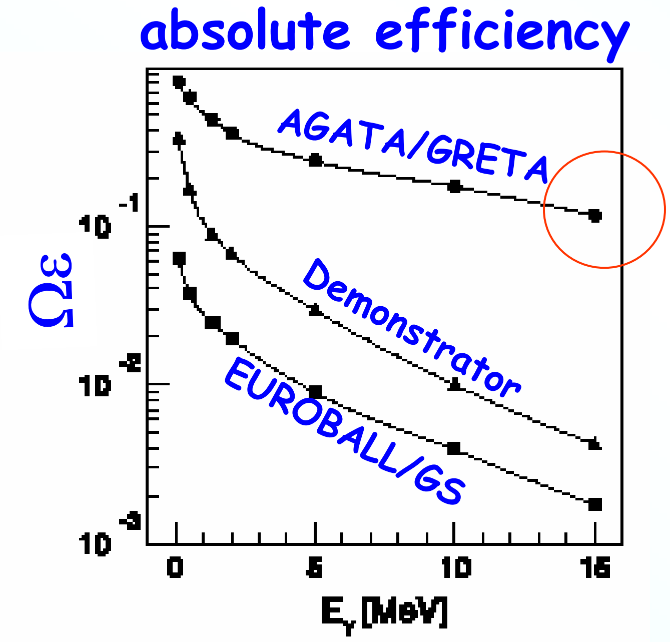
Cost ~ 7 M €

2007-2008: Commissioning & 1st physics Campaign @ LNL with PRISMA spectrometer

The AGATA-PRISMA setup



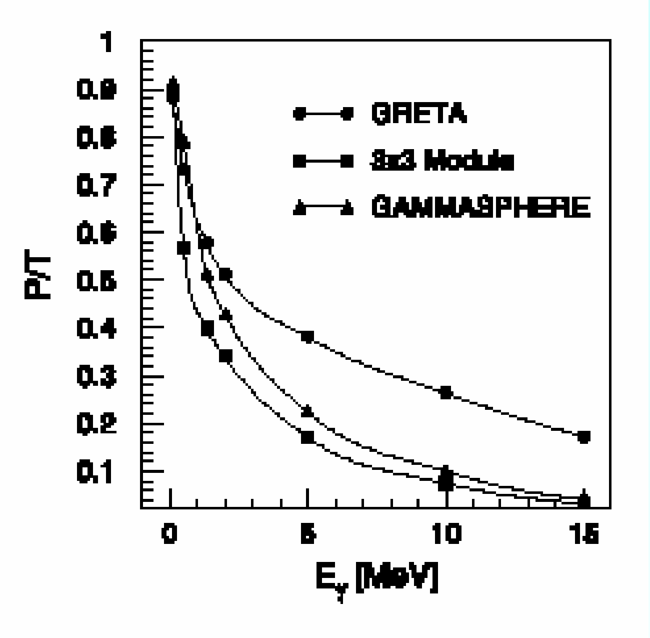
Tracking array performances



comparable with scintillators arrays

n vs. γ discrimination ?

possibly from different clustering of signals



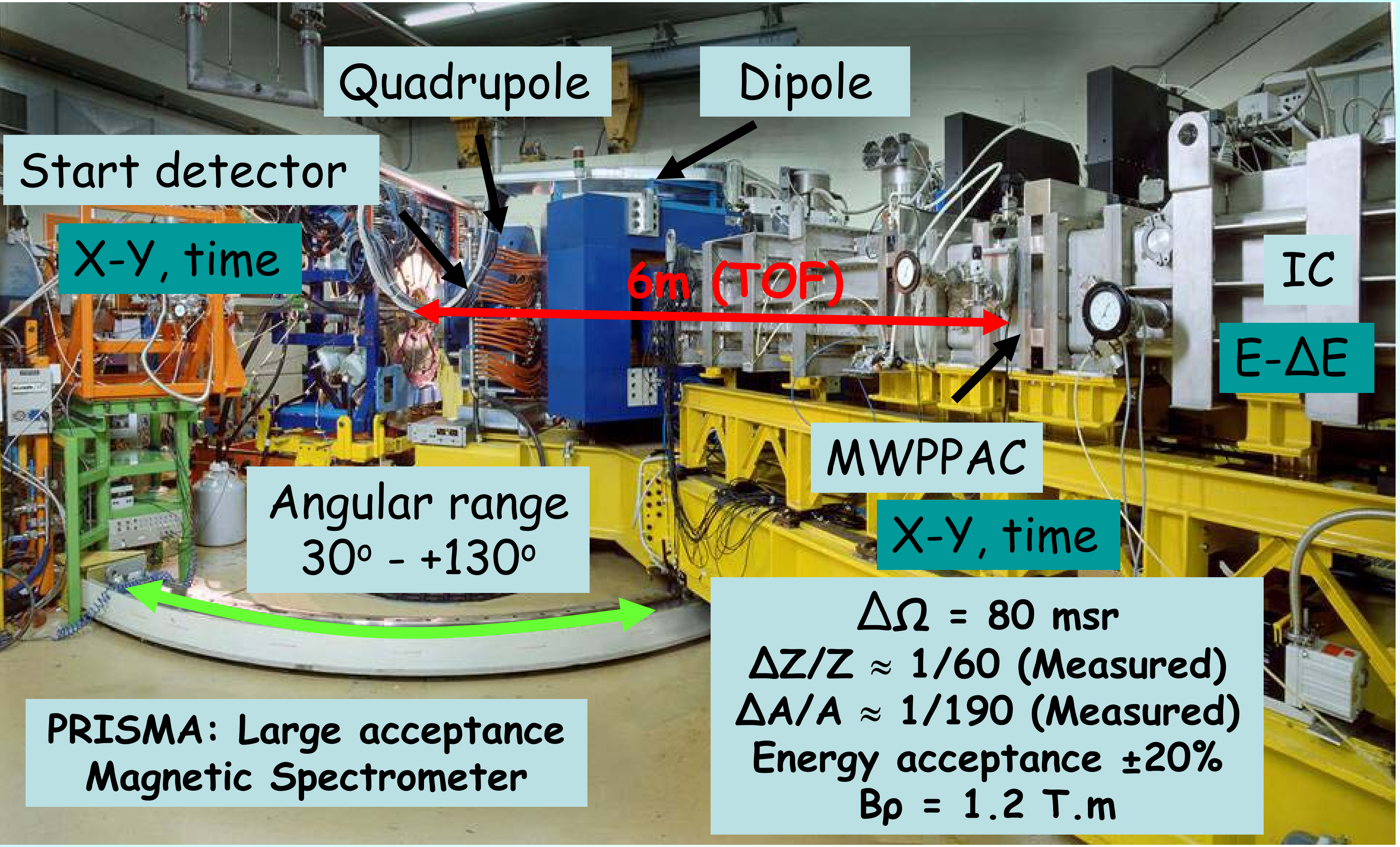
Calculations for 1 γ ray and NO tracking

Event rates will be increased by factor 20:

~ 3 MHz (M_γ = 1) - 300 kHz (M_γ = 30)

as a consequence of <u>shorter processing time</u> & <u>increased number of segments</u>

CLARA-PRISMA setup



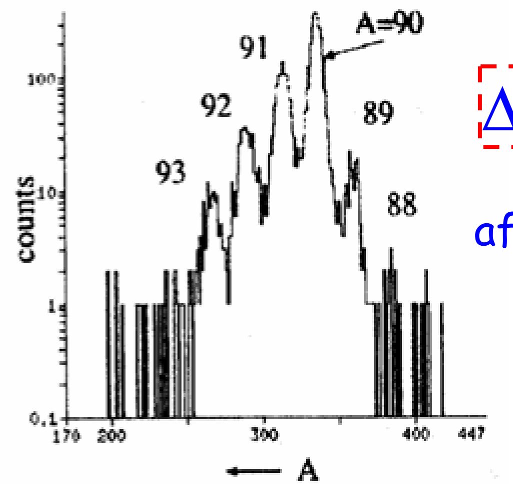
Mass & Energy reconstruction with PRISMA: via TOF

$$M = qB \times \rho / v$$
$$v = S(\theta)/TOF$$

➔ Optical elements + TOF

$$B\rho = p/q$$

$$M/q = (B\rho \times TOF)/S(\theta)$$



505 MeV $^{90}Zr + ^{208}Pb$

ΔA/A=1/280

after ion-tracking reconstruction

➔ Energy loss in IC + residual energy

$$\frac{dE}{dx} \propto \frac{M\,Z^2}{E}$$

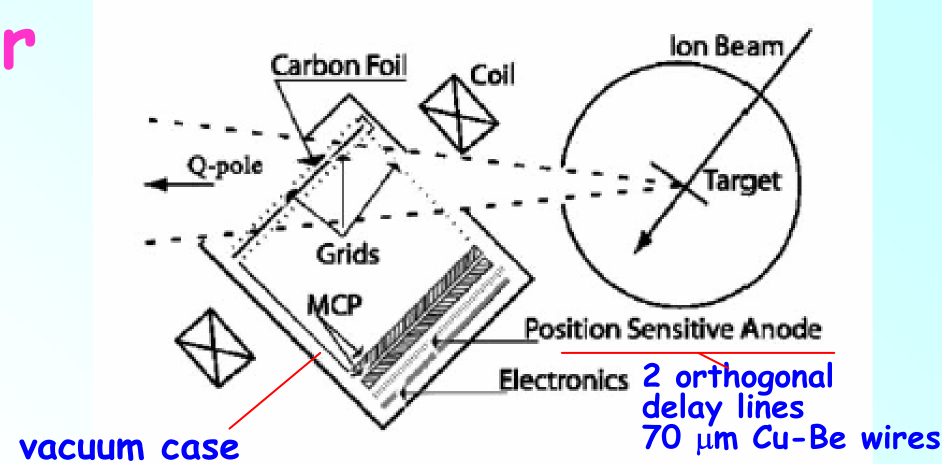
$$E\,\Delta E \simeq M\,Z^2$$

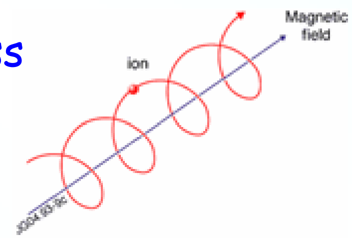
exact identification of mass (**A**) and charge (**Z**) + distinction of charge states (Q)

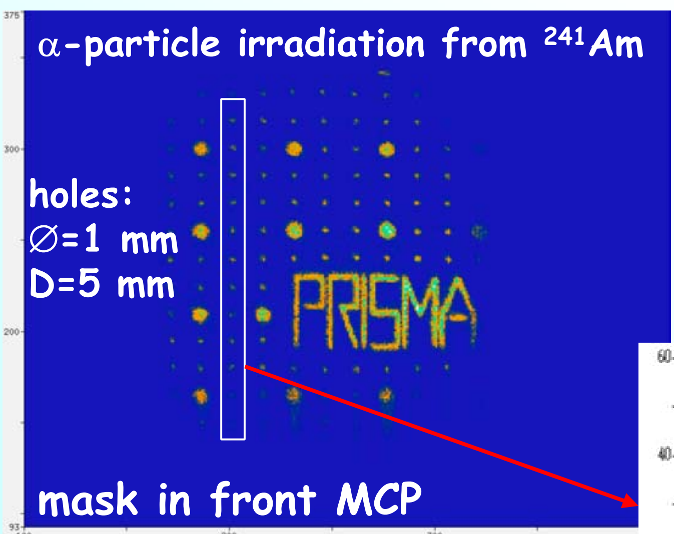
$^{A}_{Z}??^{q+}$

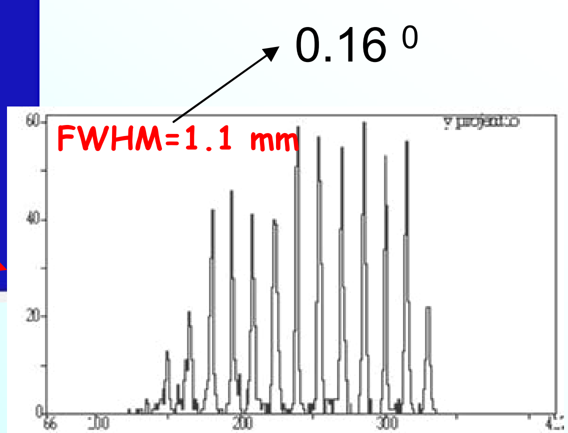
Entrance Position Detector
(Multi Channel Plate)

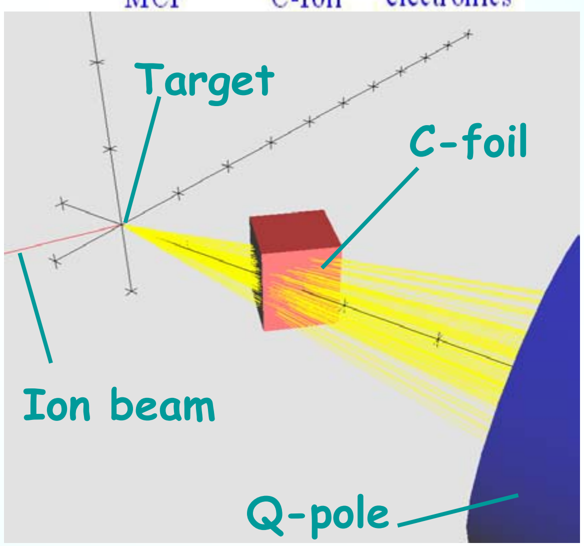
- **active area**: 8x10 cm^2 (Ω=80msr)
  ⇒ full coverage of PRISMA spectrometer
  at **d = 25cm** from target
- **timing resolution** for TOF ~ 350 ps
- **C foil**: 20mg/cm^2 thick
- E_{acc} = 30-40 kV/m
- **parallel magnetic field:** B~120 Gauss
  to limit the spread of electron cloud
  preserving particle position infformation







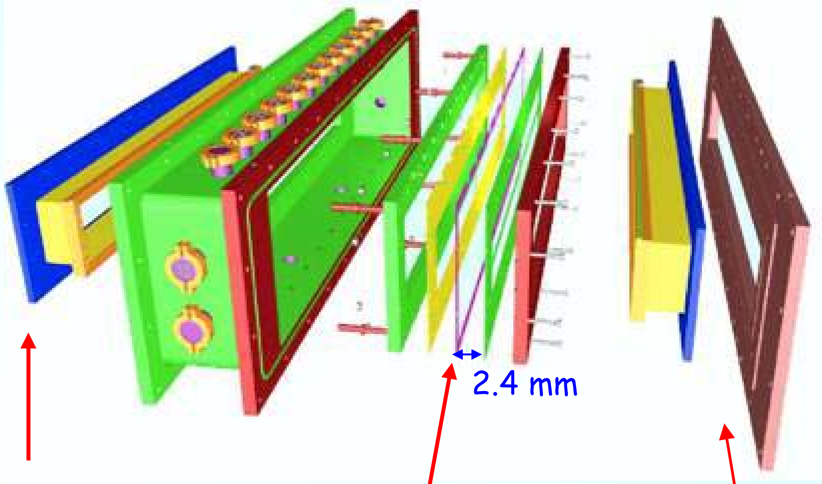




3 signals: x, y, time

Focal Plane Detectors: Multi Wire PPAC

- **active area**: 1m x 13 cm
- **3 electrode structure**:
  central cathod & 2 anodic wire planes (X and Y)
- **cathode**: 3300 wires of 20μm gold-plated tungsten
  0.3 mm spacing
  10 independent sections of 10x13 cm²
  negative high voltage: 500-600 V
- **X plane**: 10 sections of 100 wires each, 1mm spacing
- **Y plane**: common to all cathode,
  130 wires, 1 m long, 1mm steps
- **spatial resolution**: ΔX ~ 1mm, ΔY ~ 2mm (FWHM)
- **stop signal for TOF**



to ionization chambers
mylar foils
1.5 μm

3 electrode structure: 1000 wires

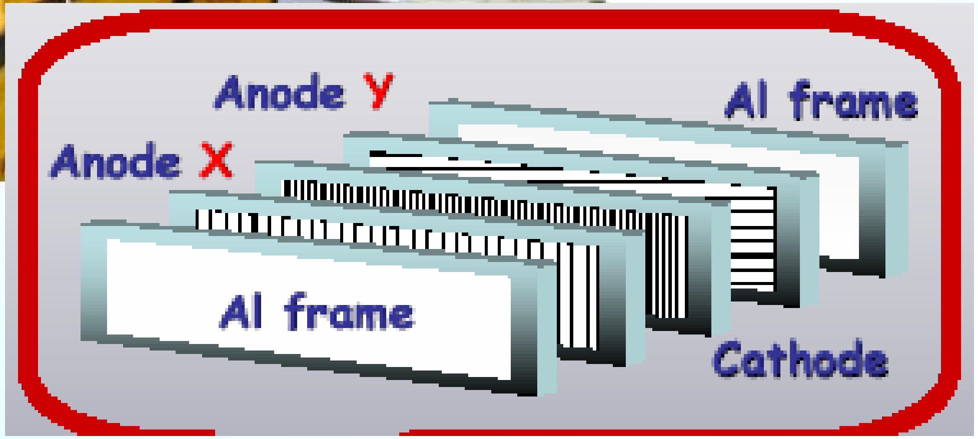
entrance window
mylar foils
1.5 μm

Filling gas: C_4H_{10}

Filling pressure: 7 mbar

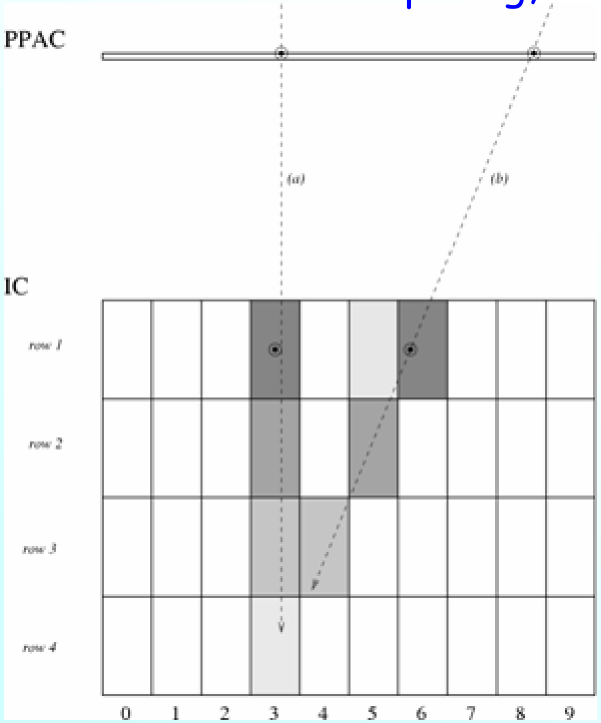
delay-line readout

10 x 3 signals (X_l, X_r, timing)
2 signals (Y_u, Y_d)

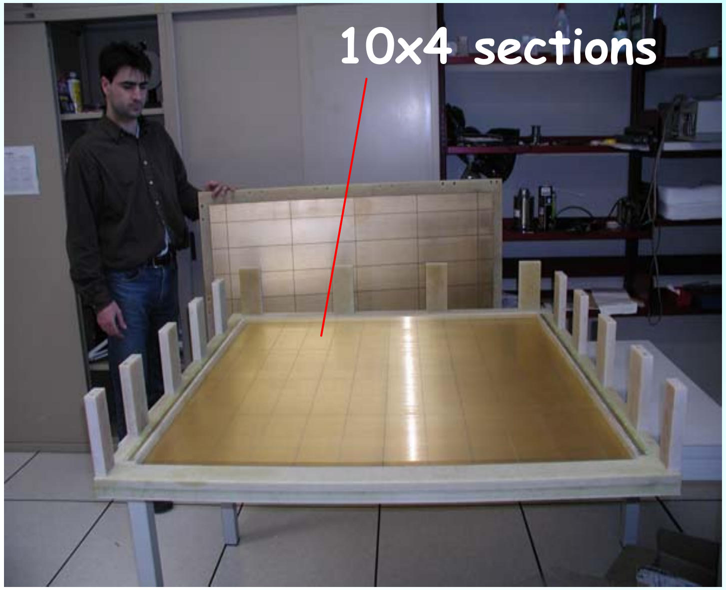

Anode Y
Al frame
Anode X
Al frame
Cathode

Focal Plane Detectors: Ionization Chamber

- 10x4 sections (10x25 cm^2)
- **depth**: 120 cm
- $\Delta E/E < 2\%$
- **anode** & **cathode**: 10x4 sections
- **Frisch grid**: 1000 wires, 100 μm diameter
  1 mm spacing, 1 m long

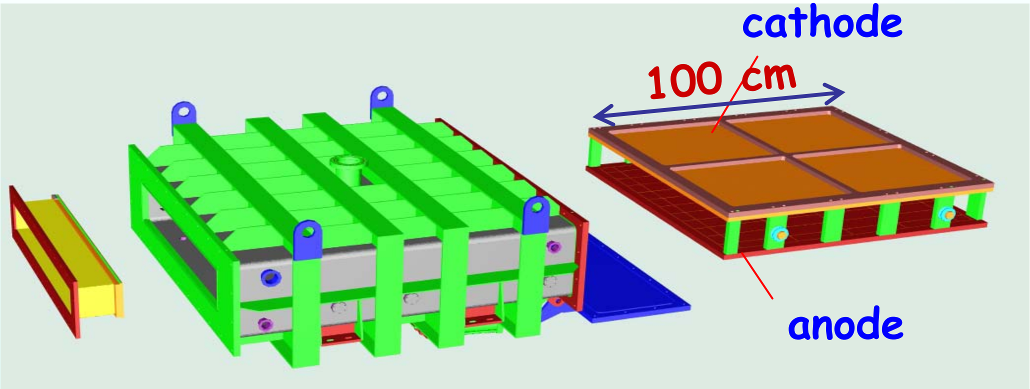


40x2 signals



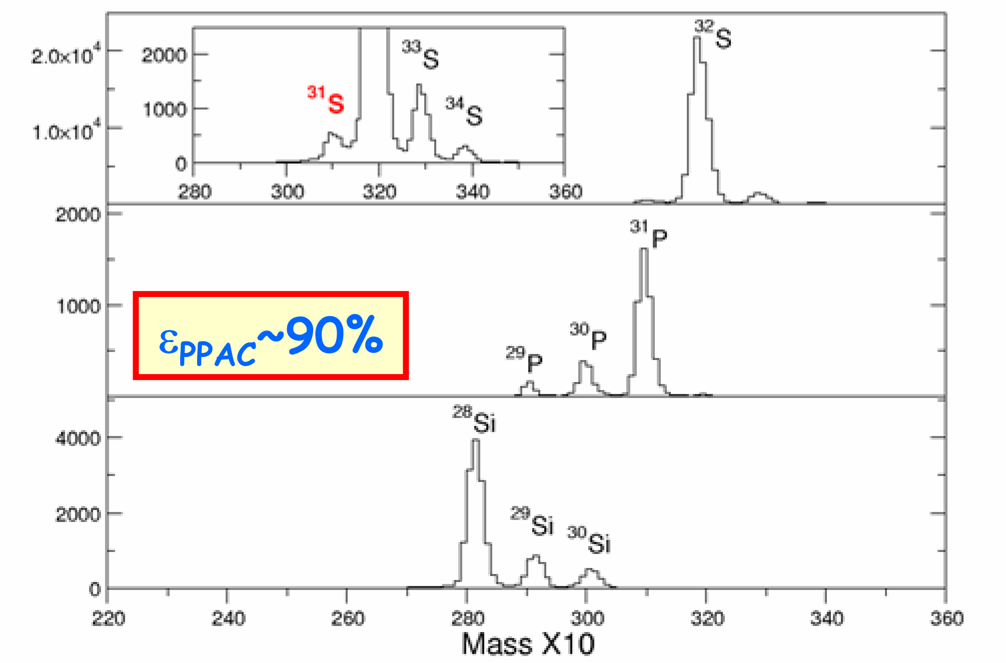
Filling gas: CH_4, 99% purity
(CF_4 for energetic heavy-ions)

Filling pressure: 20-100 mbar



FPD efficiency for light-ions

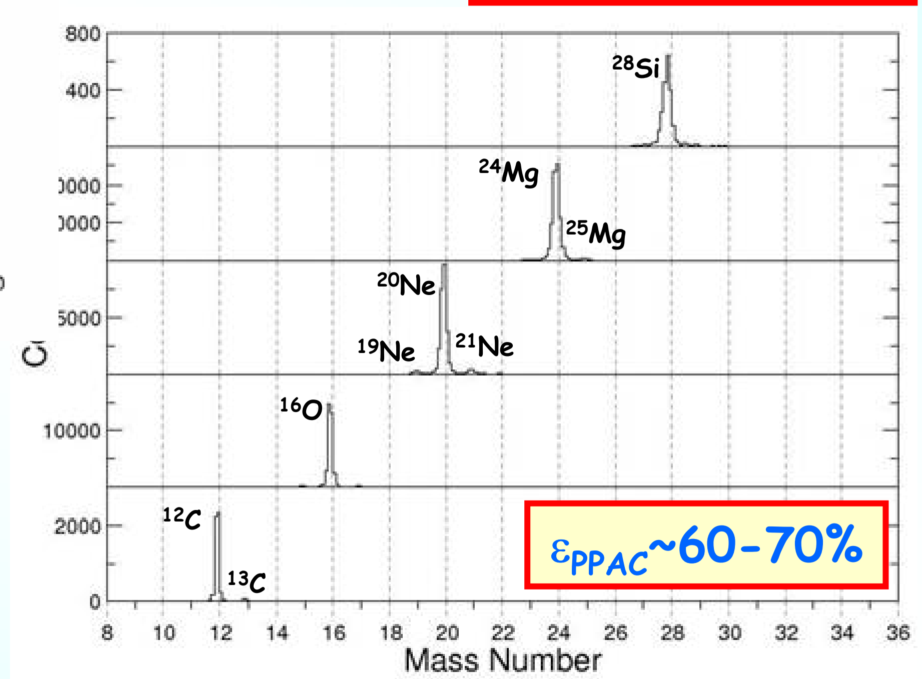
Mass region : A=12-32



ε_{PPAC}~90%

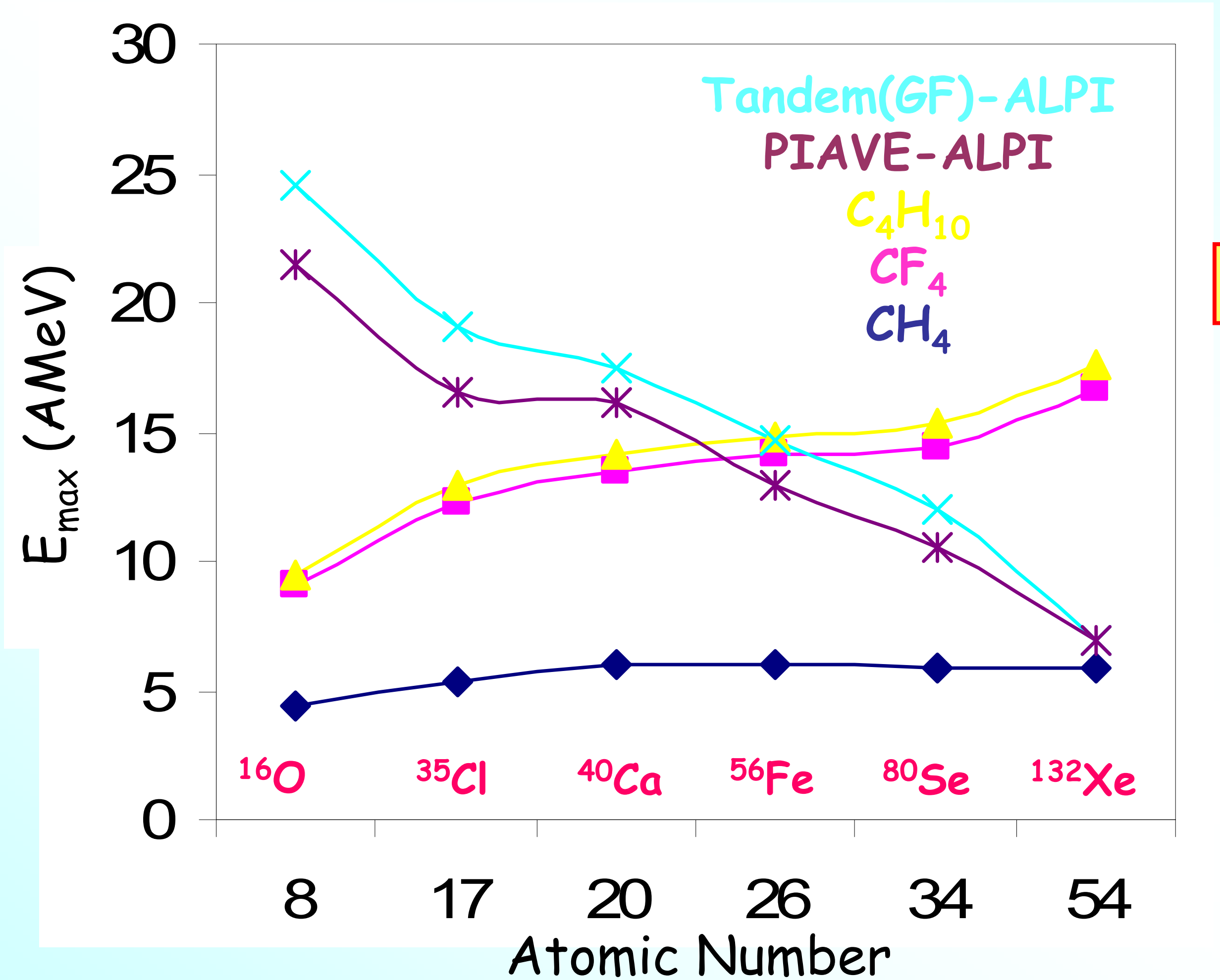
122 MeV $^{32}S+^{58}Ni$

92 MeV $^{24}Mg+^{24}Mg$



ε_{PPAC}~60-70%

Maximum energy stopped into the IC



CF_4 Si
100 hPa ~ 168 mm

14 AMeV ≤ E_{max} ≤ 16 AMeV

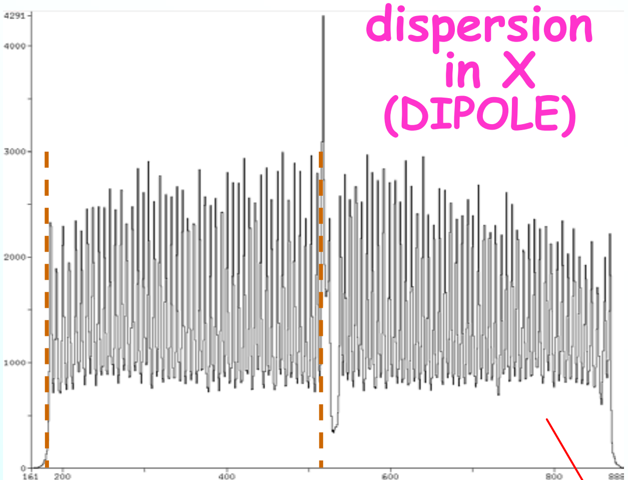
CH4 Si
100 hPa ~ 59 mm

E_{max} ~ 6 AMeV

160 MeV $^{16}O + ^{186}W$ PRISMA @ 40° <q>~8
154 MeV ^{16}O ions → 110 hPa
B_{Dipole} ~ 68% - $B_{Quadrupole}$ ~ 60%

Focal Plane Detectors: in-beam tests

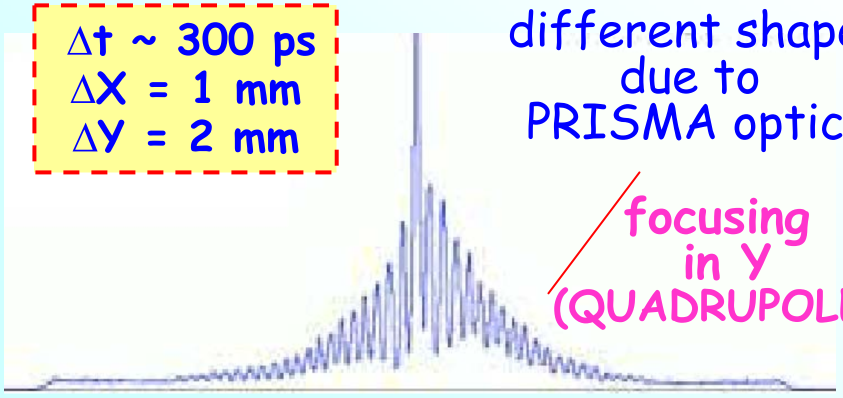
MWPPAC (ε ~ 100%)



X position (channels)

different shapes
due to
PRISMA optics

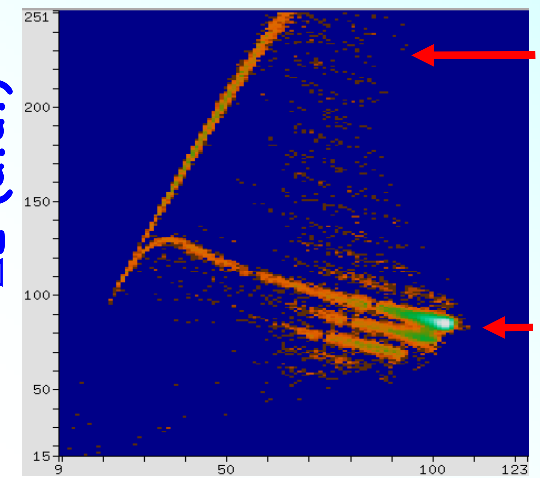
Δt ~ 300 ps
ΔX = 1 mm
ΔY = 2 mm



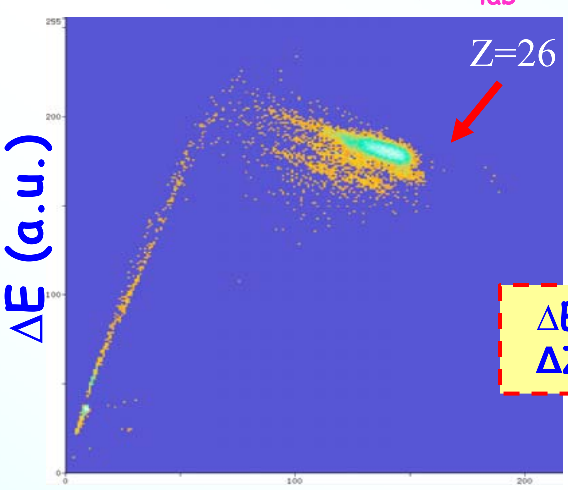
Y position (channels)

IC

195 MeV ^{36}S + ^{208}Pb, Θ_{lab} = 80°



240 MeV ^{56}Fe+^{124}Sn, Θ_{lab} = 70°



ΔE (a.u.)

E (a.u.)

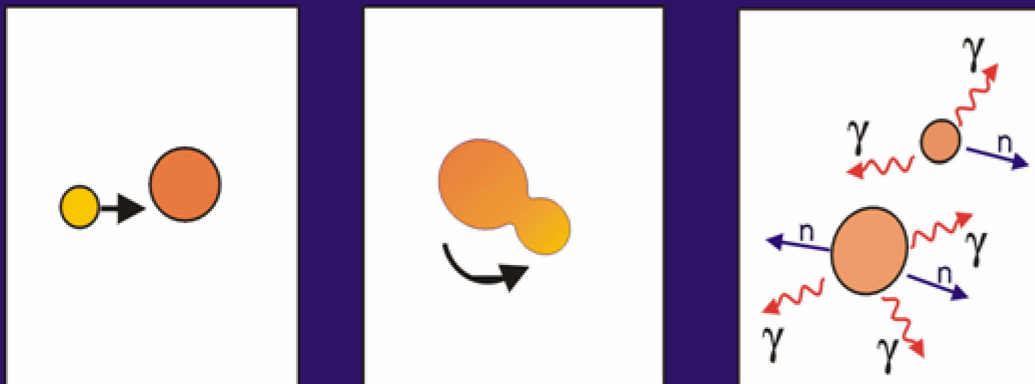
$\Delta E/E$ < 2%
$\Delta Z/Z$ ~ 60

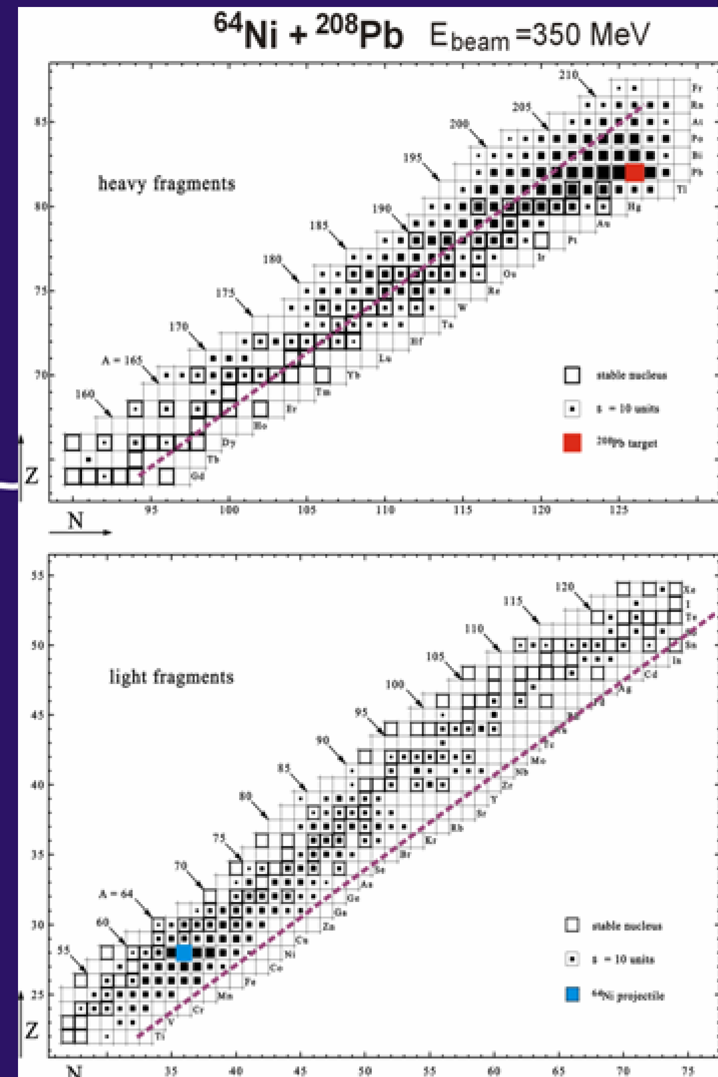
Struttura nucleare nelle misure con il dimostratore di AGATA:

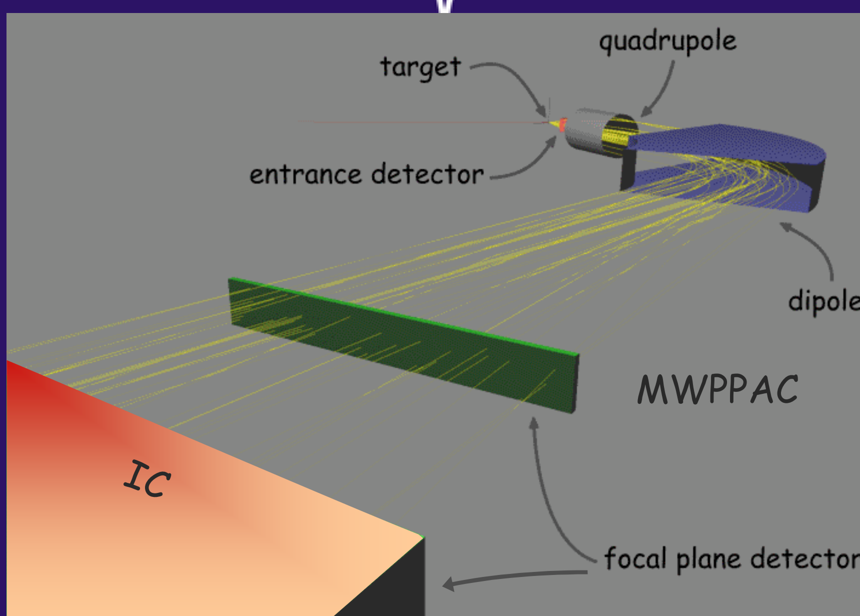
Sfruttano:

- Reazioni di deep inelastic e trasferimento
- Fusione-evaporazione (alto spin)

Deep inelastic reactions
- a tool for nuclear spectroscopy







Future Development:
PRISMA in Gas Filled Mode :
Fusion Reaction

Physics Aim: measurements of evaporation residues
with small σ, recoiling at 0°

⇒ ***need for high transmission efficiency***

Main drawback: loss of mass & energy resolution

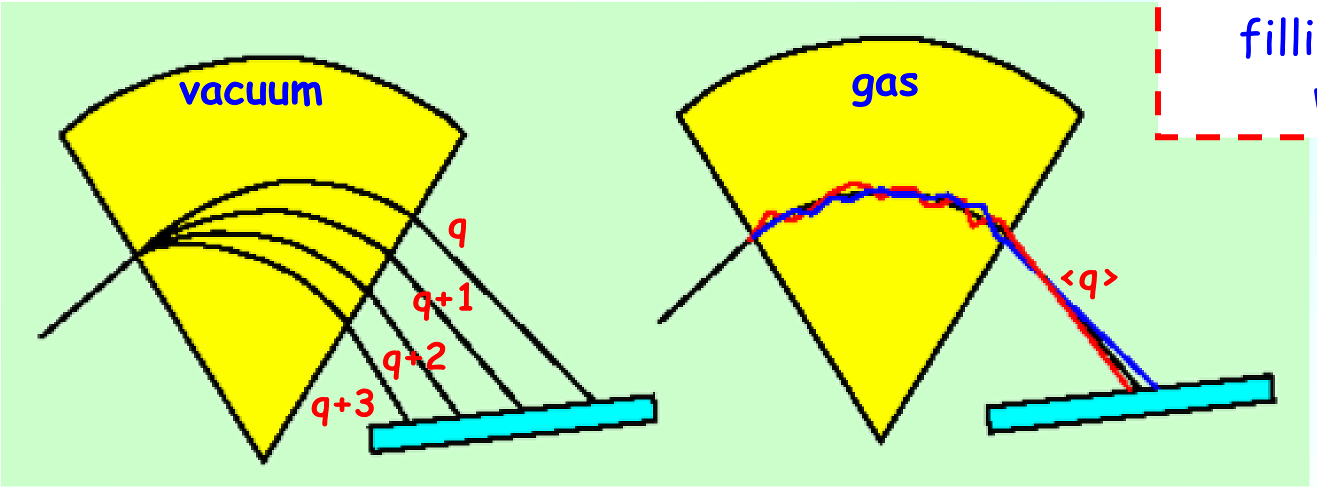
⇒ ***the magnetic spectrometer is used as a separator***

Existing devices: RITU (JYFL), TASCA (GSI), ...
for heavy element study (σ < 1nb)

M. Leino et al., NIMB99(1995)653
T. Back et al., EPJA16(2003)489

Principle of operation

high transmission efficiency can be obtained filling the **dipole region** with a **diluted gas**



- collision between reaction products and gas atoms lead to **charge state focusing**
- trajectory determined by **average ionic charge**

$$B\rho = \frac{mv}{eq_{ave}}$$

$$= \frac{mv}{e\frac{v}{v_0}Z^{1/3}} = 0.0227\frac{A}{Z^{1/3}}Tm$$

v_0 = 2.19 10^6 m/s Bohr velocity

q_{ave}= $(v/v_0)\, Z^{1/3}$ Thomas-Fermi model

- Bρ does NOT depend on v
  ⇒ **energies merge** !!!
- it can be used to get a **rough estimate** of degree of separation between
  → target-like products
  → fusion evaporation residues

example:

$^{40}Ar + ^{175}Lu \rightarrow ^{210,211}Ac + xn$

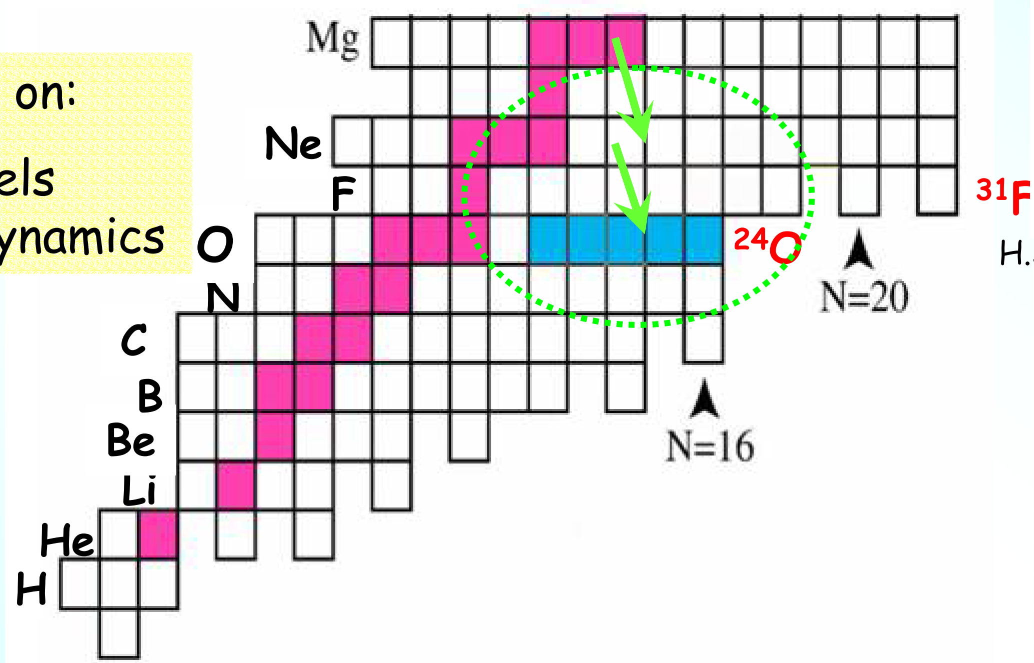
$$\frac{(B\rho)_T}{(B\rho)_{CN}} = \frac{A_T}{A_{CN}}\left(\frac{Z_{CN}}{Z_T}\right)^{1/3} = \frac{175}{210}\left(\frac{89}{71}\right)^{1/3} = 0.89$$

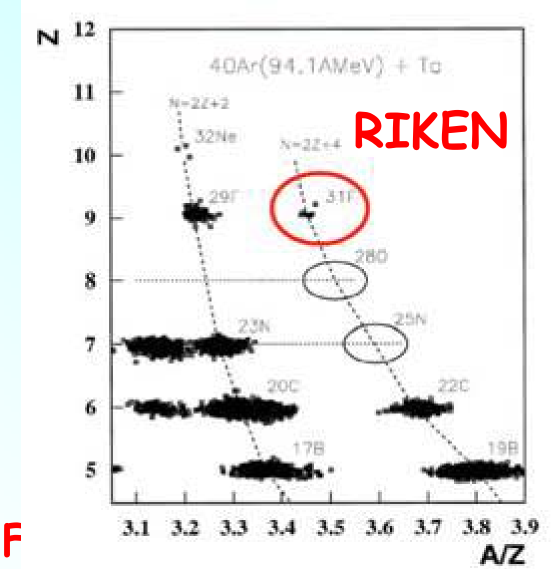
Search for the n-dripline: test of shell model

Population of n-rich Ne, F and O nuclei
with deep-inelastic collisions & multi-nucleon transfer
Milano Proposal at:
LNL/GANIL Associate European Laboratory

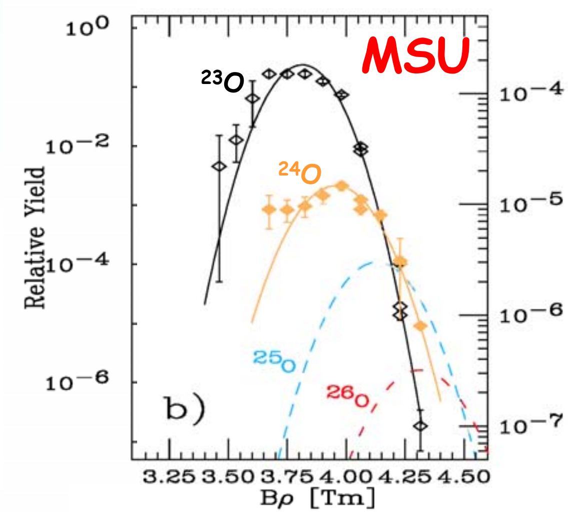
Information on:

- energy levels
- reaction dynamics





H.Sakurai et al., PLB448 (1999) 180

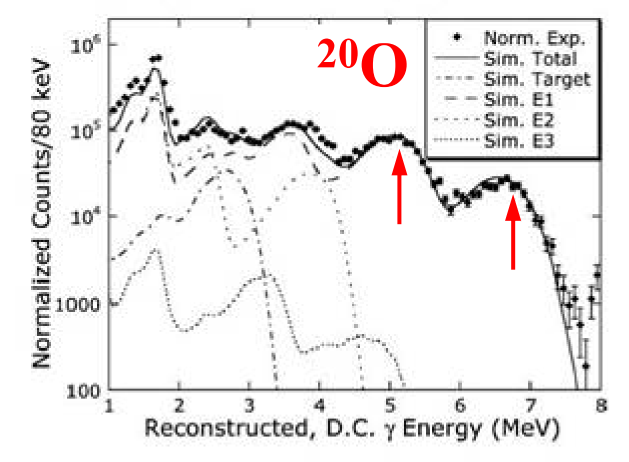


M.Fauerbach et al., PRC**53** (1996) 647

location of n drip line between F and O
is not understood : N=16 for O and N=22 for F

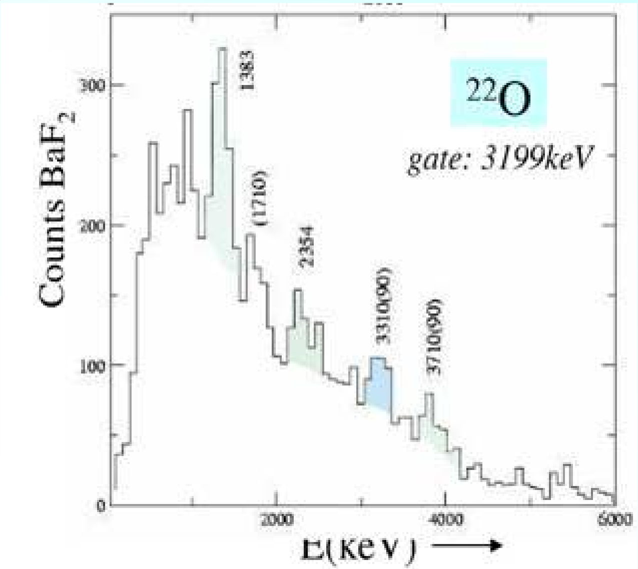
June 2005, GANIL: ^{24}Ne @ 114 MeV + ^{208}Pb, I_{beam} ~10^5
November 2006, LNL: ^{22}Ne @ 130 MeV + ^{208}Pb, I_{beam}~10^{10}
[Letter of Intent, LNL: ^{22}Ne @ 125 MeV + ^{208}Pb]

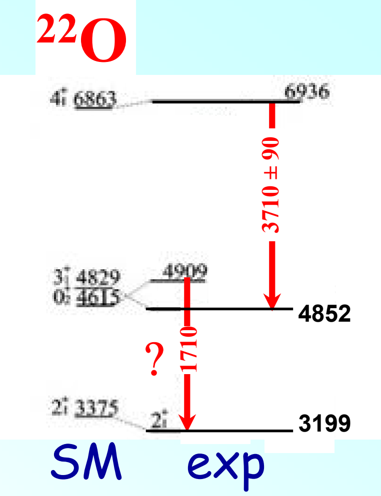
O isotopes: N = 12 and 14



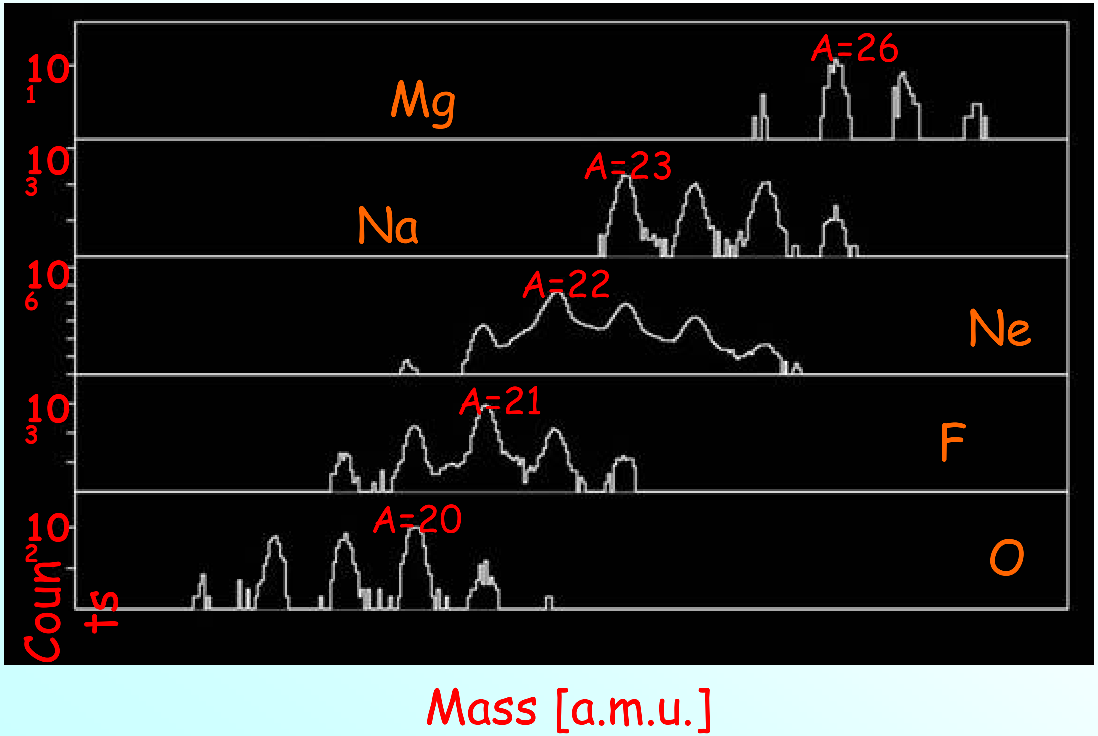
MSU Fascio di ^{20}O

E. Tryggestad et al., Phys. Lett. **B541**, 52-58(2002).





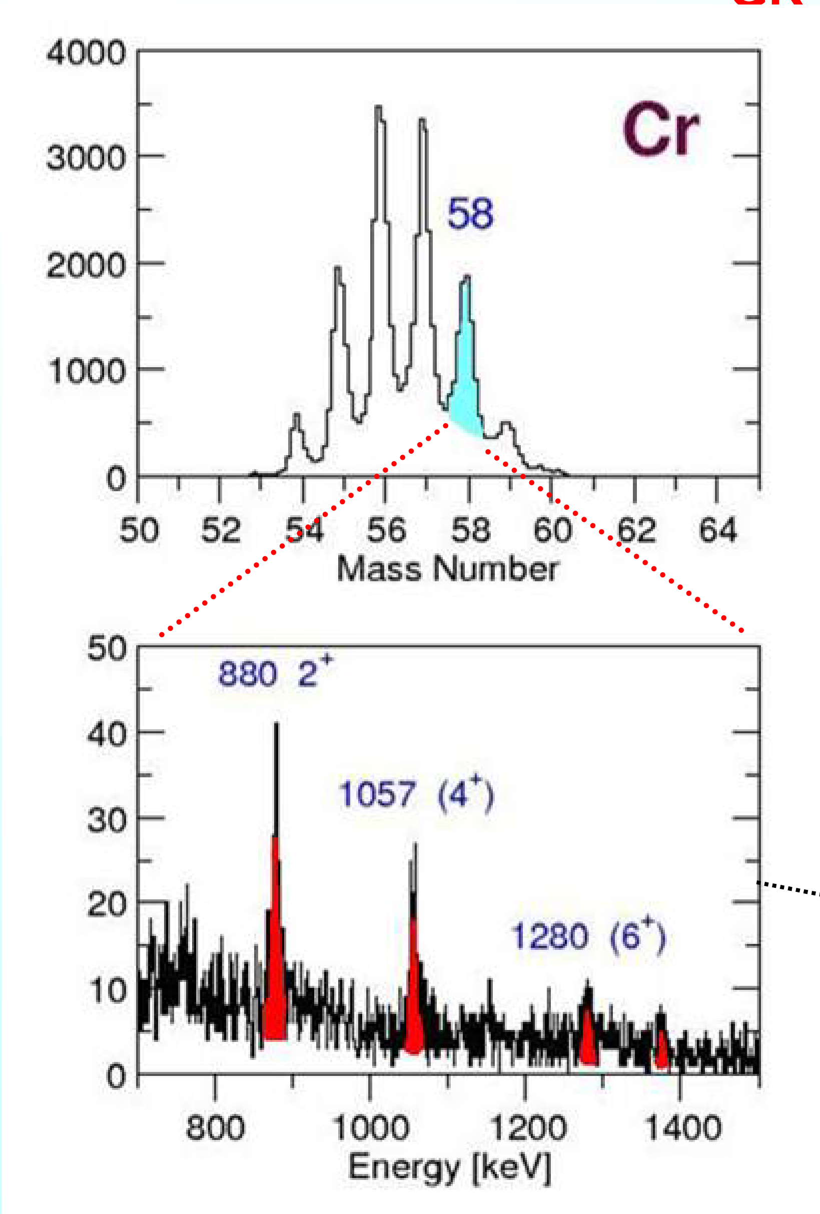
M. Stanoiu et al., Phys. Rev. **C69**, 034312 (2004).

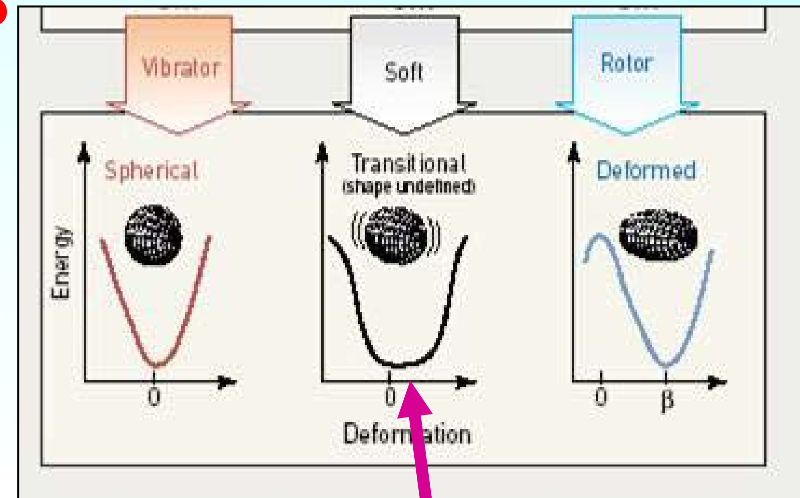


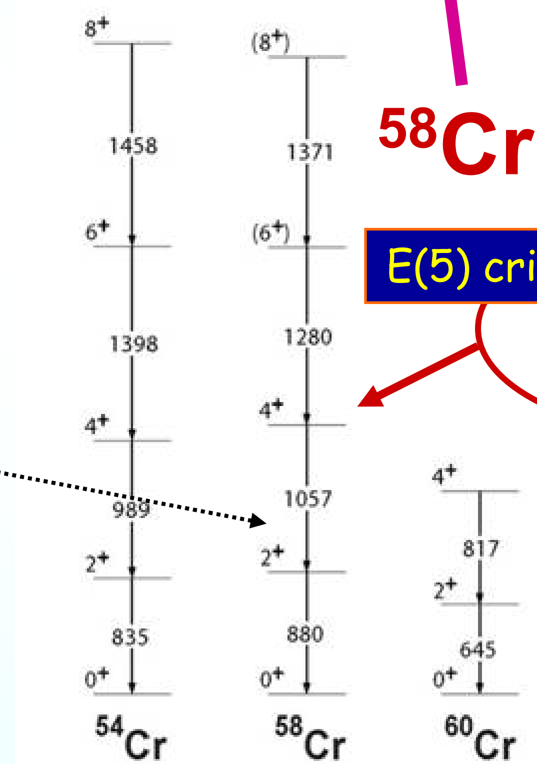
^{22}Ne ALPI-PIAVE

Details: 20 h ^{22}Ne
$I_{beam} \approx 6$pnA
Target: 300 μg/cm^2 ^{208}Pb

^{64}Ni 400MeV + ^{238}U θ_{GR} = 64°







^{58}Cr

E_{4+}/E_{2+} = 2.20

E_{6+}/E_{2+} = 3.65

E(5) critical point symmetr

vibrator to
γ-unstable rotor

F.Iachello

From our data the 1057 keV transition is the $4^+ \rightarrow 2^+$ member of the yrast cascade. Therefore ^{58}Vg.s. is probably 3^+, also predicted at low energies.

CONCLUSIONE

Il programma di fisica con i fasci radioattivi di nuova generazione e' Impegnativo e attraente e ha vome obiettivo il limite della stabilita':

Capire i meccanismi di reazione e' importante per selezionare al meglio la produzione dei nucleo d'interesse e le sue caratteristiche (fasci isomerici etc…) e formare i Nuclei ad alato spin e temperatura

Le proprieta' del nucleo devono essere studiate mediante la sua eccitazione (uso di reazioni) e il corrispondente decadimento gamma

Futuro

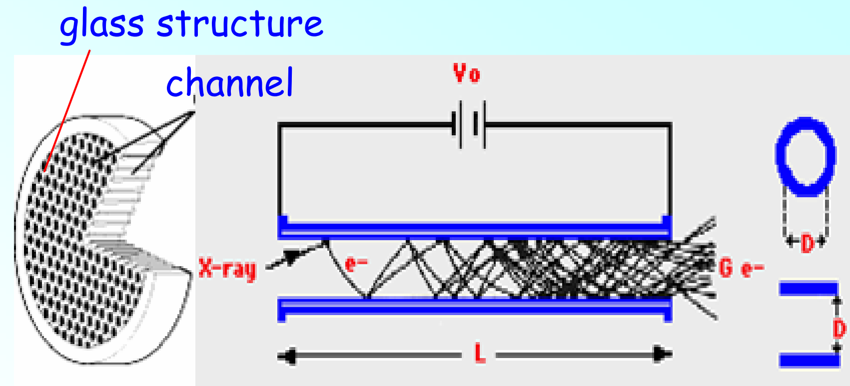
Fasci piu' intensi (10^7-10^9) e in una regione di massa poco esplorata (medium heavy e neutron rich)

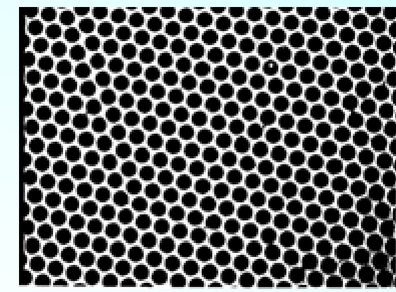
Strumento per formare nuclei esotici ecccitati (fino ad ora poco utilizzato) e' quello delle reazioni di trasferimento e deep inelastic

Spettroscopia gamma con alta efficienza, alta selettivita' e risoluzione

Microchannel plates

- compact **electron multipliers** of high gain
  $G \sim 10^6 - 10^8$
- used in wide range of
  particle and photon detection systems
- ~ 10^7 closely packed channels of common diameter
  (formed by drawing, etching, or firing
  in hydrogen, a lead glass matrix)
- typical channel diameter **D~10 μm**
- each channel acts as
  an independent, continuous dinode photomultiplier
- gain **G** increases with **L/D** (typically 75:1 – 175:1)





performances

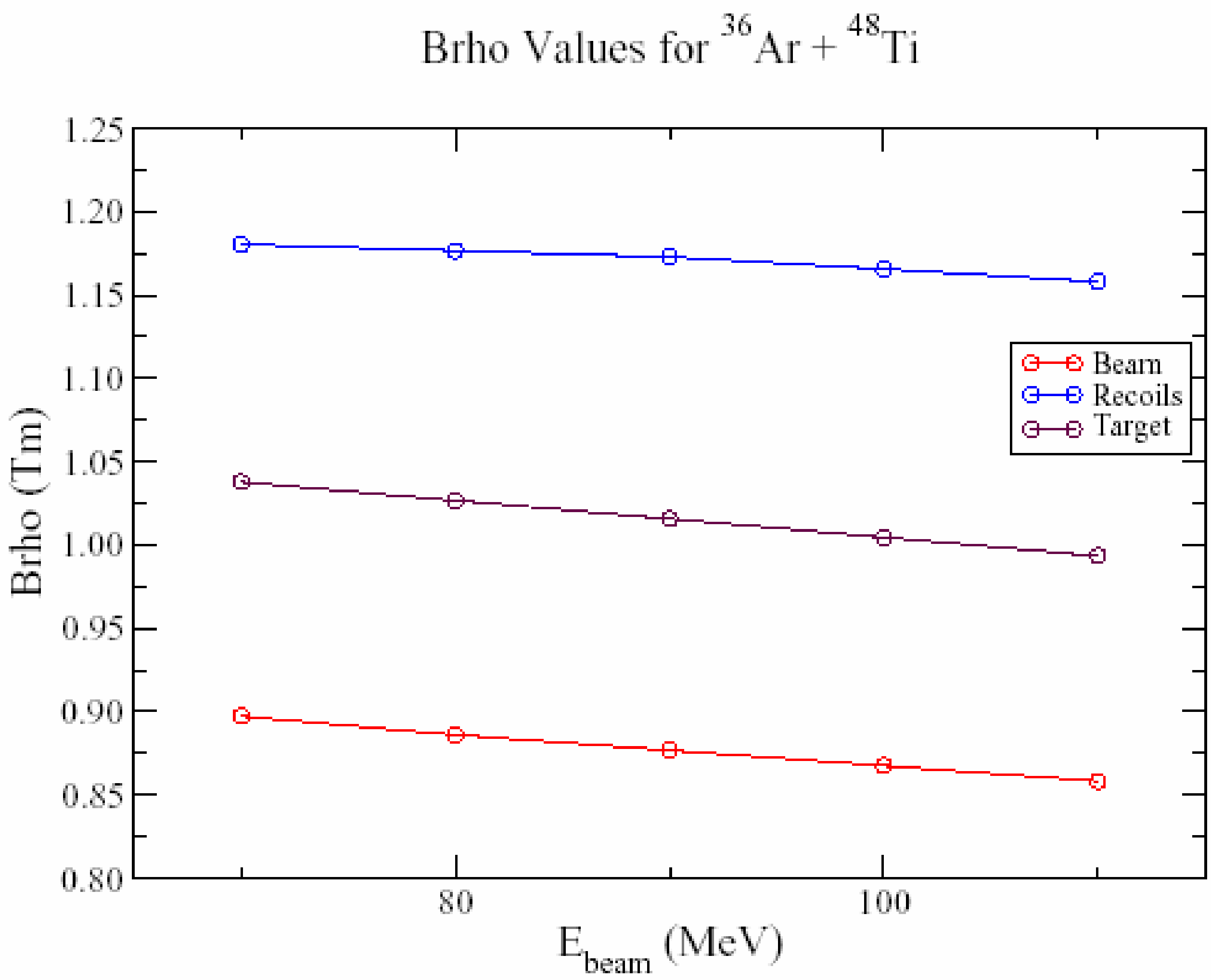
- **efficiency**
  not more than 60% for X-rays
  higher for charged particles
- **time-resolution**
  ultra-high: < 100 ps
- **spatial resolution**
  (limited by channel dimensions & spacing): 12-15 μm
- relative **immunity to magnetic fields**:
  single MCP: completely unaffected in B ≤ 0.5 Tesla
  in stack: completely unaffectd by much higher fields

efficiency

Type of radiation		Detection efficiency (%)
Electrons	0.2 - 2 keV	50-85
	2 - 50 keV	10-60
Positive ions	0.5 - 2 keV	5-85
(H+, He+, A+)	2 - 50 keV	60-85
	50 -200 keV	4-60
U.V. radiation	300 - 1100 Å	5-15
	1100-1500 Å	1-5
Soft X-rays	2 - 50 Å	5-15
Diagnostic X-rays	0.12 - 0.2 Å	~1

J. L. Wiza, NIMA162(1979)587

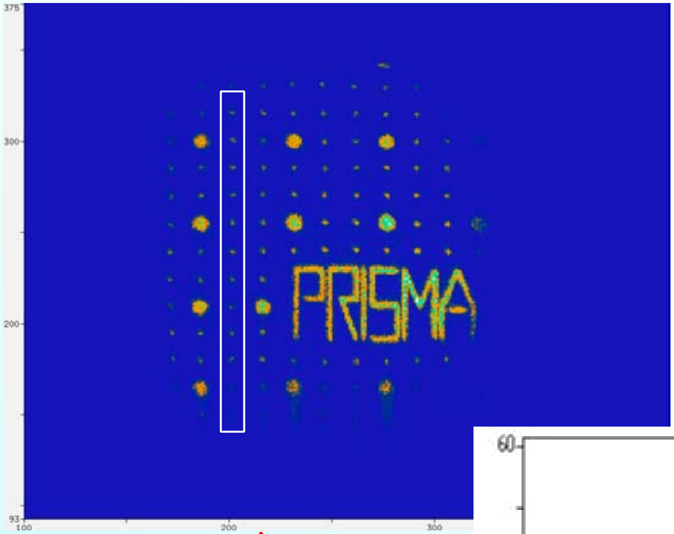
Bρ at the Limit



Entrance Position Detector: MCP

- Micro Channel Plate
- 8x10 cm^2 sensitive area (Ω=80msr)
- Timing resolution for TOF ~ 350 ps

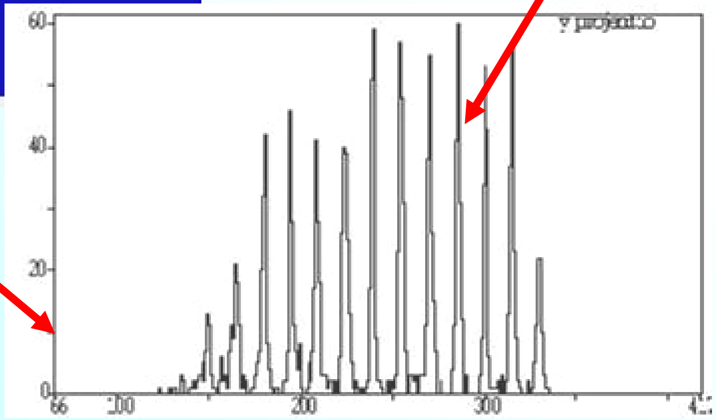
- d_{TARGET}=25 cm
- C-foil 20mg/cm^2 thick
- E_{acc}=30-40 kV/m
- B~120 Gauss

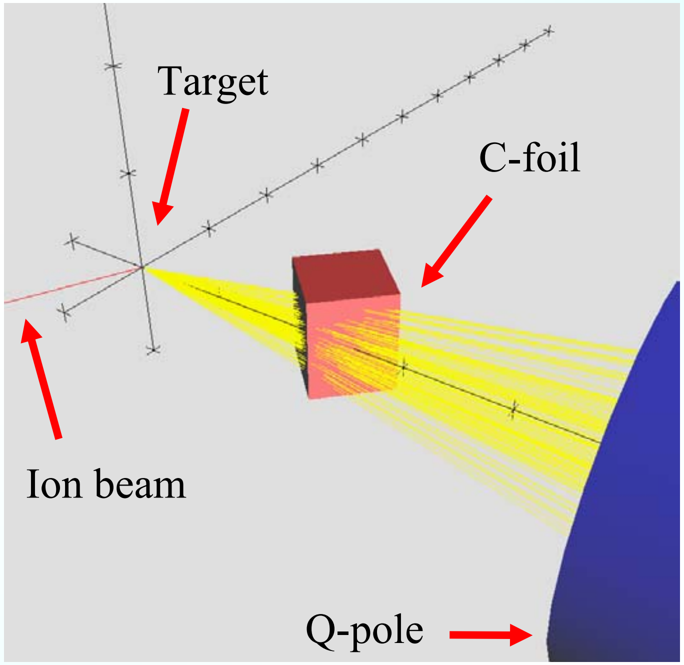


hole diameter 1 mm

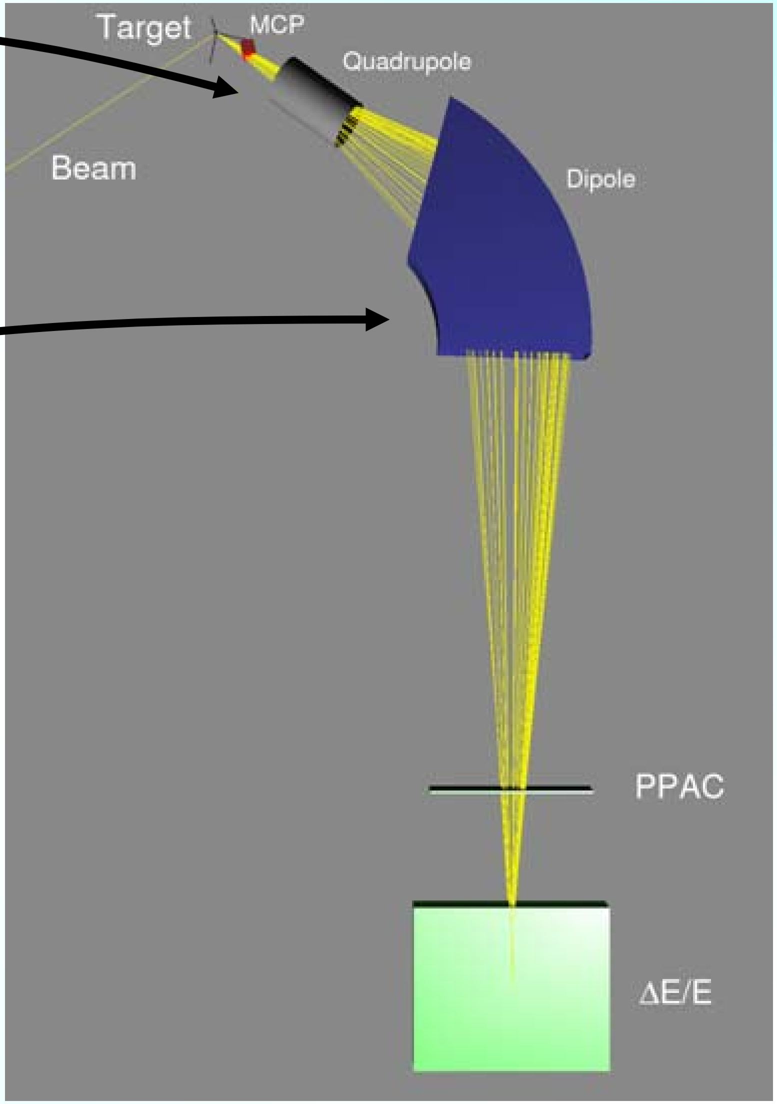
1.1 mm FWHM

3 signals





Optical Elements

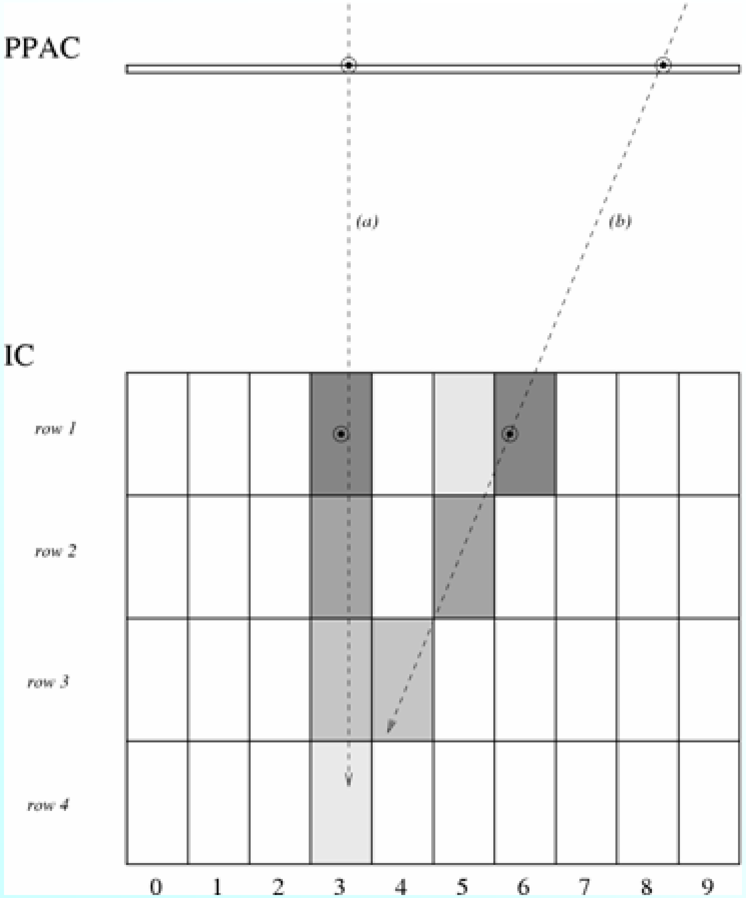


- **Quadrupole:** a singlet, focuses vertically the ions towards the dispersion plane

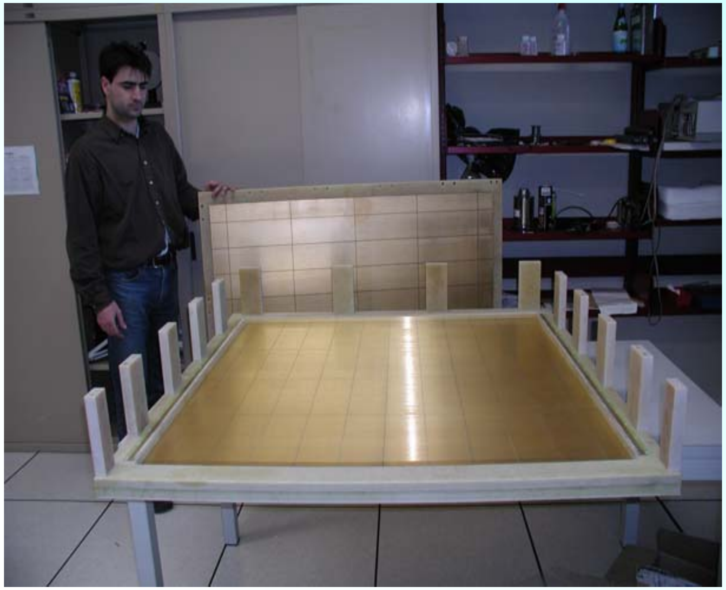
- **Dipole:** bends horizontally the ions with respect to their magnetic rigidity (Bρ)

Ionization Chambers

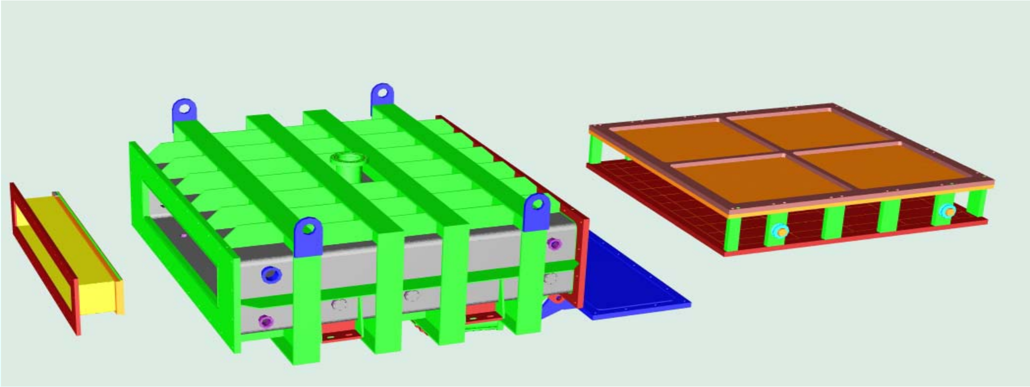
- 10x4 sections (10x25 cm^2)
- $\Delta E/E < 2\%$



40x2 signals

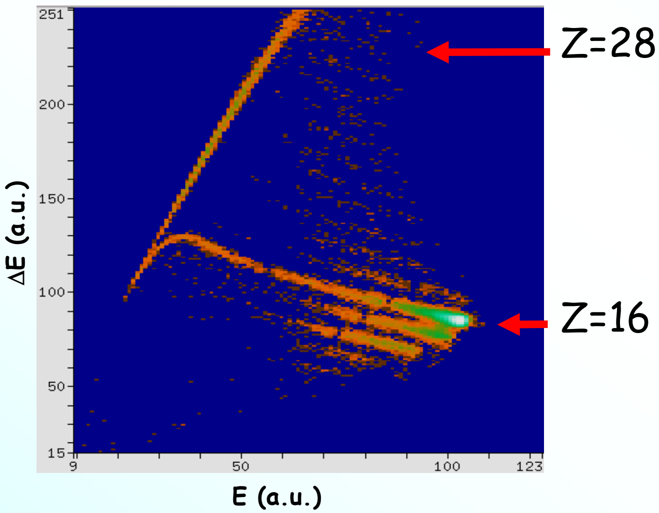


Filling gas: CH_4
Working pressure: 20-100 mbar

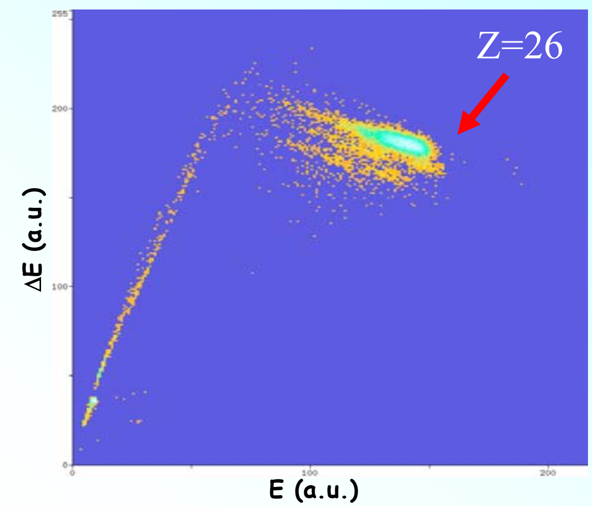


In-beam tests: Focal Plane Detectors

195 MeV $^{36}S + ^{208}Pb$, $\Theta_{lab} = 80^o$



240 MeV $^{56}Fe + ^{124}Sn$, $\Theta_{lab} = 70°$

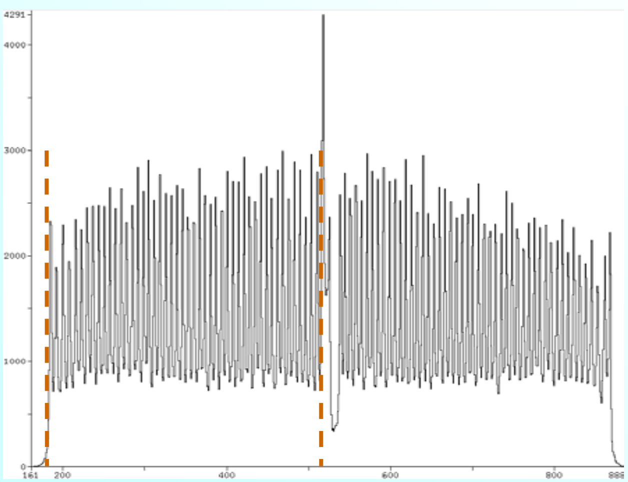


IC

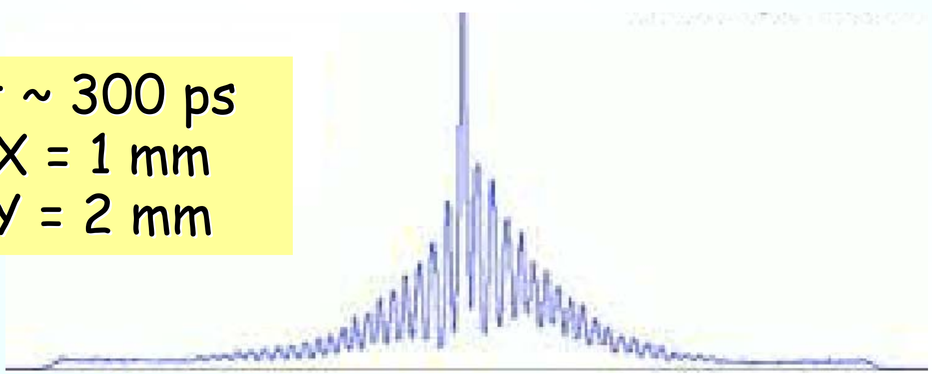
$\Delta E/E < 2\%$
$\Delta Z/Z \sim 60$

MWPPAC

$\Delta t \sim 300$ ps
$\Delta X = 1$ mm
$\Delta Y = 2$ mm



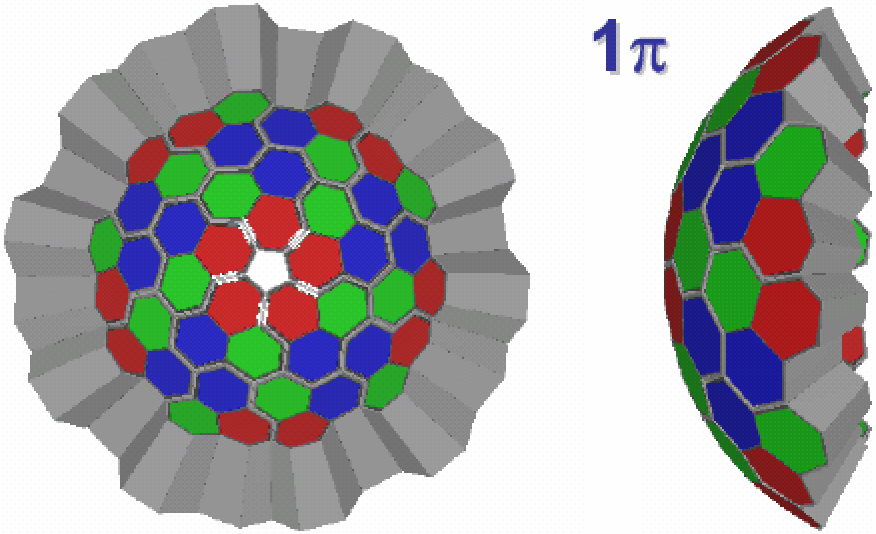
X position (channels)

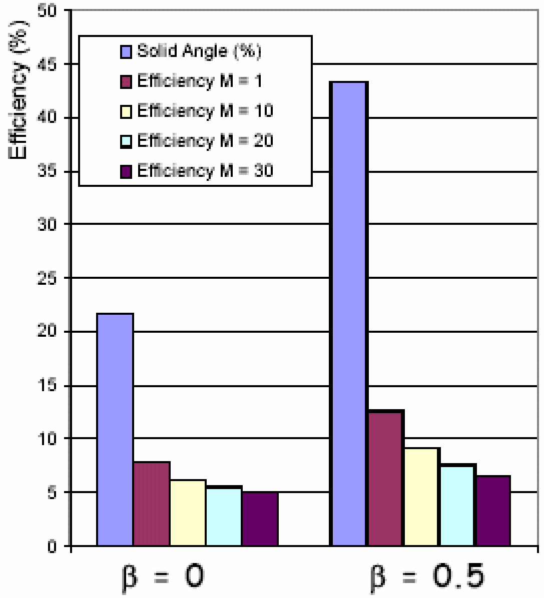


Y position (channels)

The Phases of AGATA 2

15 Clusters





The first "real" tracking array

Used at **FAIR-HISPEC**, **SPIRAL2**, **SPES**, **HI-SIB**

Coupled to spectrometer, beam tracker, LCP arrays …

Spectroscopy at the N=Z (^{100}Sn), n-drip line nuclei, …

Ready by 2010