Gamma-ray spectroscopy after slow neutron induced reactions FIPPS I

Caterina Michelagnoli

University of Warsaw – January 7th 2021

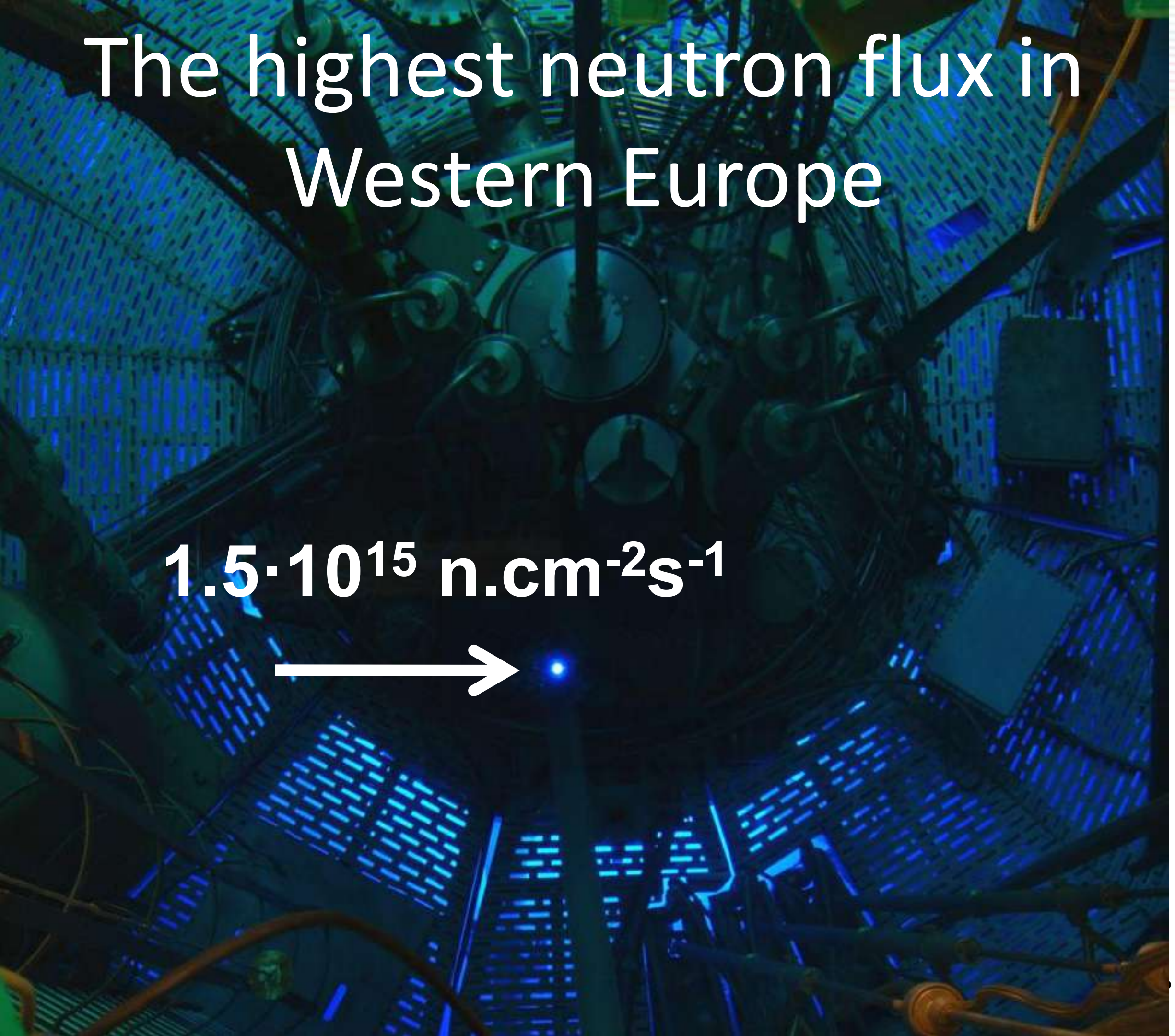
THE EUROPEAN NEUTRON SOURCE

NEUTRONS FOR SOCIETY

Outline

- Introduction –neutrons: how and why
- High resolution γ-ray spectroscopy after slow neutron reactions
  - (n,γ) reactions on stable (rare) and radioactive targets
  - (n,fission) using a *fission tag*
- Present and future for (n,fission) experiments
- Concluding remarks and future possibilities

The highest neutron flux in Western Europe

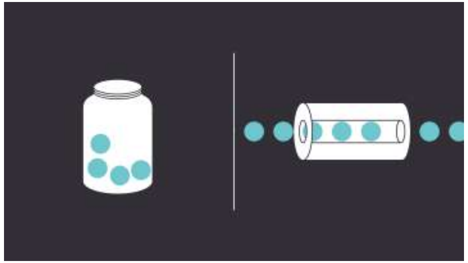


- ✓ In pile irradiations of radioisotopes
- ✓ In pile target experiments

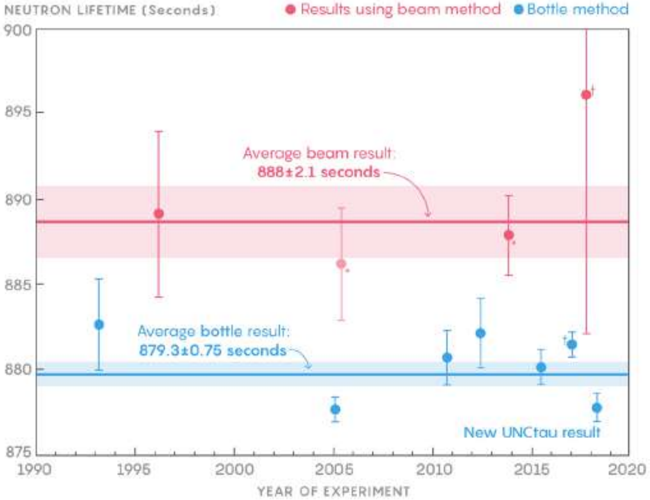
- ✓ <u>World's highest neutron flux for in-beam experiments</u>

The lightest radioactive beam…

Storage (« bottle ») vs in-beam measurements

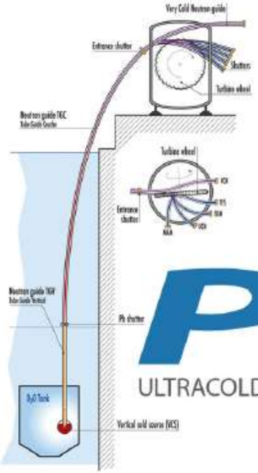


The neutron lifetime puzzle



https://www.quantamagazine.org/

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update



PF2

ULTRACOLD NEUTRONS FOR SCIENCE

Ultra-Cold-Neutrons experiments @ ILL

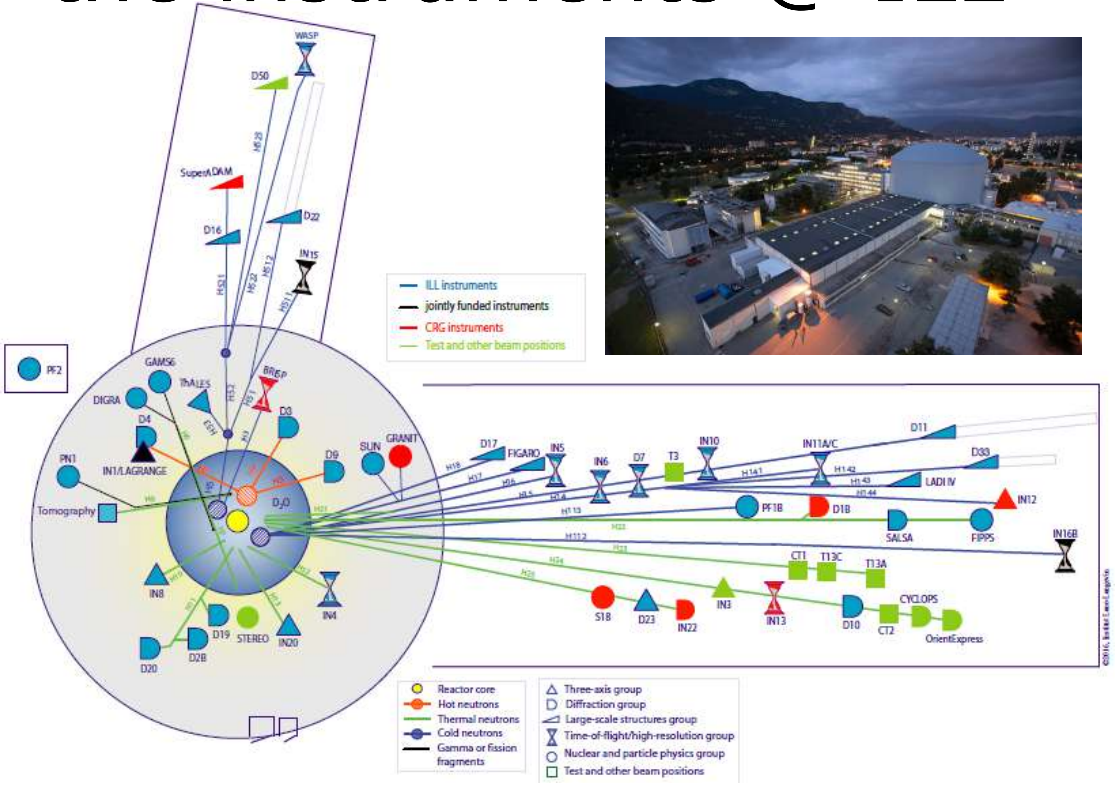
n lifetime
A.P. Serebrov et al., PRC97 (2018) 055503

Search for dark energy
T. Jenke et al., Nature Phys. 13 (2017) 920

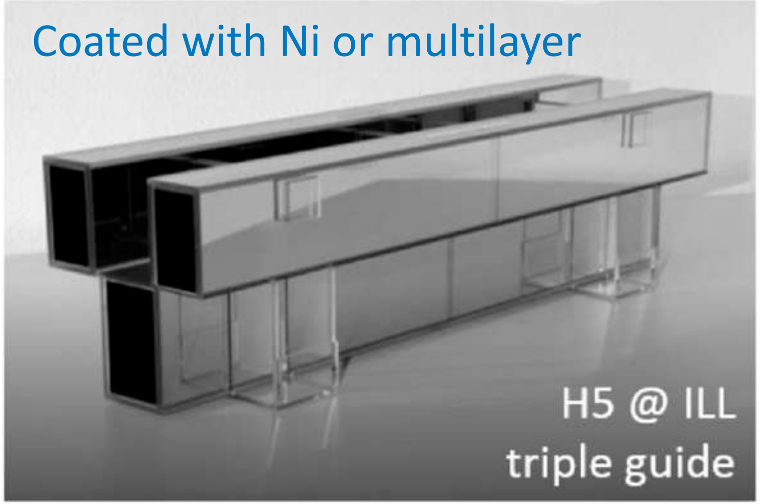
Gravity-resonance spectroscopy with neutrons
T. Jenke et al., Nature Phys. 7 (2011) 468

T. Jenke, S. Roccia, ILL

Neutron guides and the instruments @ ILL



Coated with Ni or multilayer

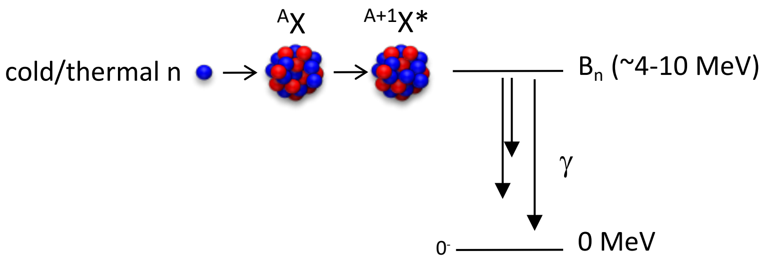


Neutrons can be guided with little losses over 100 m

Clean slow neutron beams (bent guides)

Why using neutrons?

"Slow" neutron-induced reactions



(n,γ) on stable (rare)/radioactive targets

- ➔ close to stability
- ➔ structure at low spin (below n-separation energy)
- ➔ cross-sections (applications)

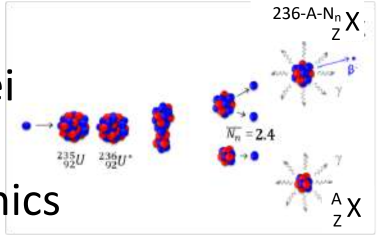
$^{27}Al(n,\gamma)$: σ=0.2 b

$^{64}Ni(n,\gamma)$: σ=1.5 b

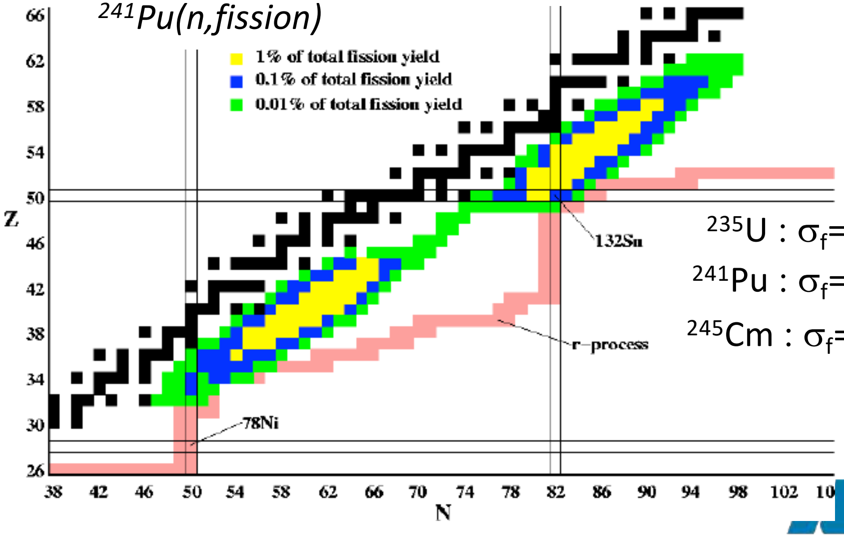
$^{157}Gd(n,\gamma)$: σ=2.5e5 b

(n,fission) on actinides

- ➔ structure of n-rich nuclei (far from stability)
- ➔ fission yields and dynamics



$^{241}Pu(n,fission)$



^{235}U : σ_f=585 b

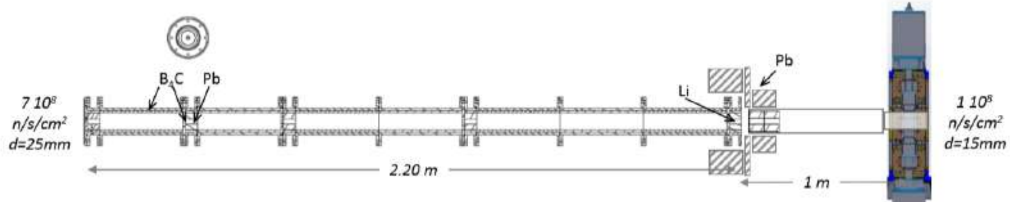
^{241}Pu : σ_f=1012 b

^{245}Cm : σ_f=2141 b

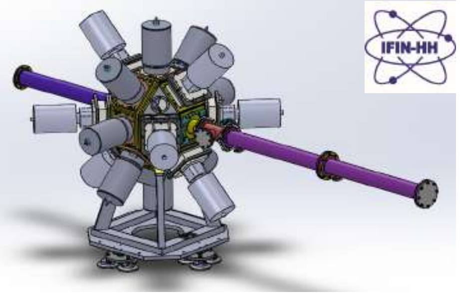
High-resultion γ spectroscopy @ n beam

The Fission-Product-Prompt Spectrometer (FIPPS)

8 HPGe clovers +
segmented anti-Compton shields (ACs)



thermal neutron beam: 10^8 n/s/cm^2 , d=15mm



Possibility of additional clover detectors+ACs (up to 16), LaBr3 (fast timing ps lifetime measurements), …

- digital electronics, list-mode (~10kHz/cry, triggerless)
- tight casemate for handling of radioactive targets

C. Michelagnoli et al., EPJ 193 (2018) 04009

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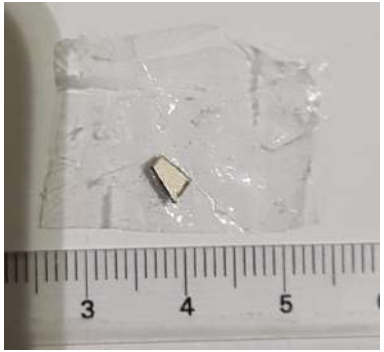
Targets for (n,γ) experiments

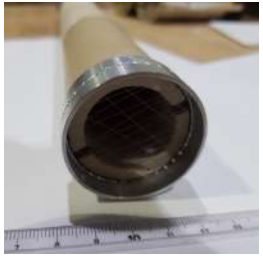
Hold in place by PTFE wiring



2 mg metal (^{nat}Ti)

120 mg powder

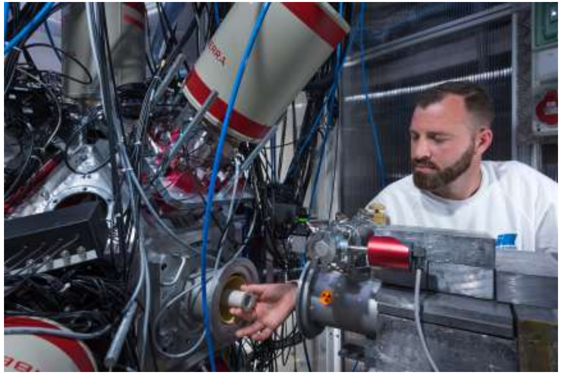
< 1 mg powder



Li target holder for scattered neutrons absorbtion

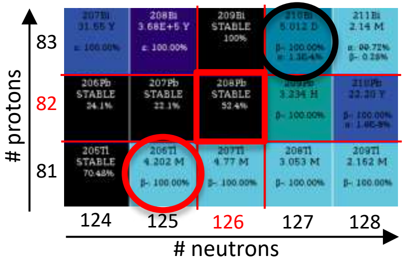
*σ*N ~ 2 mmol*barn*

3 g powder (^{13}C enriched)

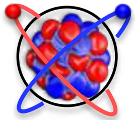


Test of *realistic* SM interactions

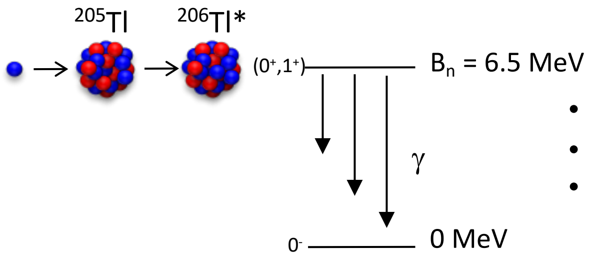
^{205}Tl(n,γ)^{206}Tl –first FIPPS experiment (Dec. 2016/Jan. 2017)



^{208}Pb "frozen" core



+ 2 particles (holes)



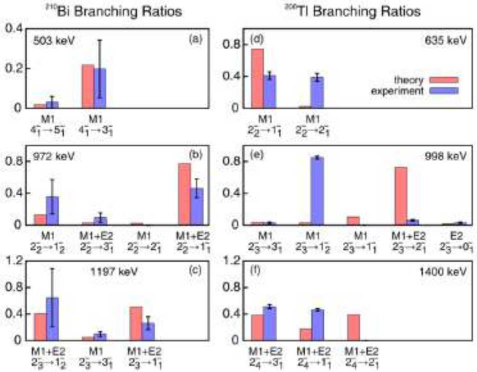
^{210}Bi data from EXILL campaign

N. Cieplicka et al. Phys. Rev. C 93 (2016) 054302

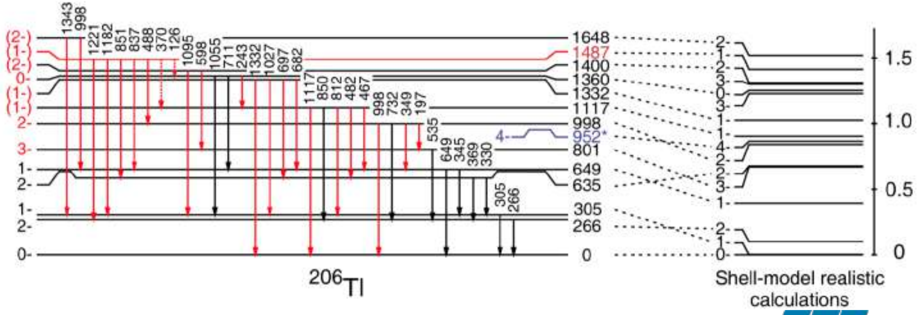
N. Cieplicka et al. Phys. Rev. C 94 (2016) 014311

M. Jentschel et al. JINST 12 (2017) P11003

- $I_n = 10^8 n/(s \cdot cm^2)$, σ = 0.11 b
- 1.9 g of ^{205}Tl (99.9% enriched)
- ~ 10 days

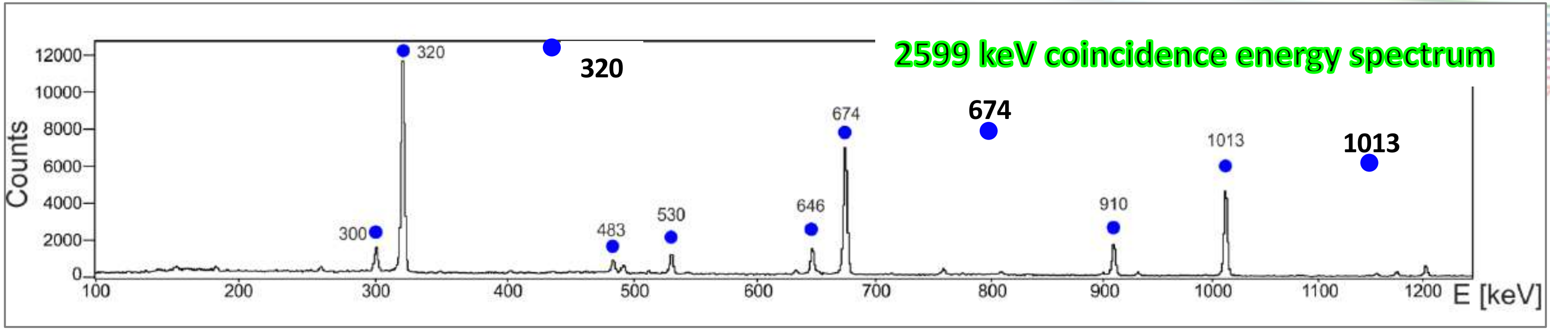


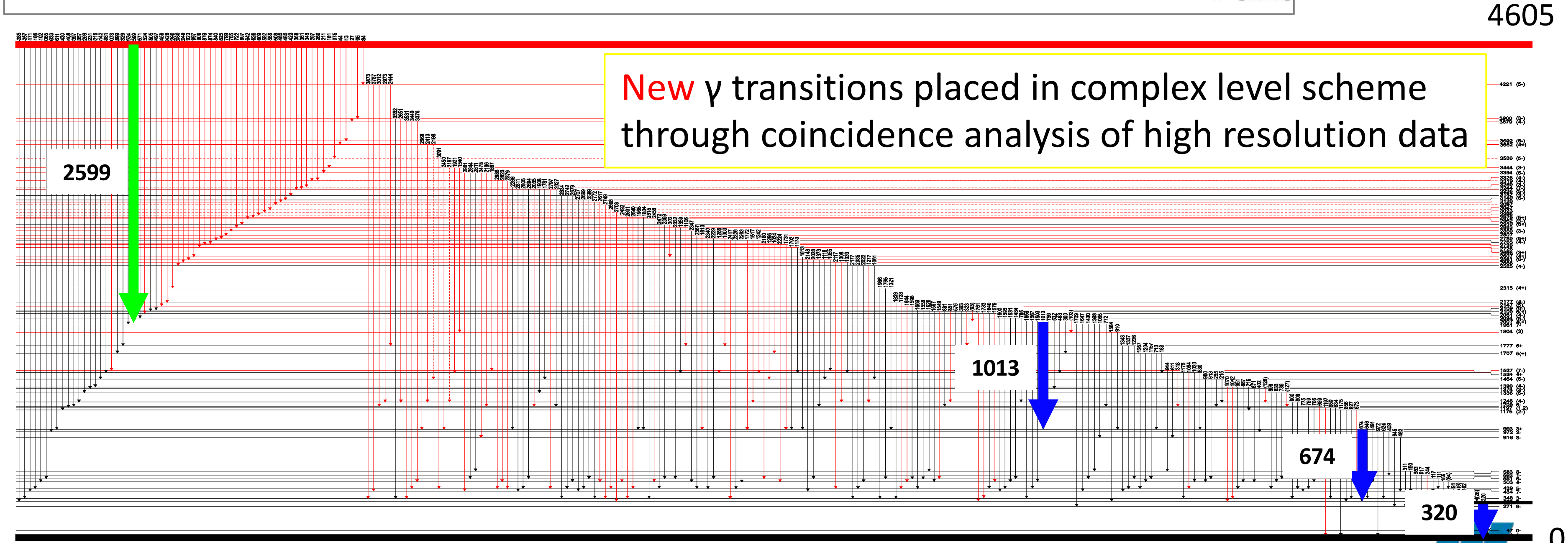
^{206}Tl : sensitivity to non diagonal matrix elements of the realistic interaction



N. Cieplicka et al. Phys. Lett. B 802 (2020) 135222

2599 keV coincidence energy spectrum





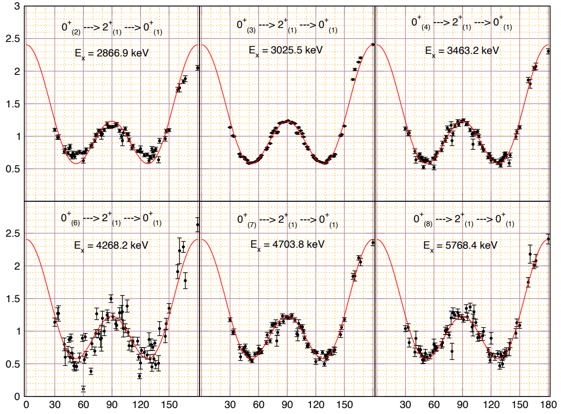
New γ transitions placed in complex level scheme through coincidence analysis of high resolution data

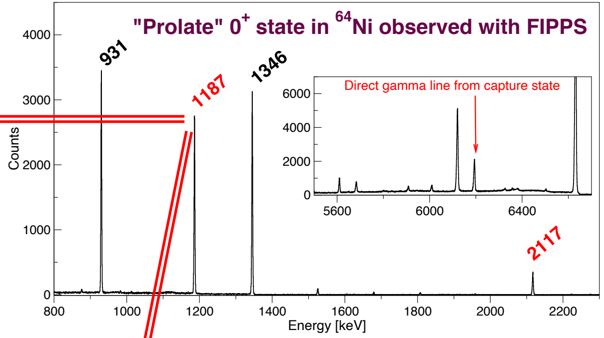
^{210}Bi

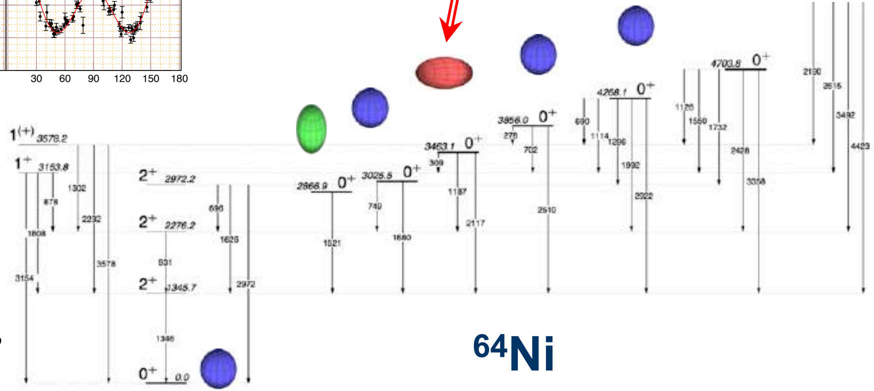
N. Cieplicka-Orynczak et al., PRC 93 (2016) 054302

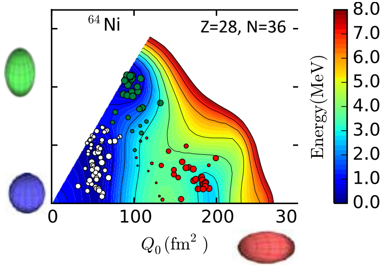
Nuclear *shape isomerism*

Pioneering evidences in light nuclei –(n,γ) on ^{63}Ni radioactive (2GBq) target @ FIPPS+IFIN-HH









Monte Carlo Shell Model Potential Energy Surface

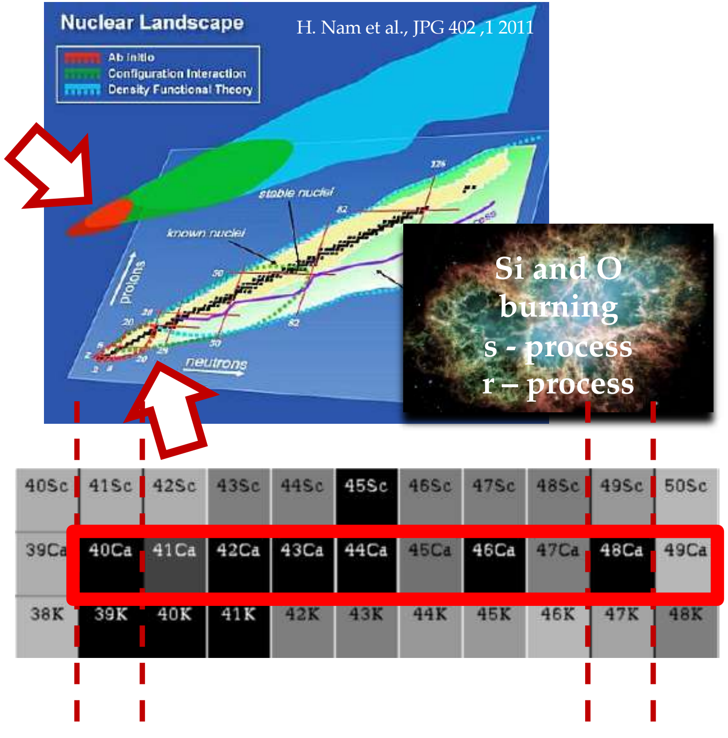
T. Otsuka et al., JPG43 (2016) 024009

Towards the miscroscopic interpretation of nuclear deformation

Nuclear Jan-Teller effect

N. Marginean et al., PRL125 (2020) 102502
C. Porzio et al., PRC 102 (2020) 064310

Ca isotopes: playground for many nuclear theories



Courtesy of S. Bottoni

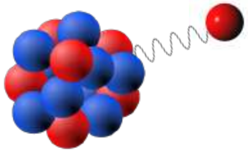
The Hybrid Configuration Mixing Model (Milano)

$$
\begin{aligned}
H &= H_0 + V, \\
H_0 &= \sum_{jm} \varepsilon_j a^{\dagger}_{jm} a_{jm} + \sum_{NJM} \hbar\omega_{NJ} \Gamma^{\dagger}_{NJM} \Gamma_{NJM}, \\
V &= \sum_{jmj'm'} \sum_{NJM} h(jm; j'm', NJM) a_{jm} \left[a^{\dagger}_{j'} \otimes \Gamma^{\dagger}_{NJ} \right]_{jm}
\end{aligned}
$$

G. Colò et al., Phys. Rev. C. 95, 034303 (2017)

S. Bottoni et al., in preparation

Particle/hole core couplings



EXILL

^{40}Ca(n,γ)^{41}Ca

^{46}Ca(n,γ)^{47}Ca

^{48}Ca(n,γ)^{49}Ca

S. Bottoni et al.,
submitted to Phys. Rev. C.

FIPPS

^{41}Ca(n,γ)^{42}Ca

^{42}Ca(n,γ)^{43}Ca

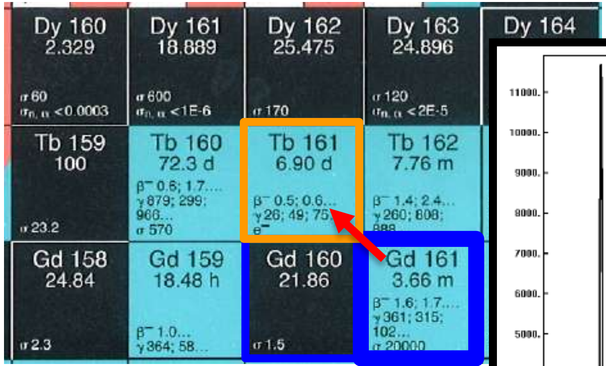
^{43}Ca(n,γ)^{44}Ca

^{44}Ca(n,γ)^{45}Ca

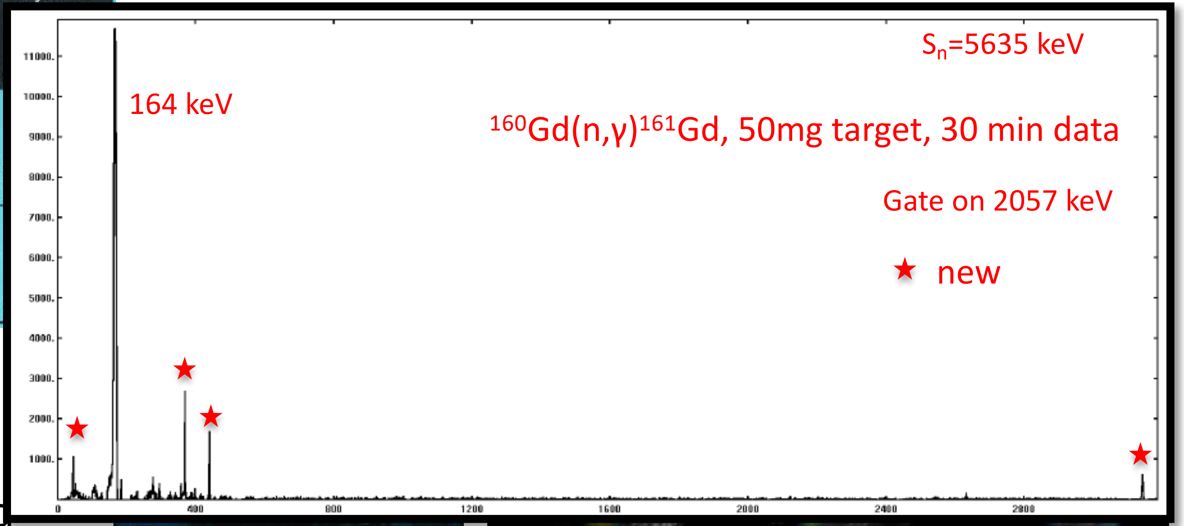
2 MBq radioactive target (13% of the enriched ^{41}Ca existing on earth)

^{161}Gd spectroscopy @ FIPPS

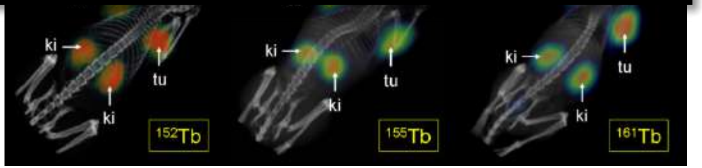
Common interest for fundamental research and radioisotope production



^{160}Gd(n,γ)^{161}Gd



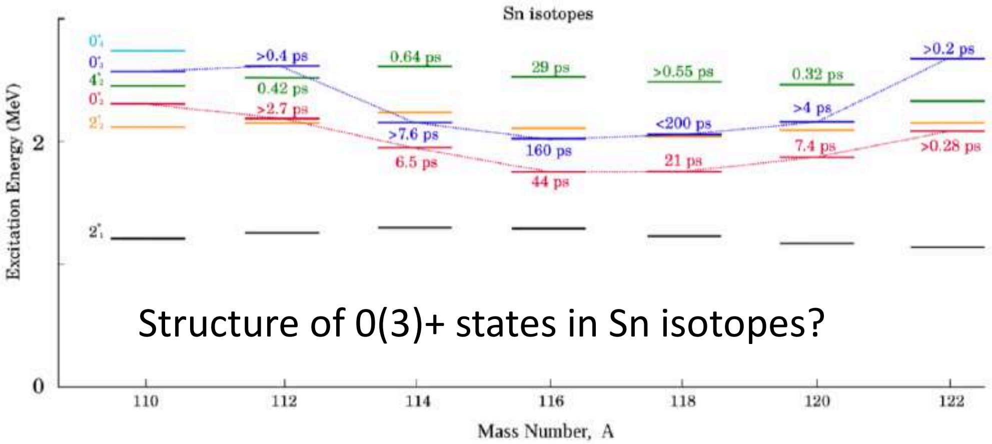
^{160}Gd(n,γ)^{161}Gd cross section measurement and ^{161}Gd gamma-ray spectroscopy at FIPPS



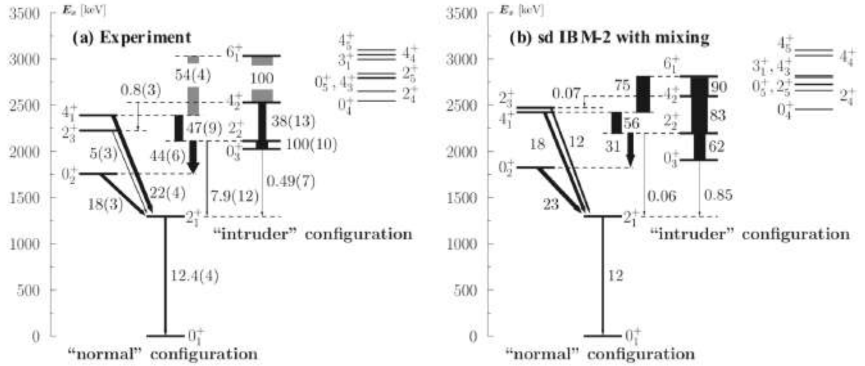
C. Michelagnoli et al.

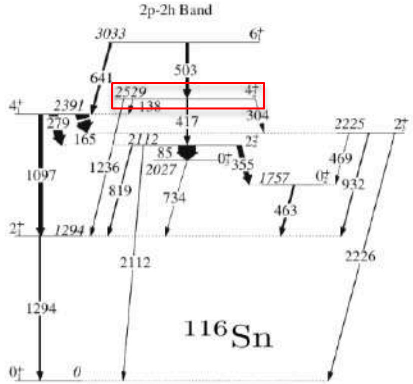
Collectivity of the 2p-2n intruder band in ^{116}Sn

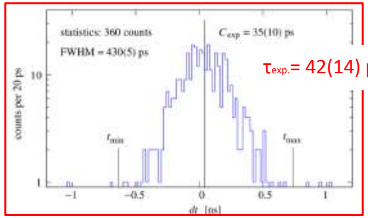
Lifetime of the 4^+_2 state measured with the fast-timing technique at FIPPS



Structure of 0(3)+ states in Sn isotopes?





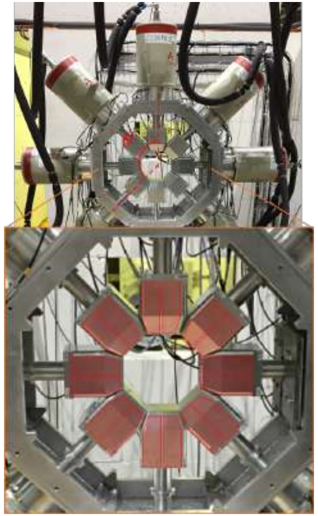


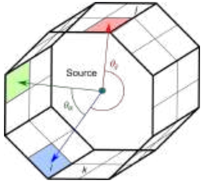
Strong mixing, intrinsic excitations of both configurations coexist at comparably low excitation energies in ^{116}Sn

C. Petrache et al., Phys. Rev. C 99 (2019) 024303
CSNSM, Univ. of Guelph, IKP Cologne collab.

Gamma-ray Induced DSAM

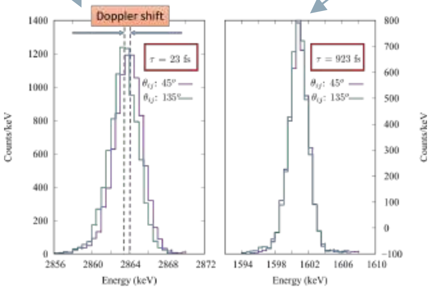
GRIDSA : Femtosecond Lifetime Measurements with Germanium Detector Arrays @ n beam





Short Lifetime
(shift observed)

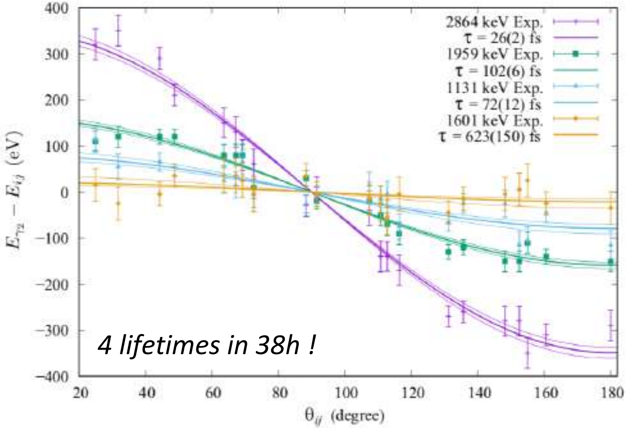
Long Lifetime
(NO shift)



Centroid position determined as barycenter (no difference to Gaussian fit)

femtosecond lifetimes from two-step γ-ray cascades

Results for different ^{36}Cl transitions



4 lifetimes in 38h !

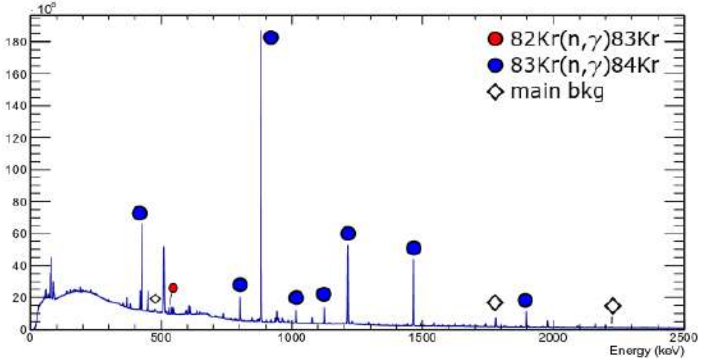
Test on different targets (nuclei):
NaCl (^{36}Cl), Ti_2O_3 (^{49}Ti),
Ti metallic (^{49}Ti), NiF_2 (^{59}Ni),
Ni metallic (^{59}Ni)

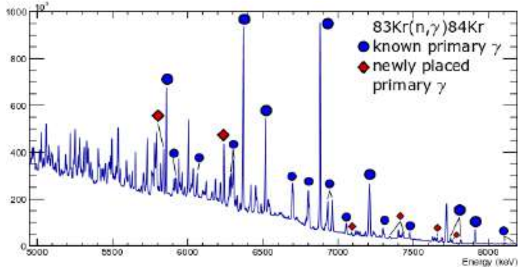
F.C.L. Crespi et al. EPJA 56 (2020) 94

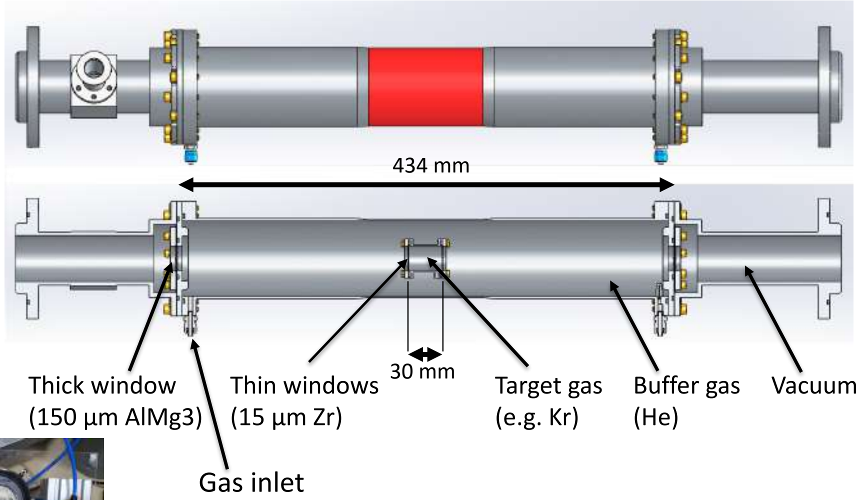
Gas target @ FIPPS

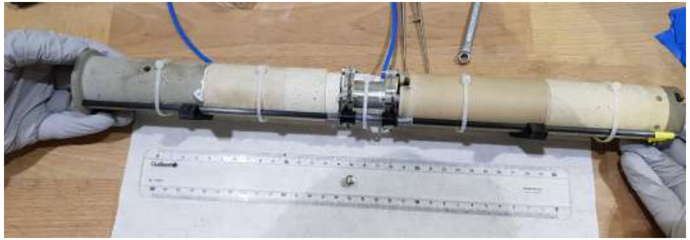
September 2020

Kr-nat, 10 bar, $\sigma_{Kr\text{-}83}$ = 198 barn



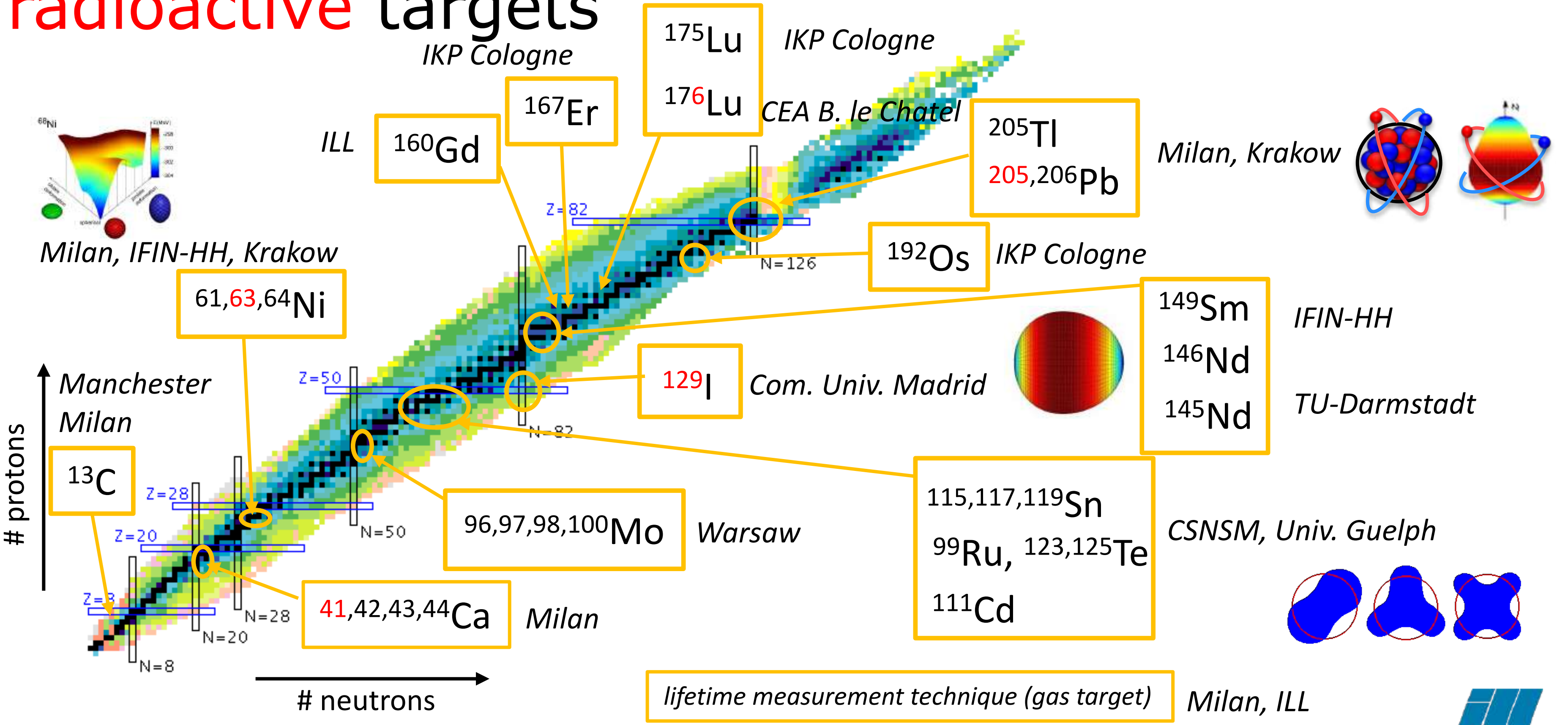






F. Kandzia, M. Jentschel et al., Courtesy of F. Kandzia

(n,γ) on stable (rare) and radioactive targets



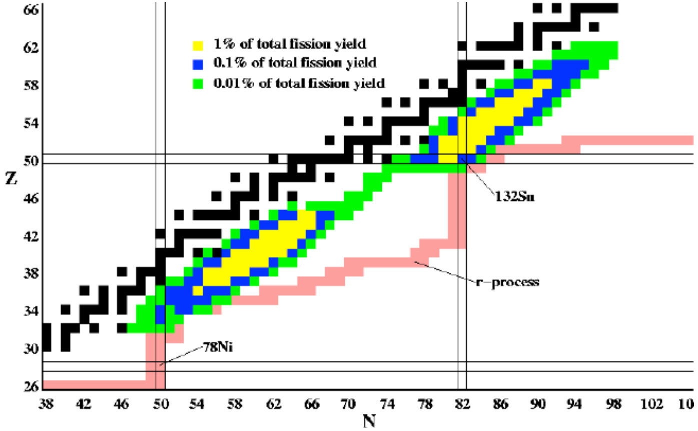
© marketoonist.com

There's not a nuclear model that explains everything!

Need to collect *good data* to benchmark different regions of the nuclear chart

Spectroscopy of fission fragments: a challenge!

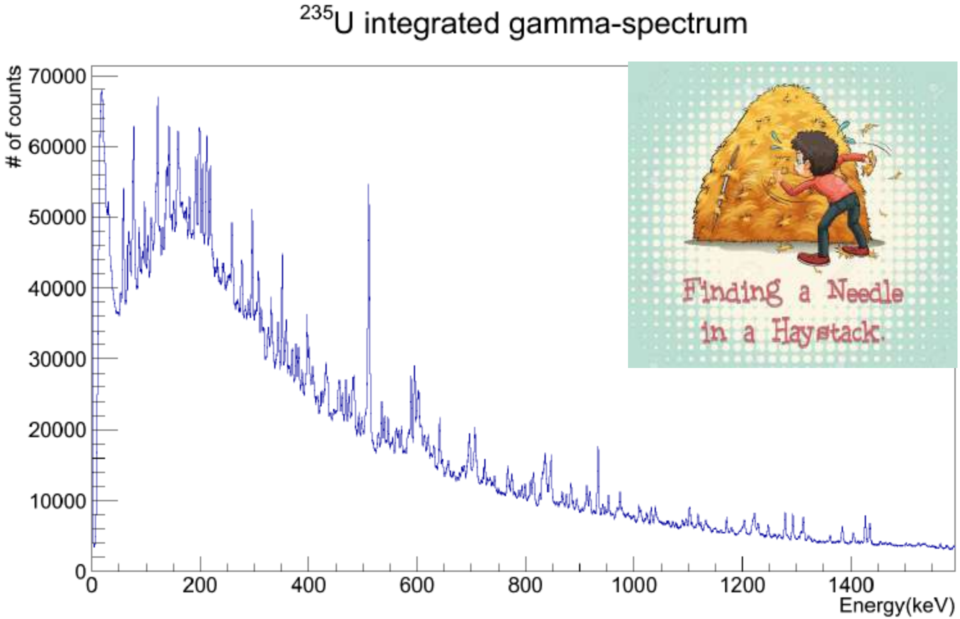
More than 150 nuclei emitting γ rays at the same time (excited fission fragments and β-decay products)



Fission populates exotic nuclei with
an « excess » of neutrons important for:

- understanding of nuclear structure far from stabilit
- modeling of the fission mechanism
- nuclear properties along *r-process* path

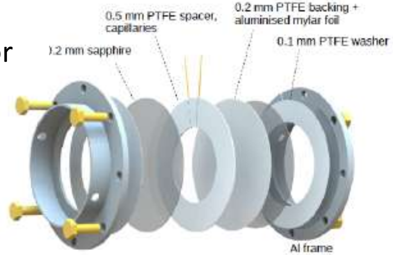
First ^{235}U(n,f) campaign at FIPPS+IFIN-HH



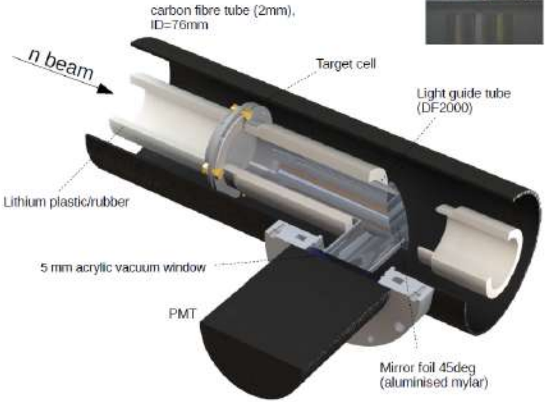
Active fission target

FILL2030 postdoc project @ ILL

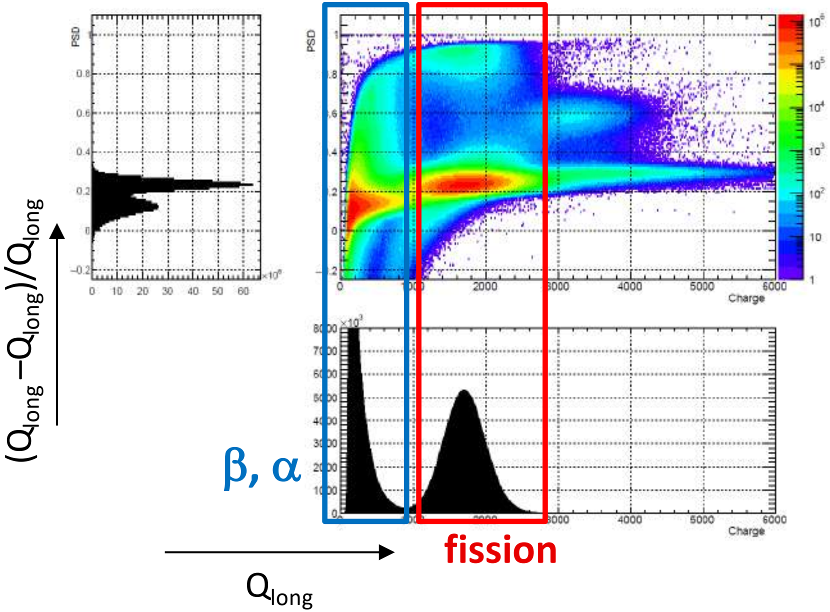
^{235}U diluted in liquid scintillator



target cell



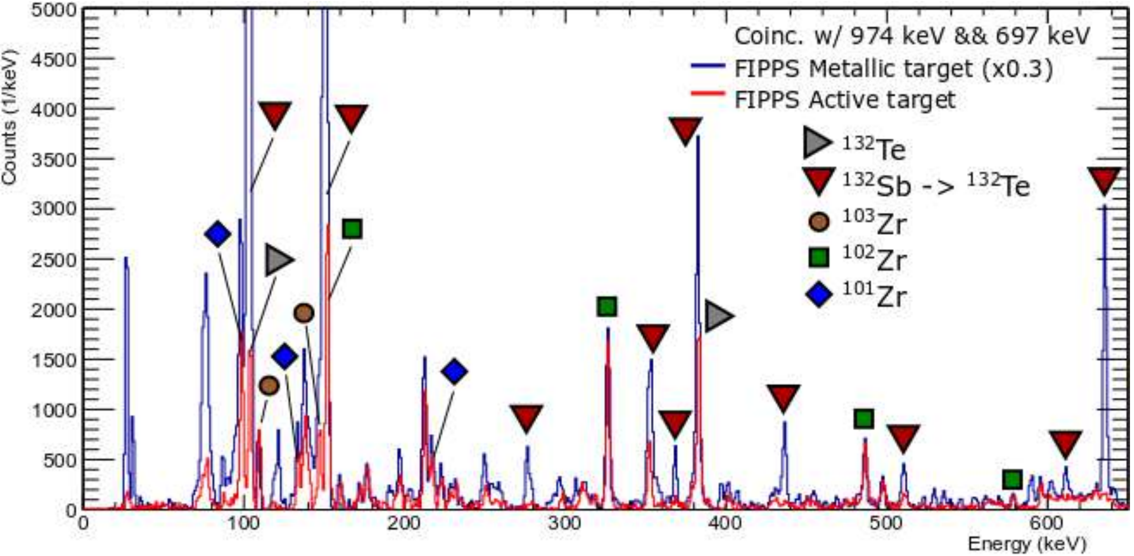
PSD (Pulse-Shape-Discrimination)

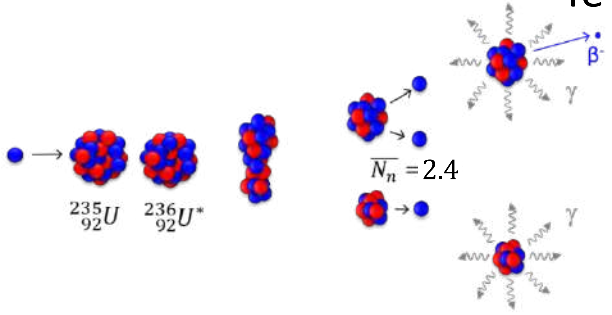


F. Kandzia, G. Bélier, et al. EPJA 56 (2020) 207

Example of β-induced background suppression

γ–γ–γ analysis (double coincidence gate on ^{132}Te)





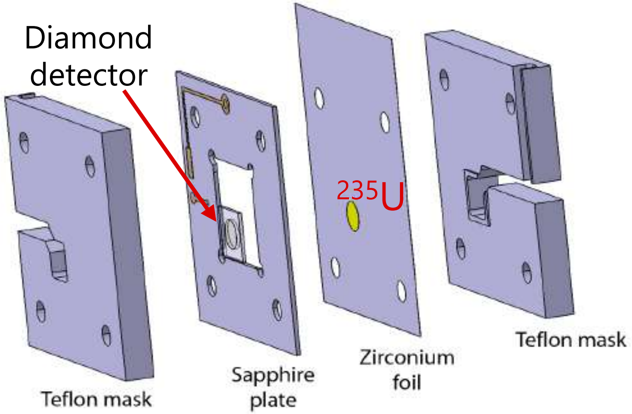
Also: increased sensitivity for prompt-delayed coincidence analysis

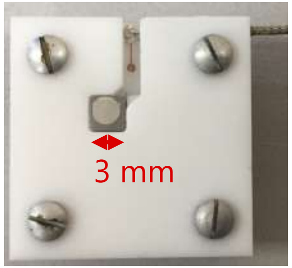
L. Iskra et al. PRC 102 (2020) 054324

September-October 2018

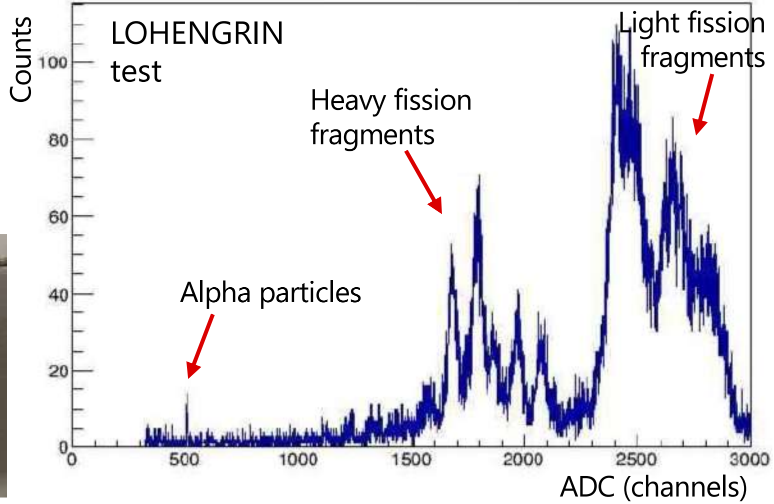
Diamond-based fission tag

- Single crystal CVD diamond detector (4.5 × 4.5 × 0.517 mm^3)
- Radiation hardness, temperature insensitivity, high mobility and lifetime for electrons and holes
- Ability to detect fission fragments verified at the LOHENGRIN mass spectrometer at ILL





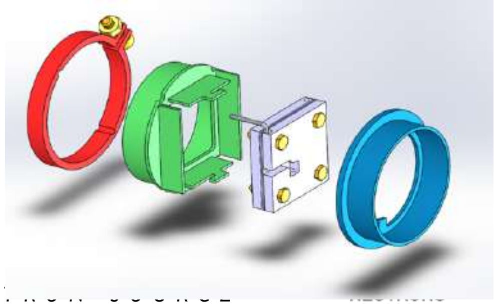
FIPPS test



G. Colombi, Master Thesis, Univ. Milano and ILL (2020)

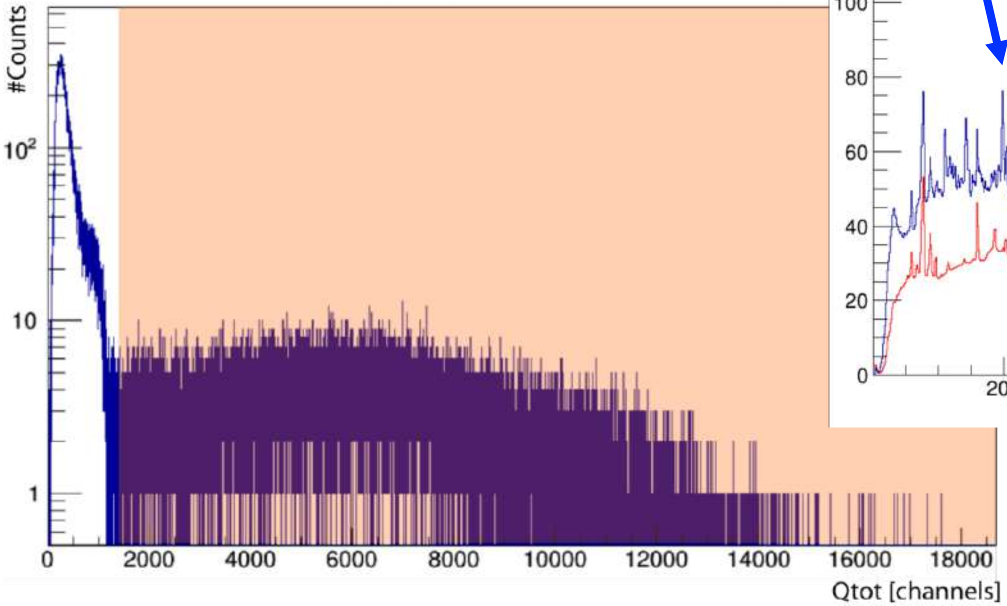
Collaboration to develop a fission trigger for FIPPS (LPSC / ILL / IFJ Krakow / INFN Milano)

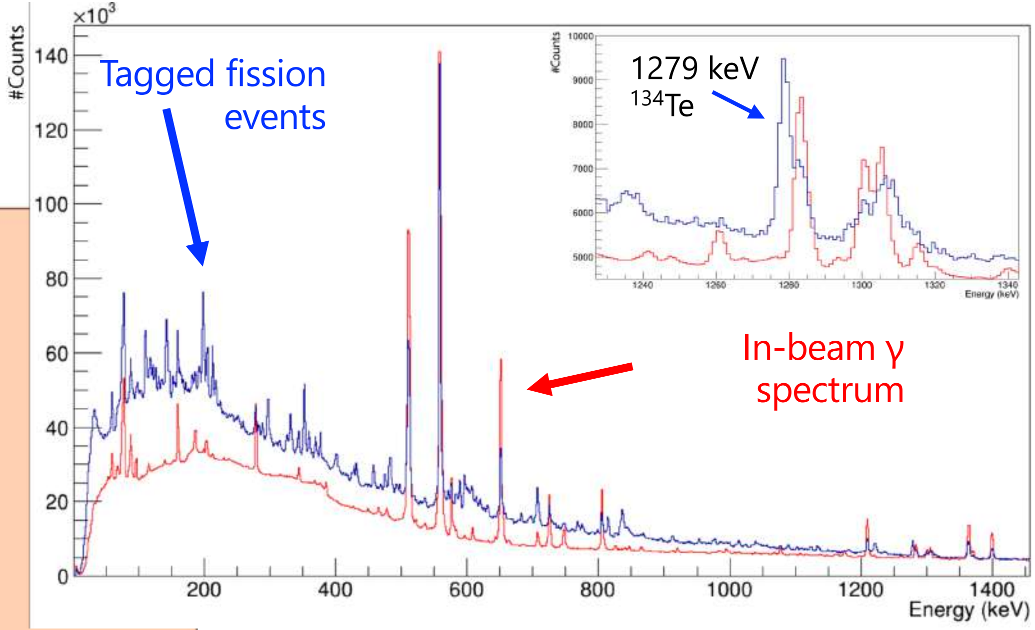
Important development for **heavier actinide** targets (e.g. ^{245}Cm, not applicable in solutions due to radioprotection safety rules)



First test of a diamond-based fission tag @ FIPPS

G. Colombi, Master Thesis, Univ. Milano and ILL (2020)





- Fission fragments detected by the diamond detector
- Enhancement fission events in the γ–ray spectrum

Going more and more *exotic*…

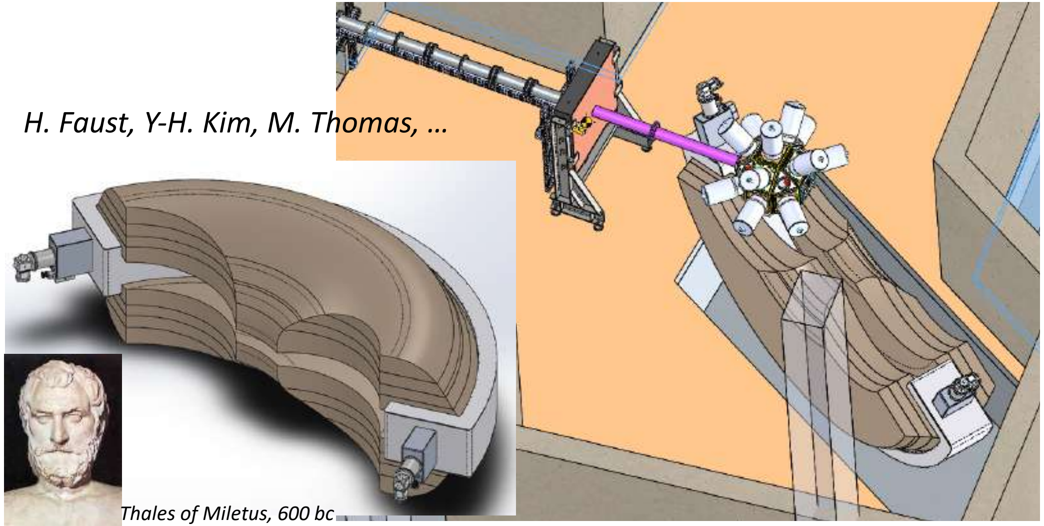
Gain of order of magnitudes in sensitivity for fission studies and spectroscopy of n-rich nuclei using a **Gas-Filled-Magnet (GFM) separator**

HPGe array + fission fragment separator

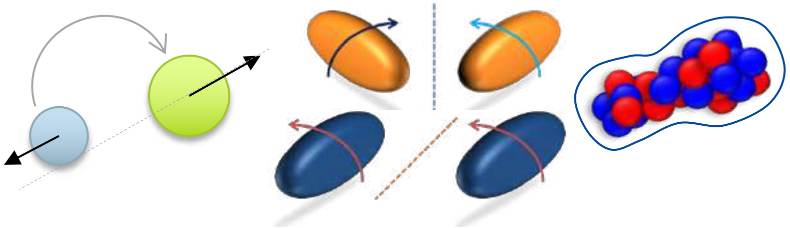
Special geometry:
large acceptance and horizontal focusing indipendent from the ion trajectory

→ Structure of very neutron rich nuclei
→ Understanding of generation of angular momentum and excitation energy in fission

H. Faust, Y-H. Kim, M. Thomas, …



Thales of Miletus, 600 bc



?

- ✓ Pre-design studies
- ✓ Instrument review(s)

Concluding remarks

- Rich Nuclear Physics program at ILL using FIPPS+IFIN-HH/$LaBr_3$ using slow-neutron induced reactions
- ^{235}U(n,f) and ^{233}U(n,f) with *fission tag*: new spectroscopic info on n-rich fission fragments is now available trough multiple gamma-ray coincidences analysis (data are open for LoI)

  → bridge for the science program at FIPPS phase 2 (FIPPS+GFM)

- Next ILL proposal submission deadline: February 2021

  → "all targets can be used at FIPPS" (or, at least, many…)

  → a fission run with ^{245}Cm is foreseen for April-May 2021

- The physics program and detector developments at FIPPS depend on your input! Hope to see you all soon at ILL…
- … or at least in Grenoble for the **CGS17** or in Avignon for **ARIS2020**

Advances in Radioactive Isotope Science 2021

5 – 10 September 2021 in “Palais des Papes”, Avignon, France

www.aris2020.eu

17th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics - CGS17

August 23 – August 27, 2021
Grenoble, France

- Nuclear Structure
- Nuclear Reactions
- Nuclear Astrophysics
- Fundamental Interactions and Symmetries
- Nuclear Data
- Experimental Techniques and Facilities
- Interdisciplinary Studies and Applications

Deadlines:
- Abstract: 31/03/2021
- Registration: 30/06/2021

Contact:
https://workshops.ill.fr/event/188/
Email: CGS17@ill.fr


F. Kandzia, R. Pommier


E. Ruiz-Martinez


D. Reygadas (PhD st.)


G. Colombi (PhD st.)

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Many thanks to all collaborators!!!

INSTITUT LAUE LANGEVIN

U. Köster, Y-H. Kim, H. Faust, M. Thomas, P. Mutti, M. Barani, C. Duthoit, M. Jentschel -- *ILL*
N. Marginean, C. Mihai, R. Lica, S. Pascu, A. Turturica, … -- *IFIN-HH*
S. Leoni, F. Crespi, S. Bottoni, …. -- *Univ. and INFN Milano*
B. Fornal, N. Cieplicka, L. Iskra, … -- *PAN Krakow*
W. Urban, J. Wisniewski, … -- *Univ. Warsaw*
T. Materna, … -- *CEA Saclay*
G. Bélier, J. Aupiais -- *CEA B. le Chatel*
G. Kessedjian, … -- *LPSC Grenoble*
…..


J. Dudouet, IP2I Lyon

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Endurance
Setting the pace

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

cea

Future of FIPPS with gas filled magnet: FIPPSII

Yung Hee KIM

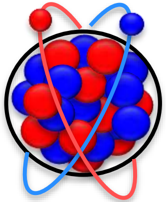
Univ. of Warsaw 7-Jan-2021

Overview

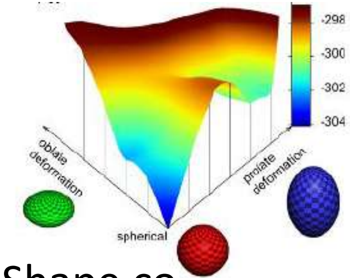
- Motivation of FIPPS phase II
- Conventional methods to separate n-induced fission fragment
- Concept & design process of FIPPS GFM
- Simulated performance of FIPPS GFM

Objective of FIPPS phase2

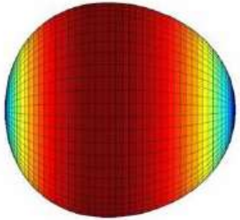
- Study more exotic part of nuclear chart



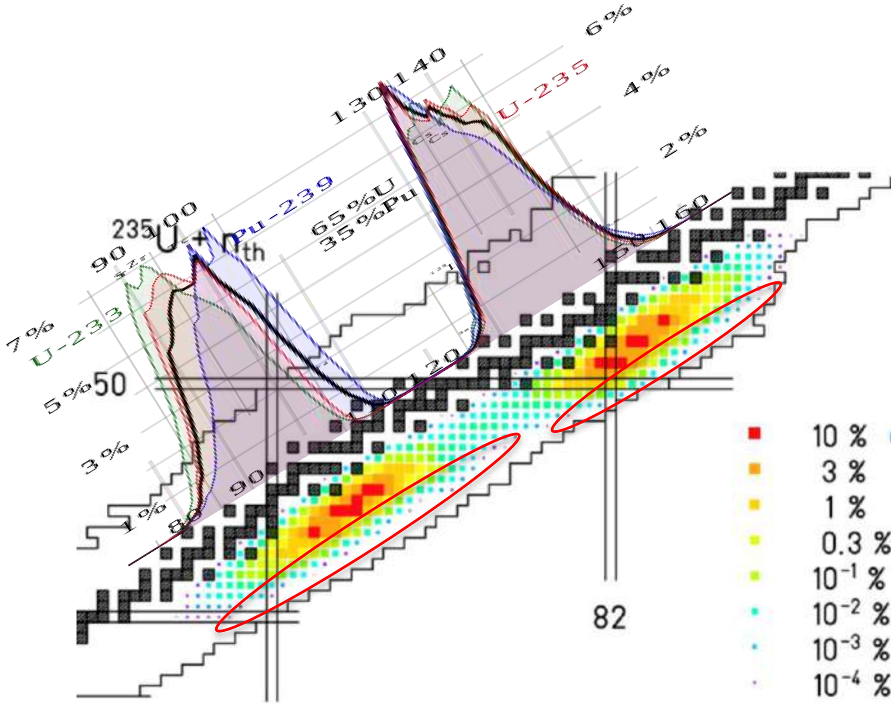
nuclear interaction



Shape co-extance/transition



Rare shape



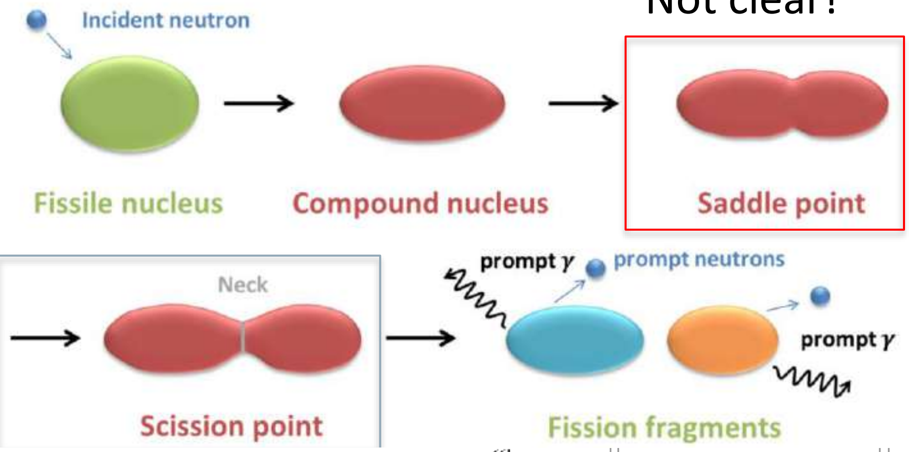
- Rarely populated

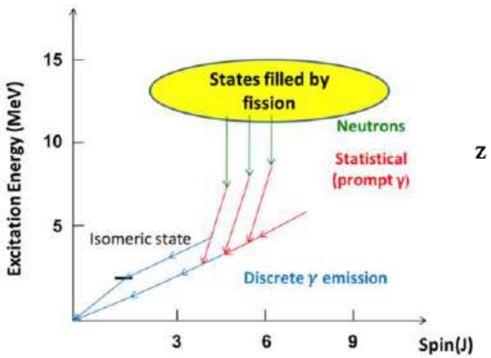
  -> **Better selectivity** of fission fragment needed

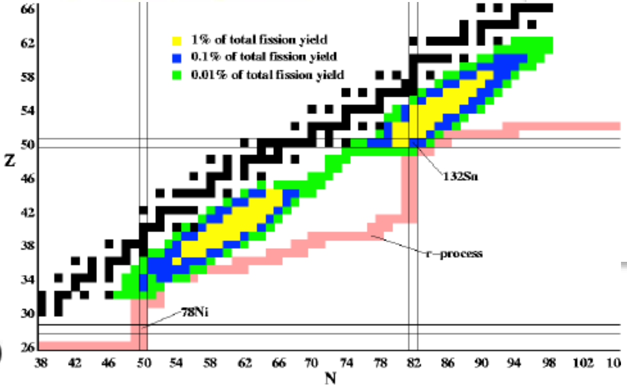
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **10**, 014701 (2007)

Nuclear fission needs more study

Not clear!







- 80 year since discovery
- Source of electric power
- Access to very neutron rich nuclei

- No consistent model description of fission
  - How angular momentum is generated?
  - How nuclear structure affects in fission dynamics?

Objective of FIPPS phase2

- Study more exotic part of nuclear chart

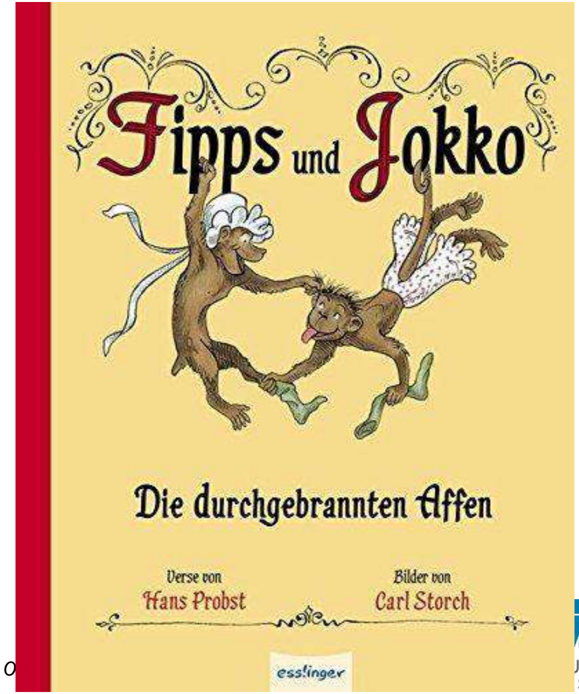
  -> **Better selectivity** of fission fragment

- New physics capability

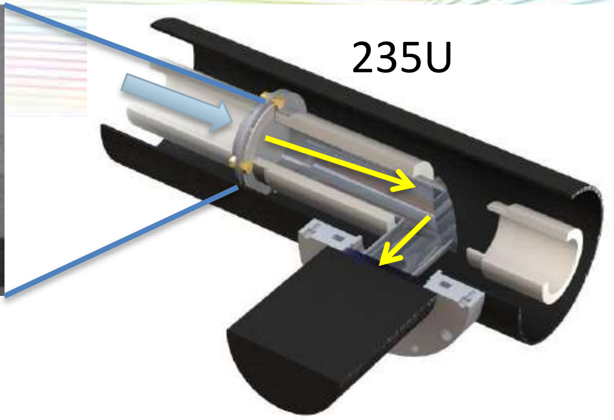
  e.g. Fission dynamics: how angular momentum is generated?

  ->**Kinetic energy** of fission fragment

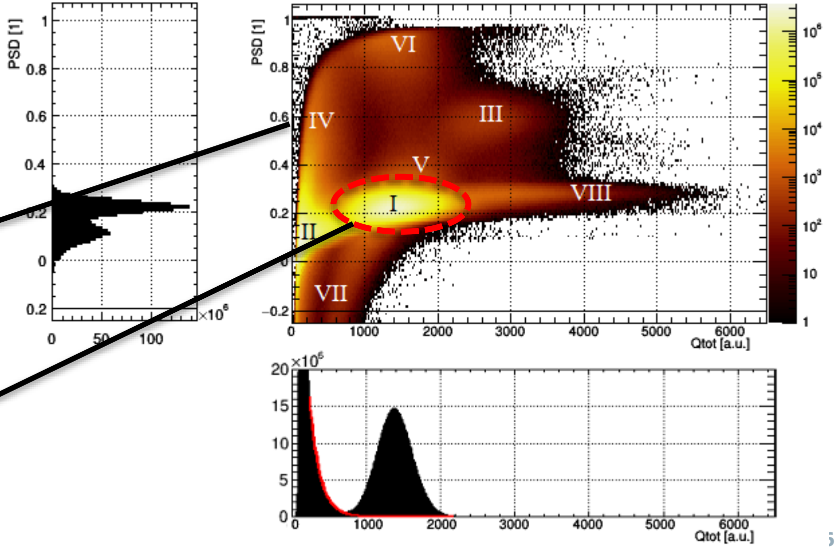
- Complementary device

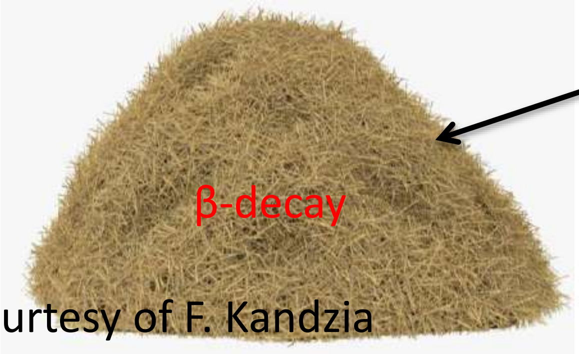


FIPPS fission tag



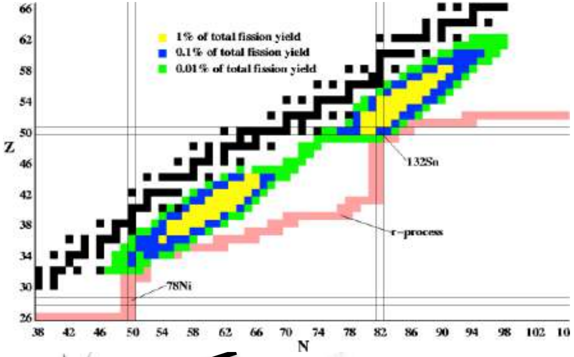
- Fission rate 12 kHz
- Coincidences PMT- $\gamma - \gamma$: 10 kHz
- Total: 1.5E11 fission tagged $\gamma - \gamma$ coinc. (36 days, Sep-Oct 2018)
- Fission detection efficiency: 85% (preliminiary)
- Fission mis-identification: 0.3%
- β-mis-identification: ~0.4%





Courtesy of F. Kandzia

How to distinguish different nuclei?



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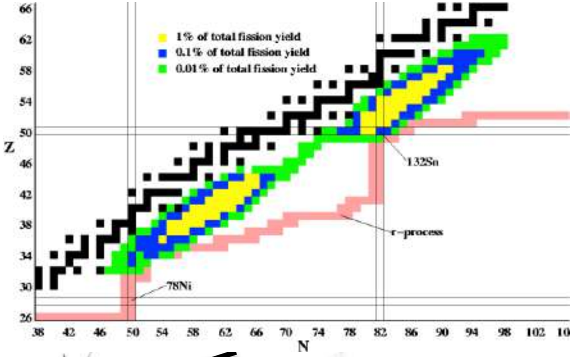

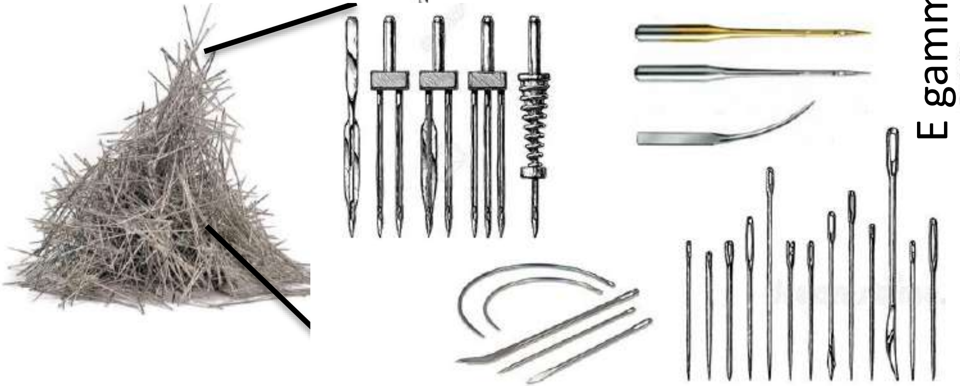

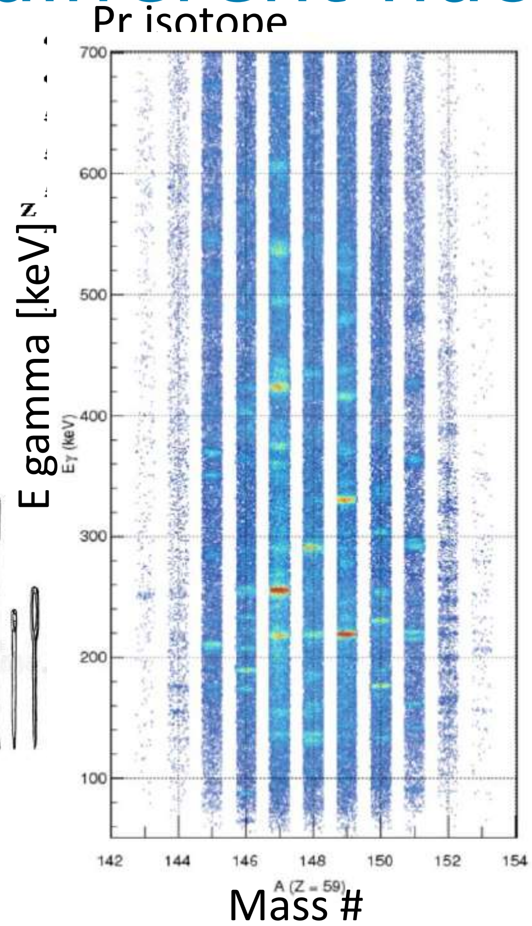

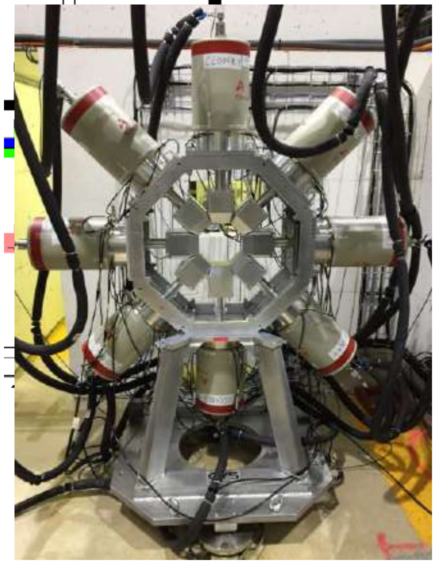

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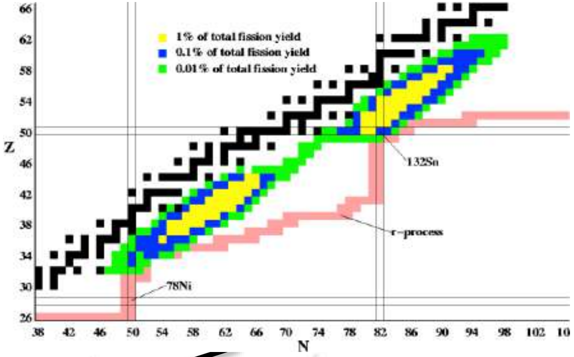
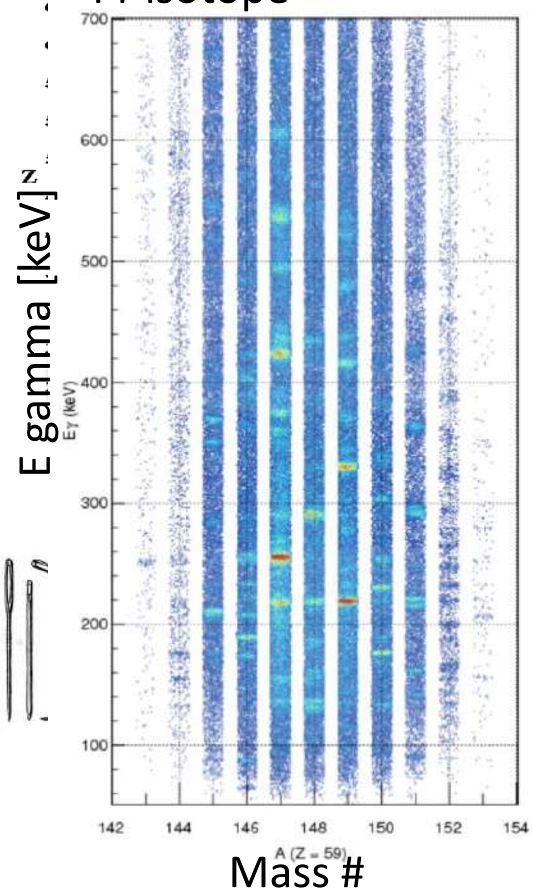
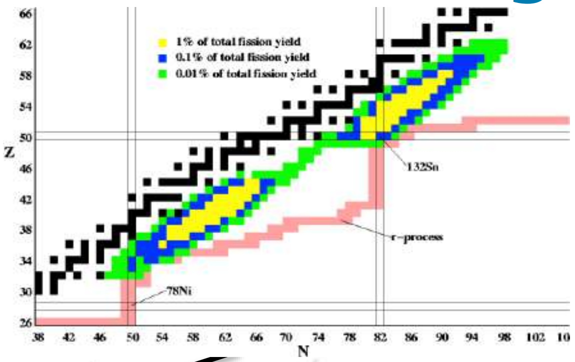


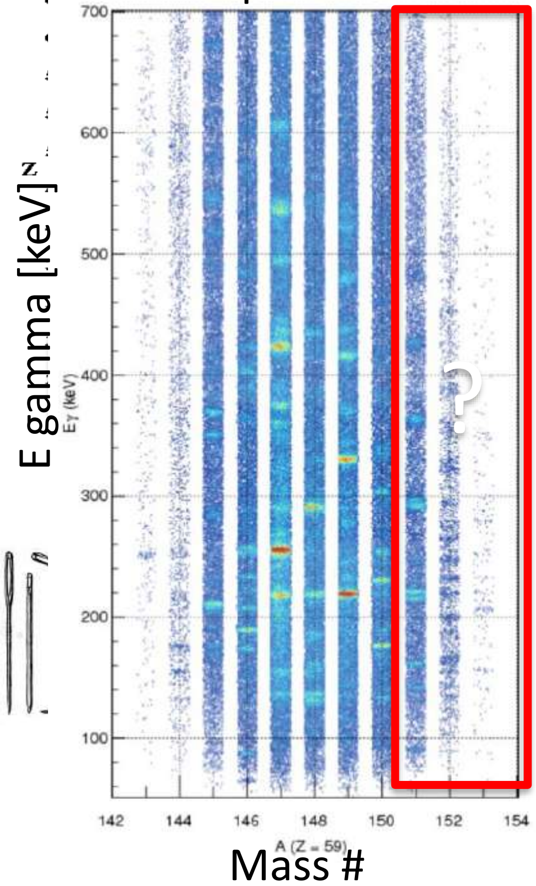
Pr isotope



Difficult to separate only with γ-ray coincidences

How to distinguish different nuclei?





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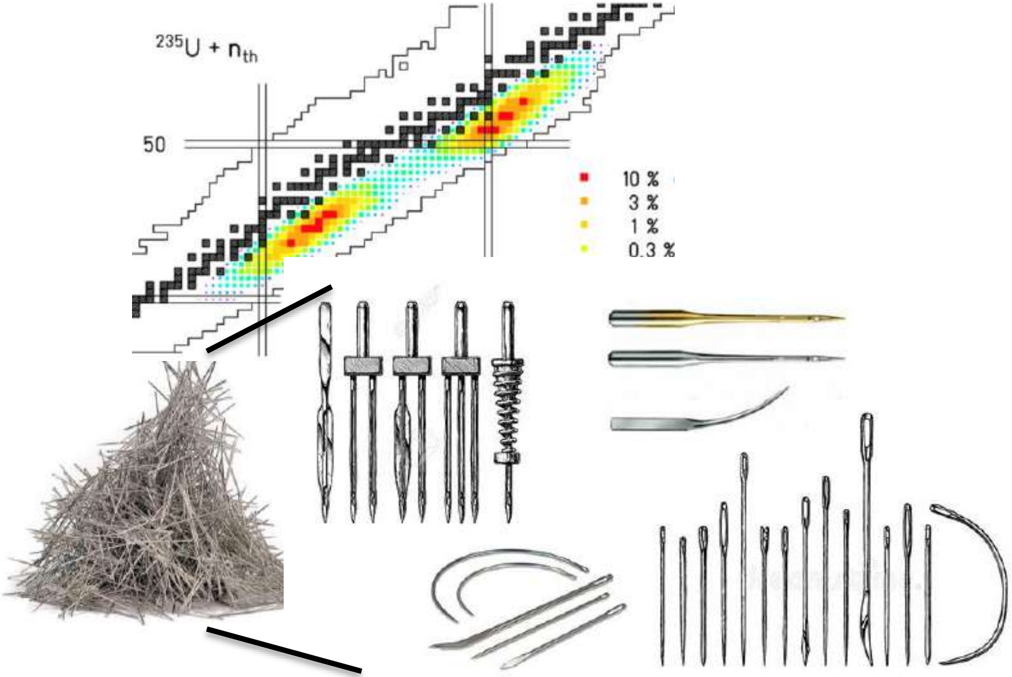
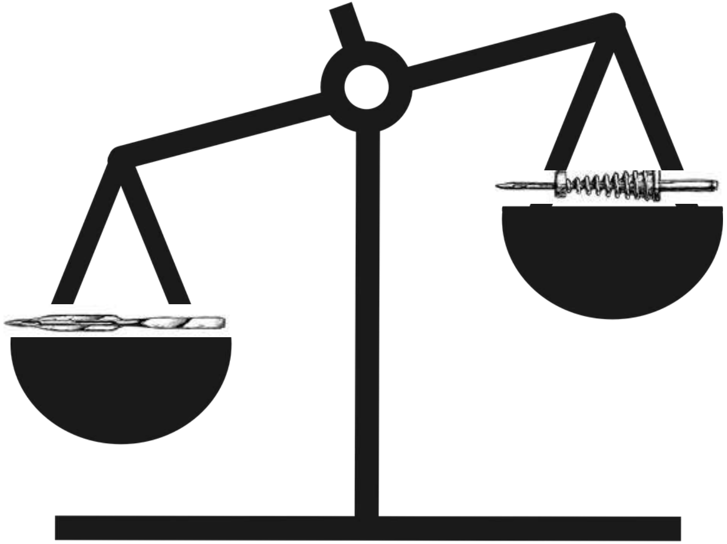
How to distinguish different nuclei?





Separate by mass of fission fragment!

Objective of FIPPS phase2

- Study more exotic part of nuclear chart

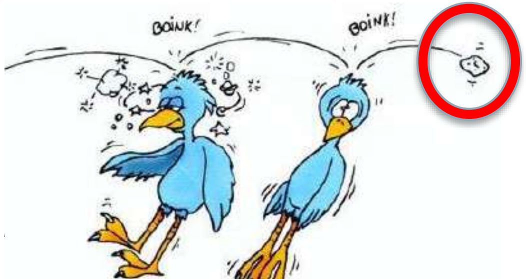
  -> **Better selectivity** of fission fragment

- New physics capability

  e.g. Fission dynamics: how angular momentum is generated?

  ->**Initial energy** of fission fragment

- List of requirements
  - ☐Large acceptance (>50 msr & dp/p>10%)
  - ☐Good mass resolution (<4 amu @ A=150)
  - ☐Kinetice energy detection (dE > several MeV)
  - ☐Easy operation

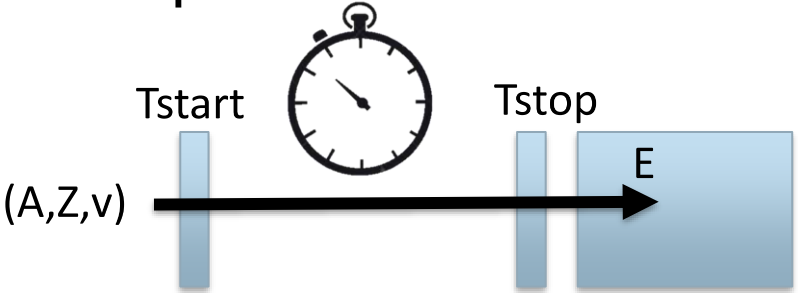


???

What solution is suitable for FIPPS II ?

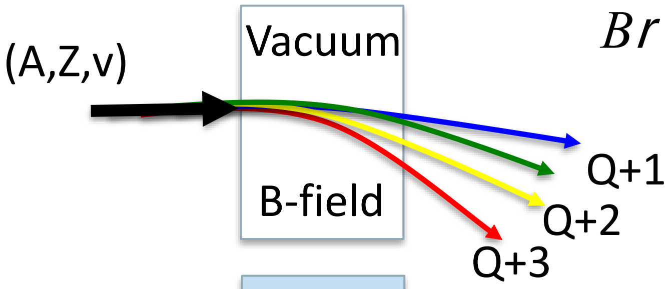
How to select mass of low energy fission fragments?

- v-E spectrometer

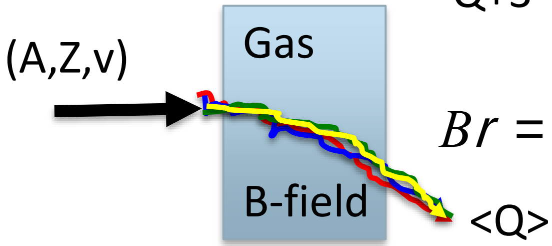


- E & v measurement
- M from simple principle $kE=(\gamma-1)Mc^2$, $v=L/t$

- Electro-Magnetic



$$Br = \frac{M}{Q} bg$$



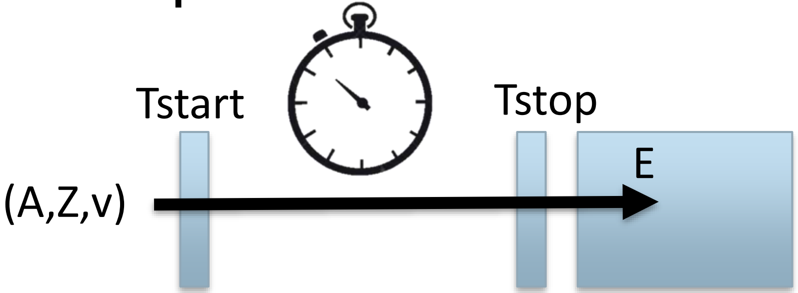
$$Br = \frac{M}{Q} bg \sim \frac{M}{Z^a}$$

- Q & **V** independent

->Large efficiency!

How to select mass of low energy fission fragments?

- v-E spectrometer



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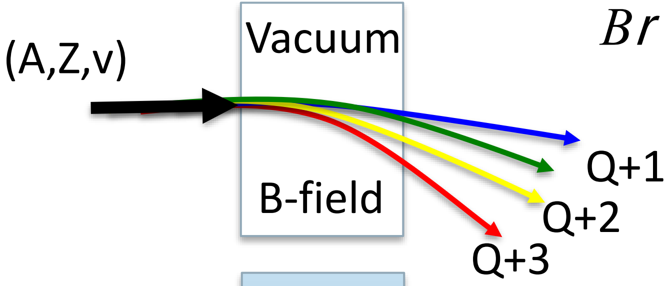

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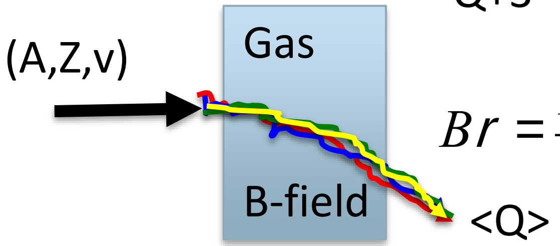

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- Q & **V** independent
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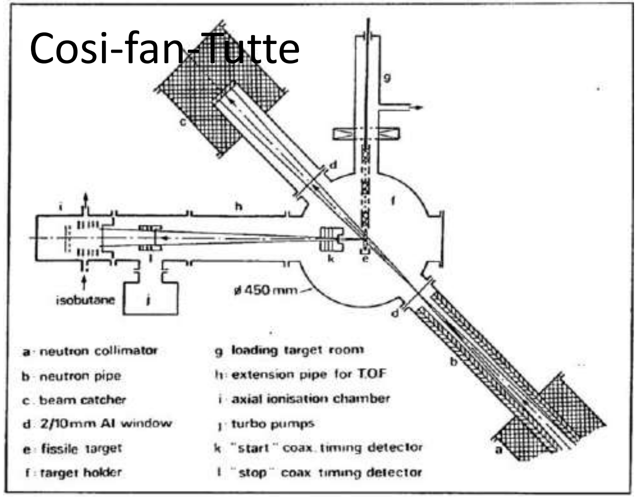
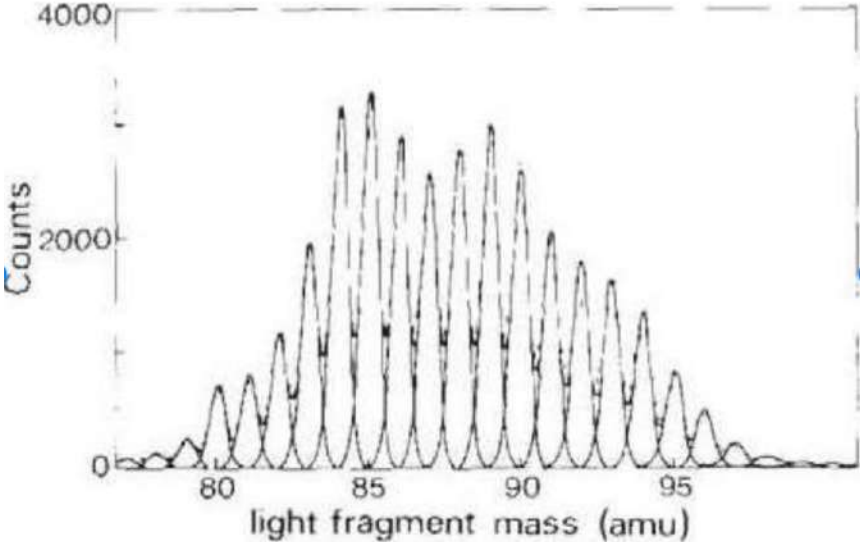
Separating fission fragments by its Mass using v-E spectrometer



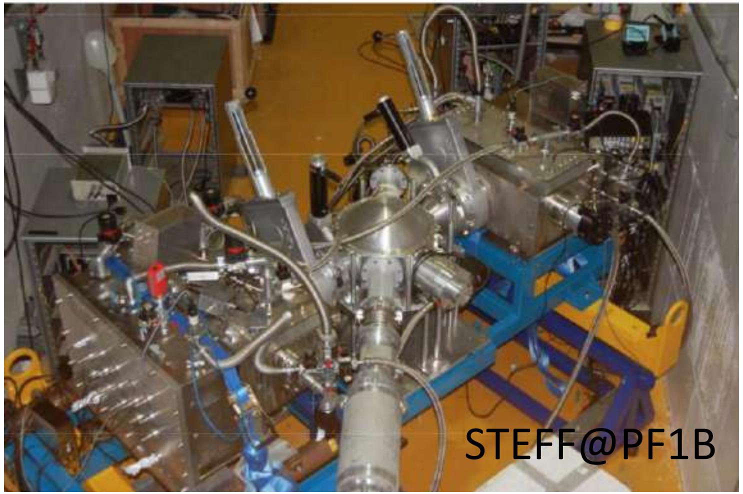


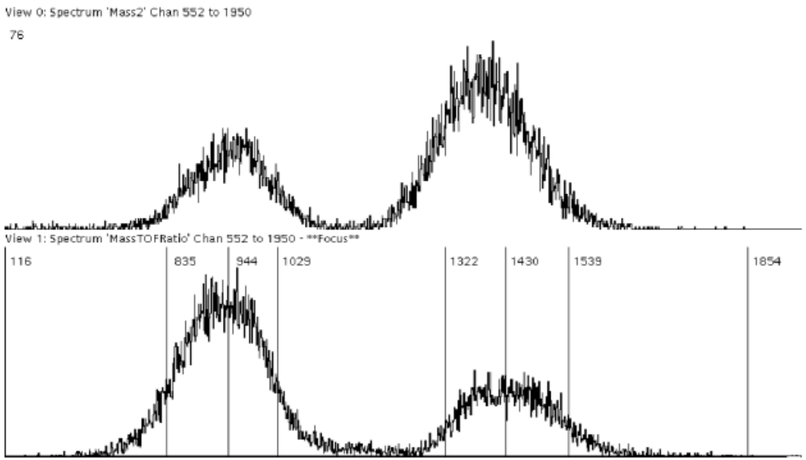
- **First sucessful type Cosi-fan-Tutte from ILL dA=**0.64 (acceptance 0.07 msr)
- **Direct measurement of kE and ToF (simple principle & less cost)**

A=2kE/v (v=L/ToF)

N. Boucheneb et al., Nucl. Phys A, 502 (1989) 261-270

Separating fission fragments by its Mass using v-E spectrometer





A.J. Pollitt PhD thesis (2013), S. G. Warren PhD thesis (2016)

LARGE ACCEPTANCE?

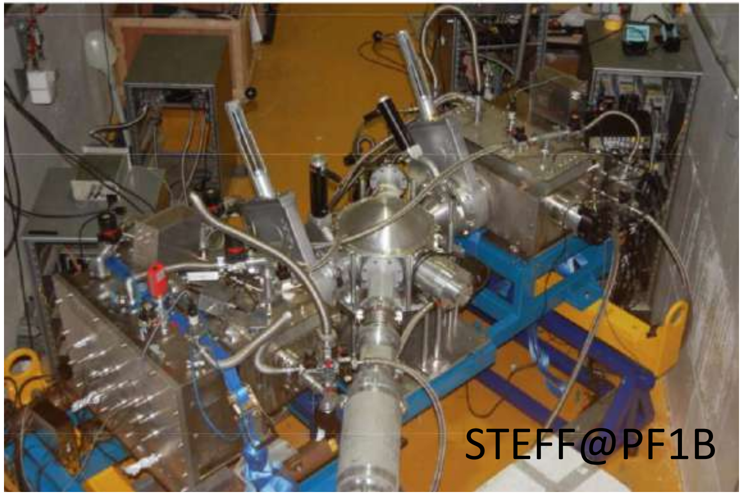
STEFF, FiFi used in ILL for fission but dA>4 amu (FiFI dA>8)

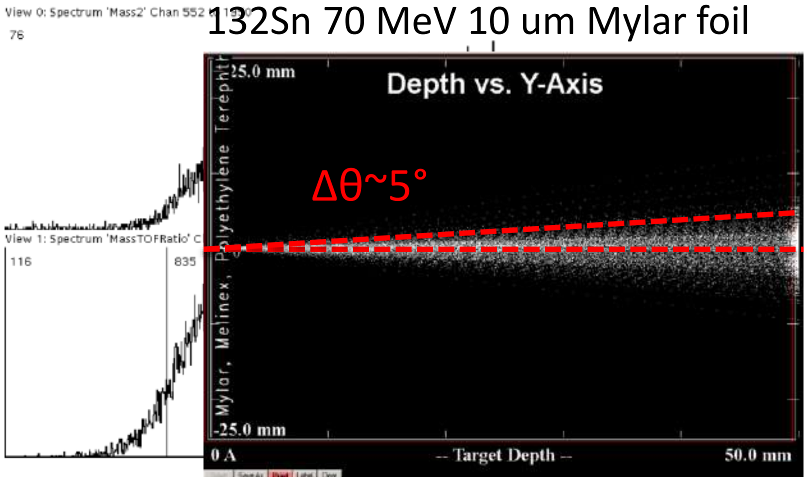
- **Uncertainty from energy loss, angular straggling.**
- **Difficult to have large acceptance with Ge-detector array**

Separating fission fragments by its Mass using v-E spectrometer

TRIM simulation

132Sn 70 MeV 10 um Mylar foil





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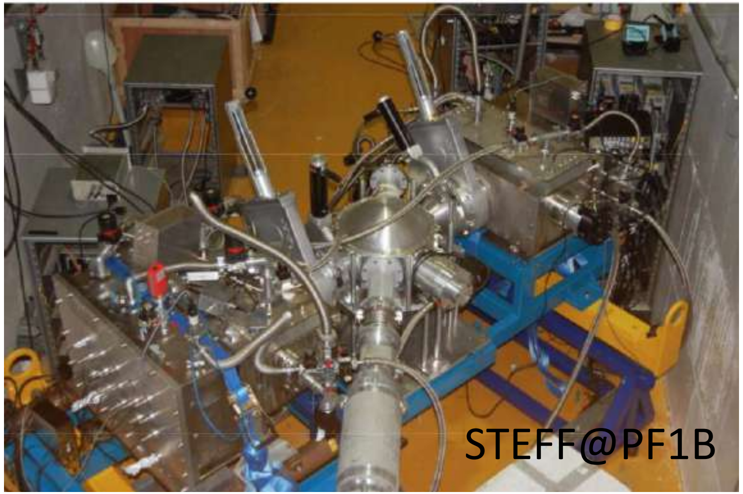

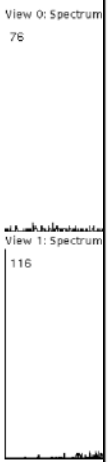

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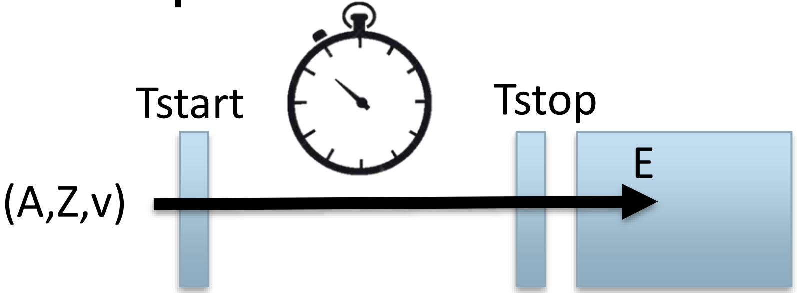
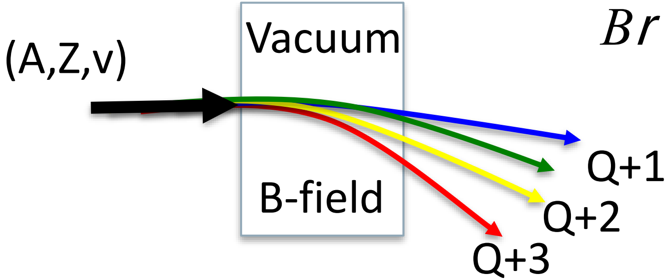
How to select mass of low energy fission fragments?

- v-E spectrometer



- E & v measurement
- M from simple principle $kE=(\gamma-1)Mc^2$, $v=L/t$
- Not easy to make large acceptance

- Electro-Magnetic



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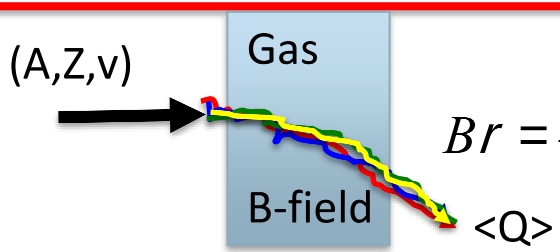


$$Br = \frac{M}{Q} bg \sim \frac{M}{Z^a}$$

- Q & **V** independent
  ->Large efficiency!

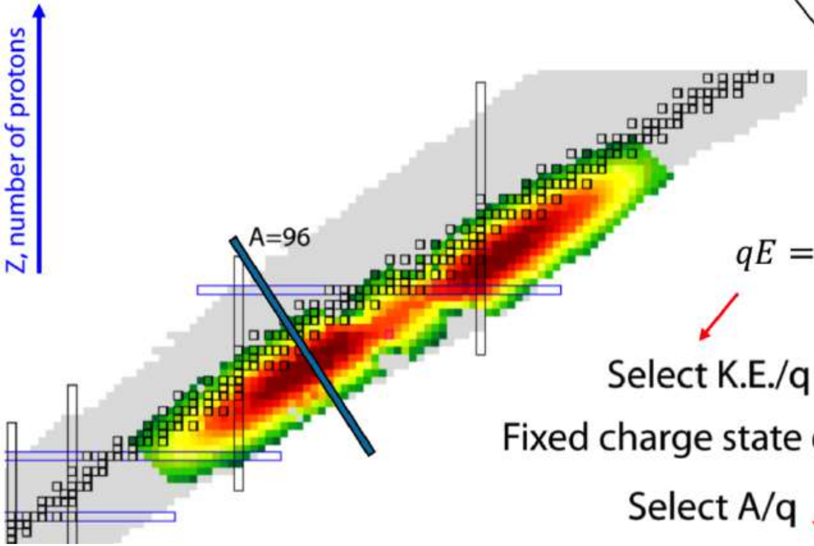
Lohengrin spectrometer

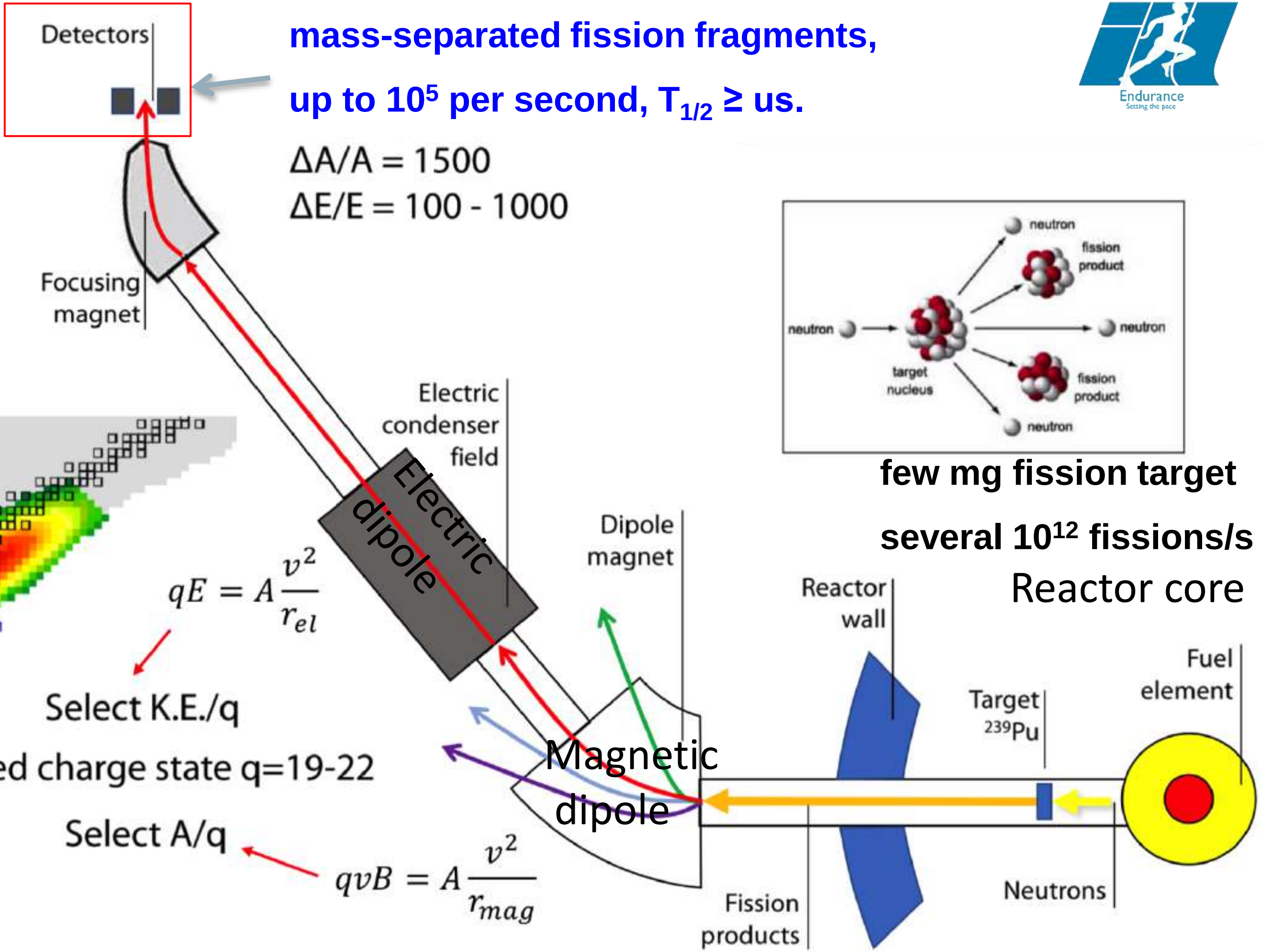
mass-separated fission fragments,

up to 10^5 per second, $T_{1/2} \geq$ us.

$\Delta A/A = 1500$

$\Delta E/E = 100 - 1000$





$$qE = A\frac{v^2}{r_{el}}$$

Select K.E./q

Fixed charge state q=19-22

Select A/q

$$qvB = A\frac{v^2}{r_{mag}}$$

few mg fission target

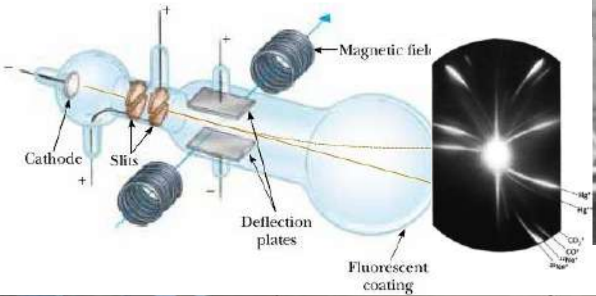
several 10^{12} fissions/s

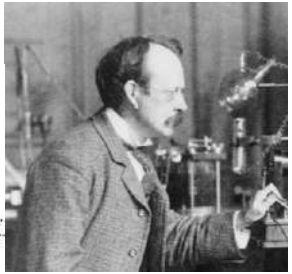
Reactor core

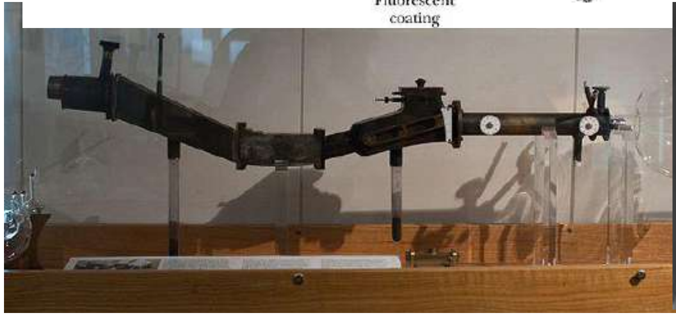
LOHENGRIN spectrometer

J.J. Thomson & F. Astons

mass spectrograph first isotopic separation $^{20/22}$Ne



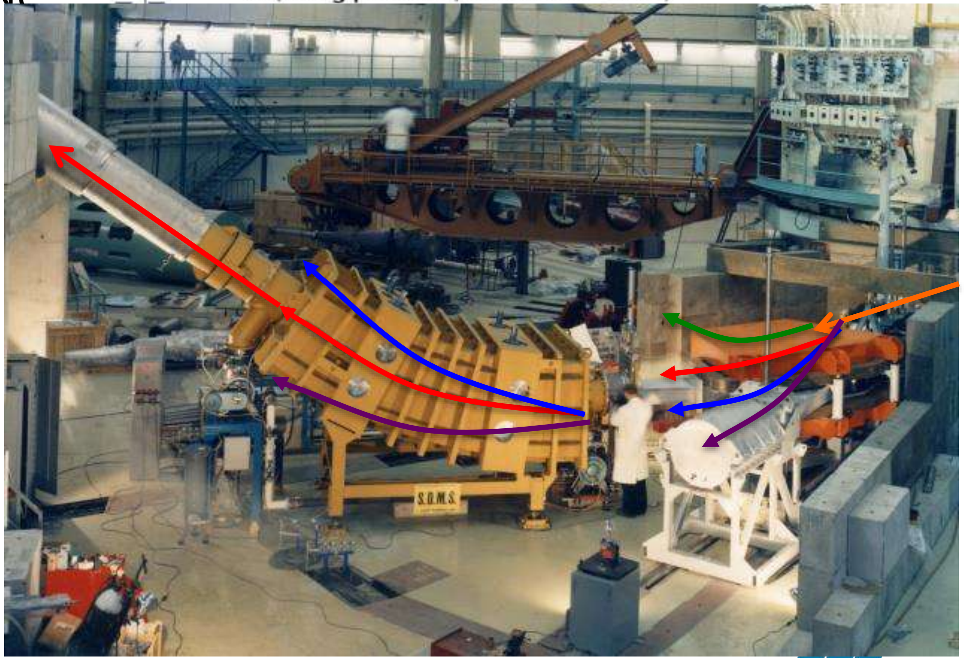




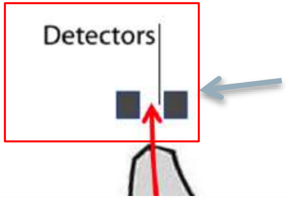
Lohengrin GIANT descent

Detectors

Δl (along parabola)=7.2 cm for 1%ΔE,



Lohengrin spectrometer



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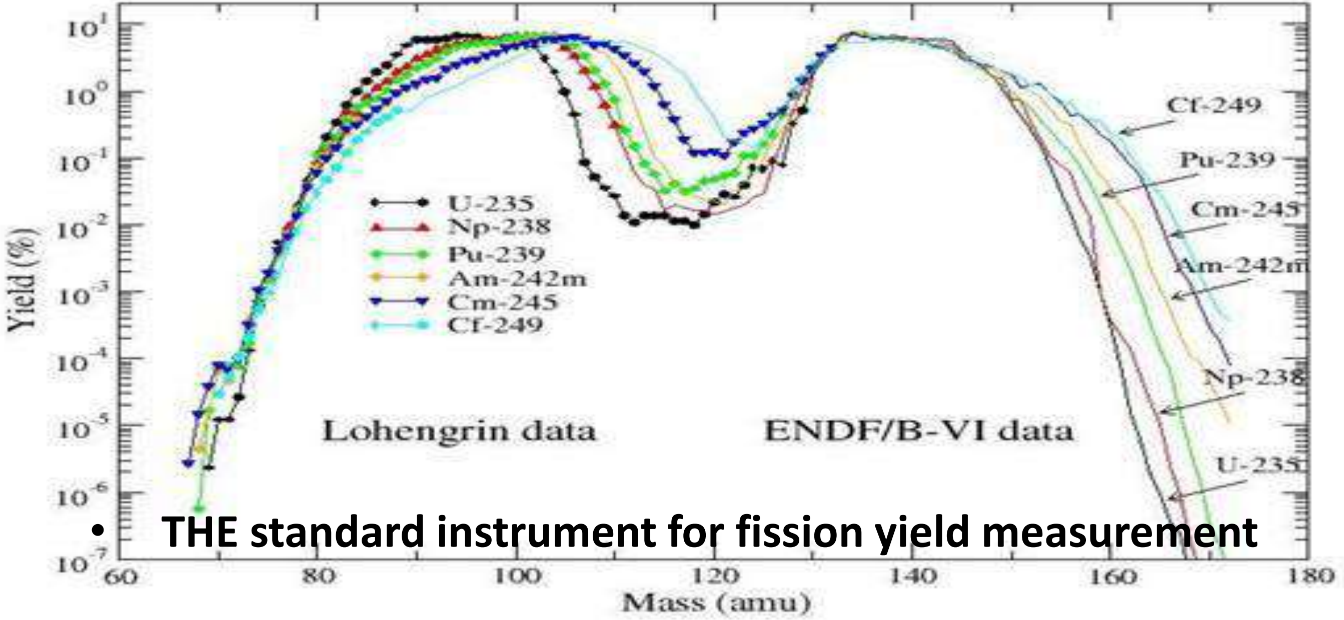
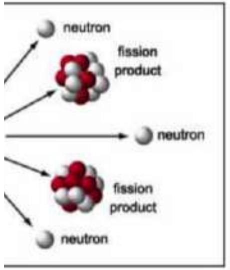
up to 10^5 per second, $T_{1/2} \geq$ us.

$\Delta A/A = 1500$

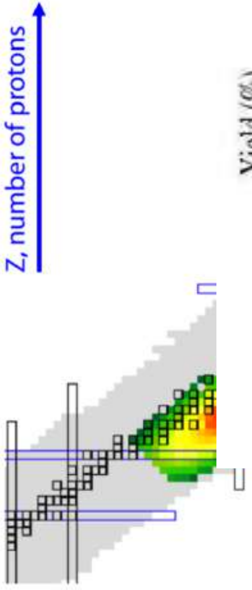


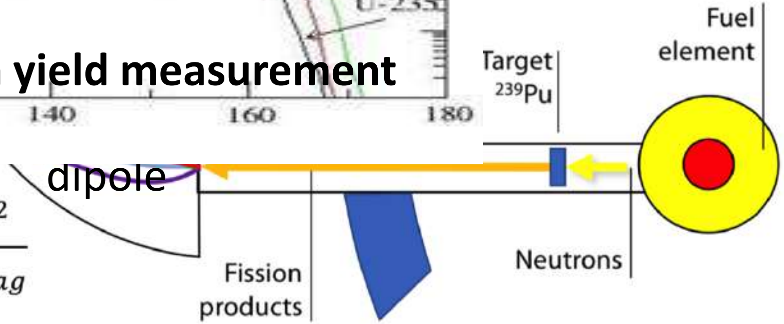
- **THE standard instrument for fission yield measurement**



ıg fission target

al 10^{12} fissions/s





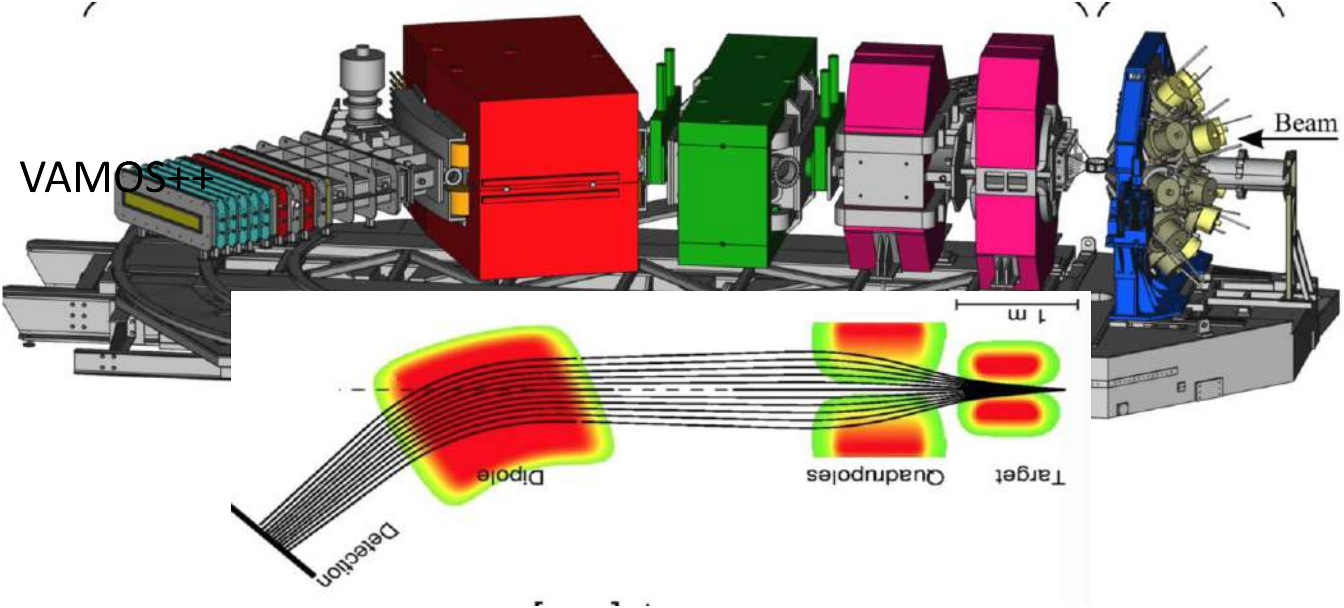
Select A/q

$$qvB = A\frac{v^2}{r_{mag}}$$

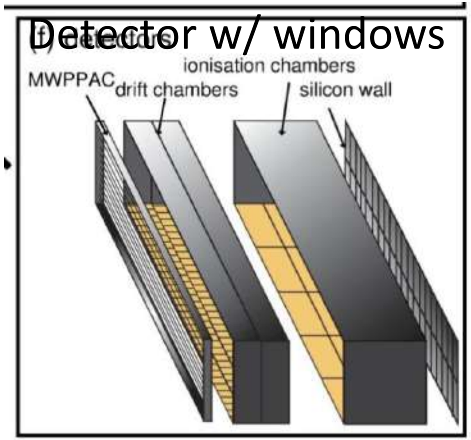
- **very small acceptance (0.032 msr)**

Conventional large acceptance spectrometer

VAMOS++



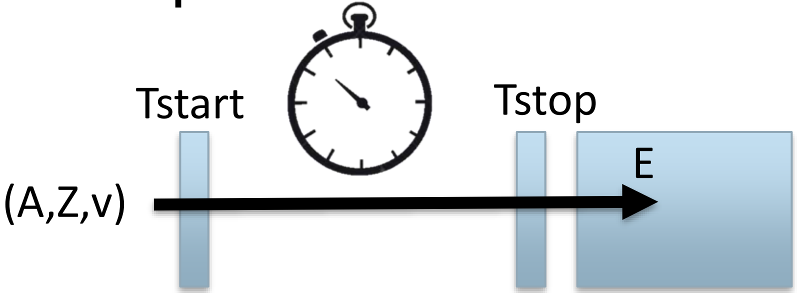
Detector w/ windows



- Tracking of ions inside using detecors
- Need simple magnet+complex detector & software
- Tracking of ions at n induced fission? : **« Windowless » tracking detector at low pressure He X**

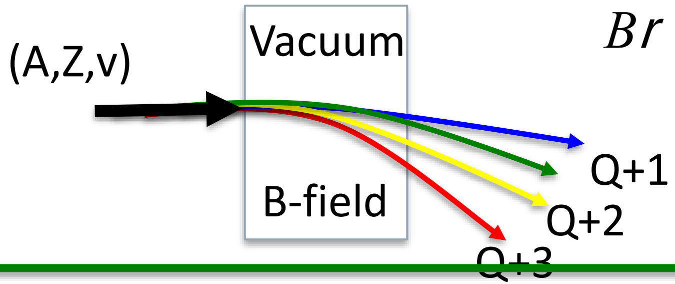
How to select mass of low energy fission fragments?

- v-E spectrometer

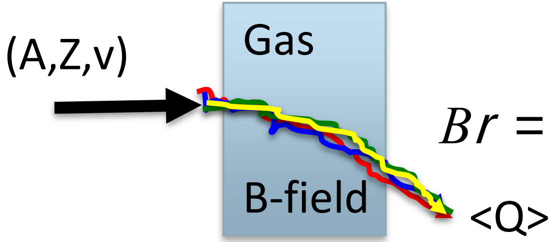


- E & v measurement
- M from simple principle $kE=(\gamma-1)Mc^2$, $v=L/t$
- Not easy to make large acceptance

- Magnet



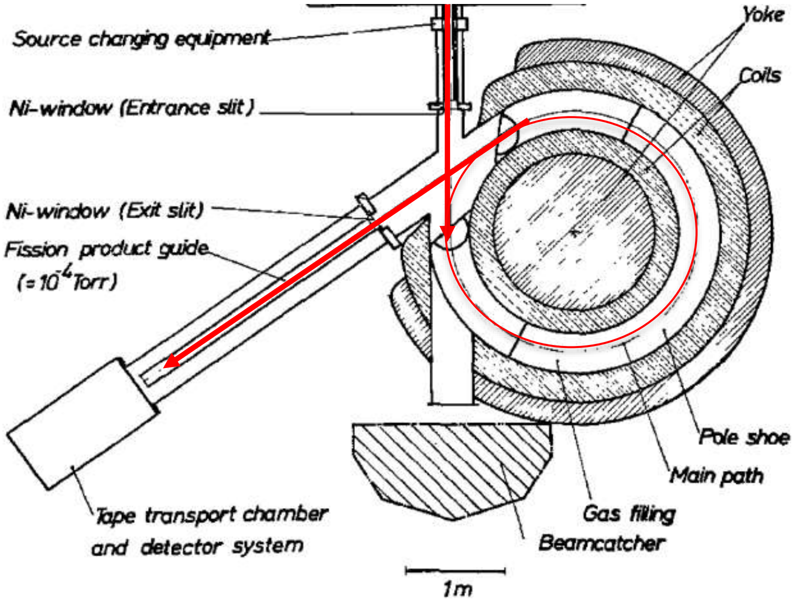
$$Br = \frac{M}{Q} bg$$



$$Br = \frac{M}{Q} bg \sim \frac{M}{Z^a}$$

- Q & **V** independent
  ->Large efficiency!

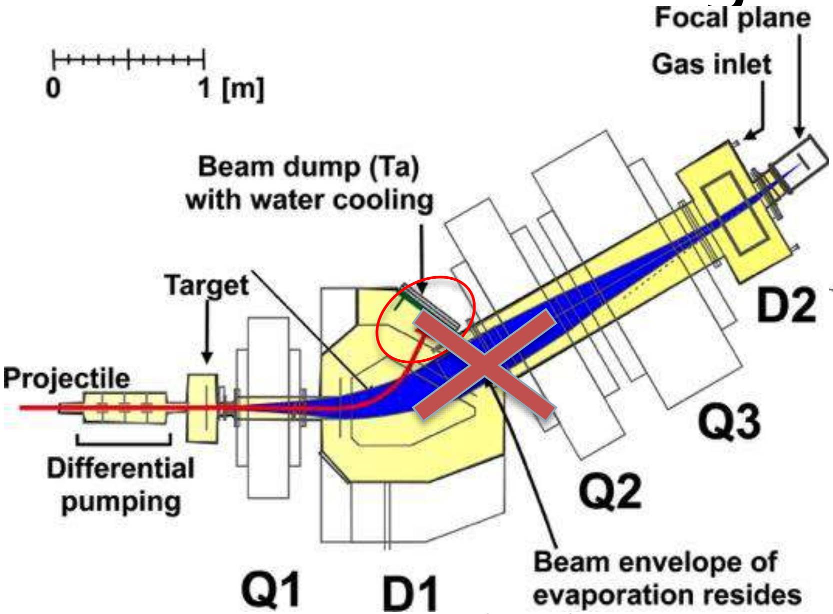
Gas Filled Magnet for fission fragment: JOSEF spectrometer



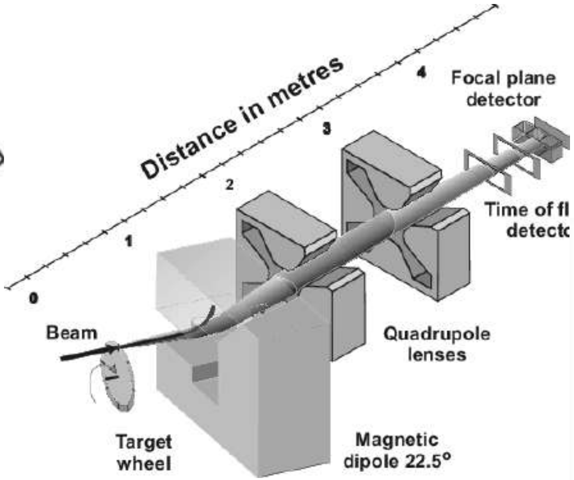
$$Mass \approx Const * (B\rho\, Z^{1/3})$$

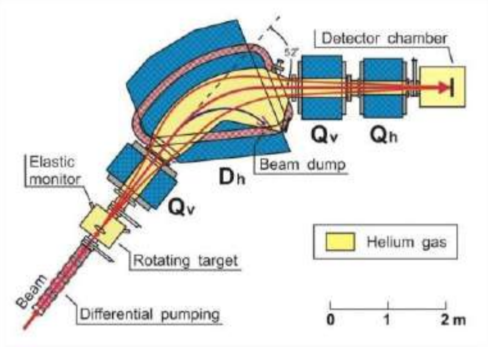
- Gas filled magnet for fission fragment
- 1/r-field: high separation power (dispersion:)
- Can separate only ion with straight direction -> **Small acceptance (0.022 msr)**
- **Good mass resolution ~1.3 amu**

Difficulties using conventional system



D. Kaji et al., NIMB 317 (2013) 311





- Conventional gas filled magnet design Needs

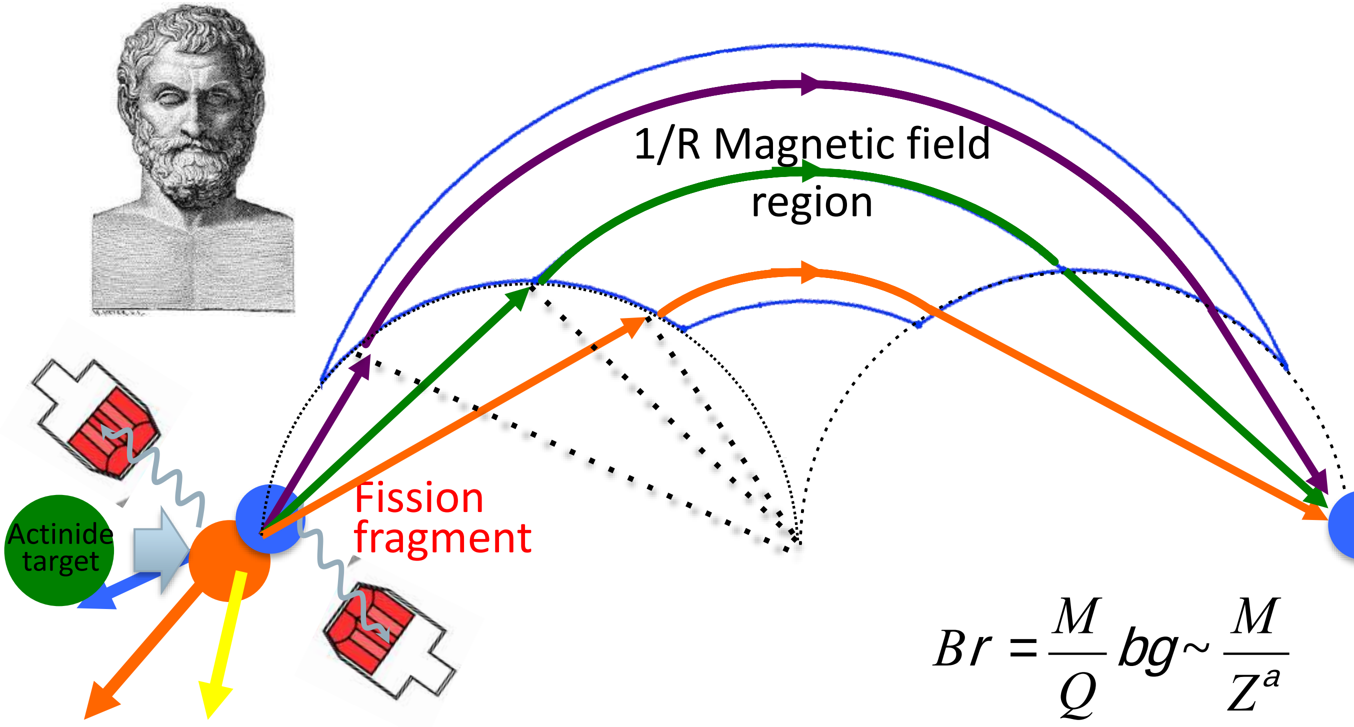
  Reaction fragment are forward focused: **Fission products X**

  Clear separation of products & beam : **Fission products X**

No existing solution…

New method needed ?

New Concept- 1/r +Thales circle



- Fragment trajectory vertical to the radial direction of magnet center
- 1/R field ->Same Bρ in all region

->Automatic Focusing!

$$B r = \frac{M}{Q} b g \sim \frac{M}{Z^a}$$

Objective of FIPPS phase2

- Study more exotic part of nuclear chart

  -> **Better selectivity** of fission fragment

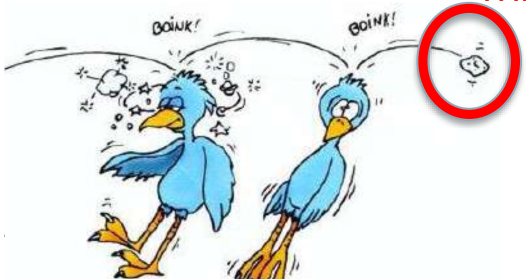
- New physics capability

  e.g. Fission dynamics: how angular momentum is generated?

  ->**Initial energy** of fission fragment

- List of requirements
  - ☐Large acceptance (>50 msr & dp/p>10%)
  - ☐Good mass resolution (4 amu @ A=150)
  - ☐Kinetice energy detection (dE > several MeV)
  - ☐Easy operation

GAS FILLED MAGNET

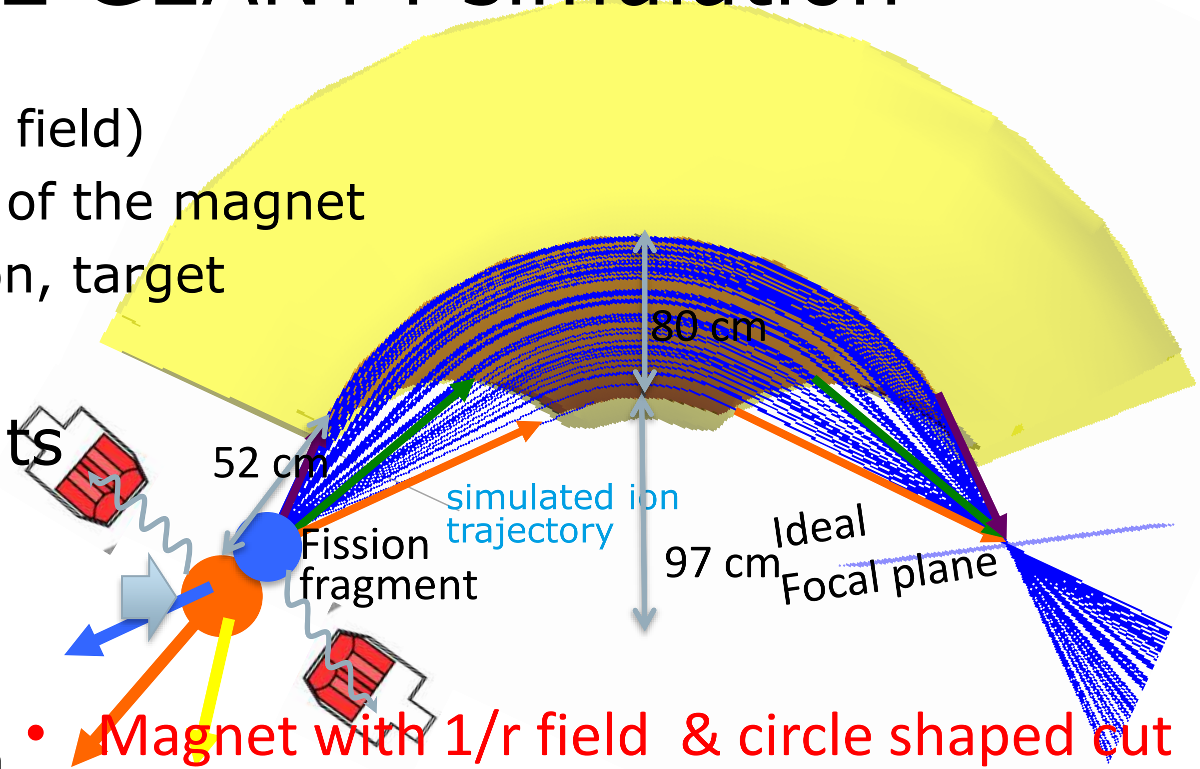


FIPPS-PHASE2 GEANT4 simulation

ISSUE in the concept

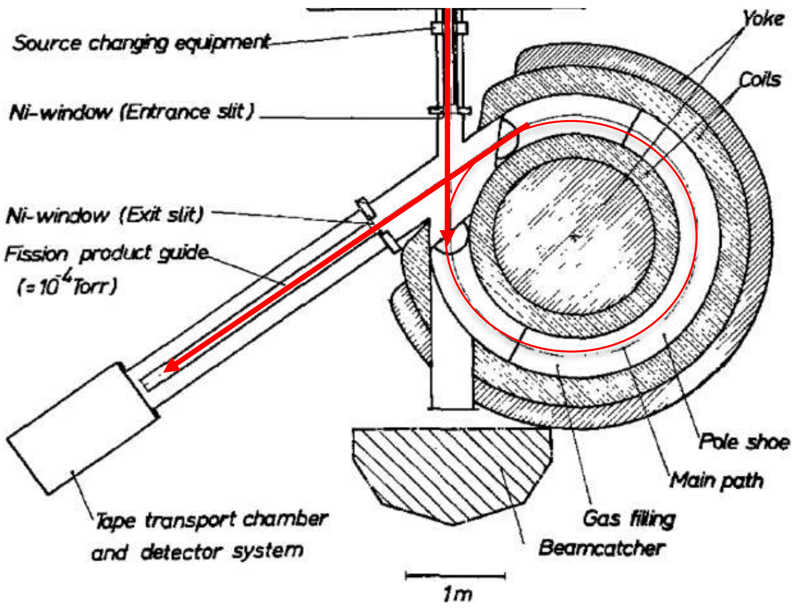
- Ideal field (No fringing field)
- Initial geometry study of the magnet (radius, good field region, target position)

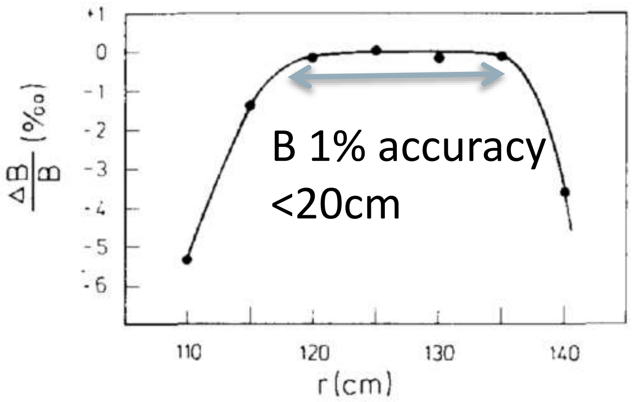
- List of requirements
  - ☐Large acceptance (>50 msr & dp/p>10%) ✓
  - ☐Good mass resolution (4 amu @ A=150) ✓
  - ☐Kinetice energy detection (dE > several MeV)
  - ☐Easy operation ✓



- Magnet with 1/r field & circle shaped cut of 80 cm width never made before
- Effect from gas is not considered

Realistic field: previous case



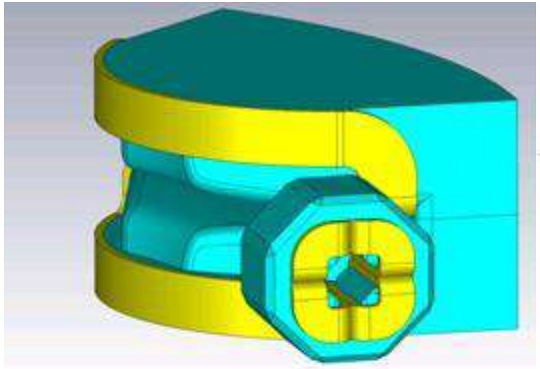


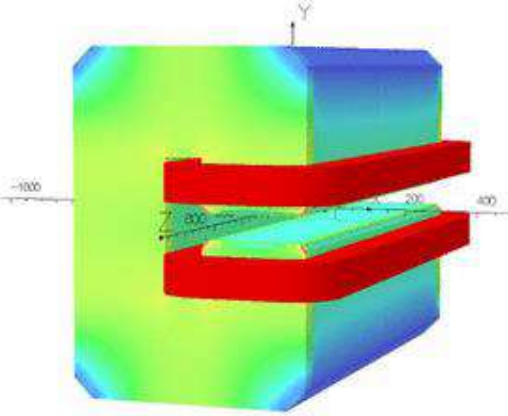
- No one made 1/R field with large width
- Modern computation simulation might give better result?

H. Lawin et al., NIM 137 (1976) 103

Realistic field : New Methods

AGFA recoil separator



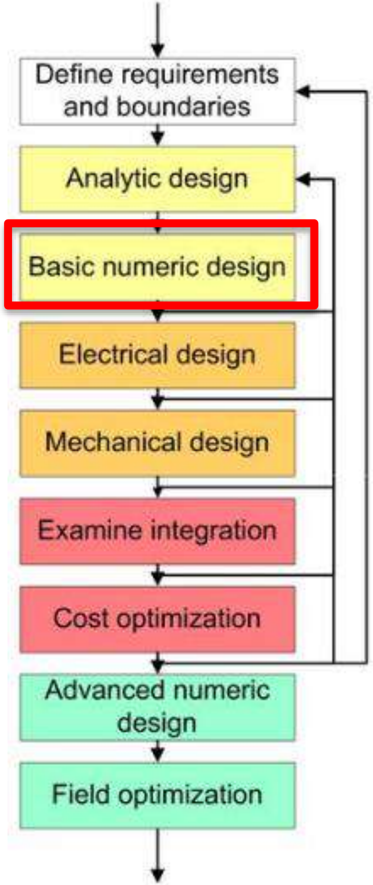


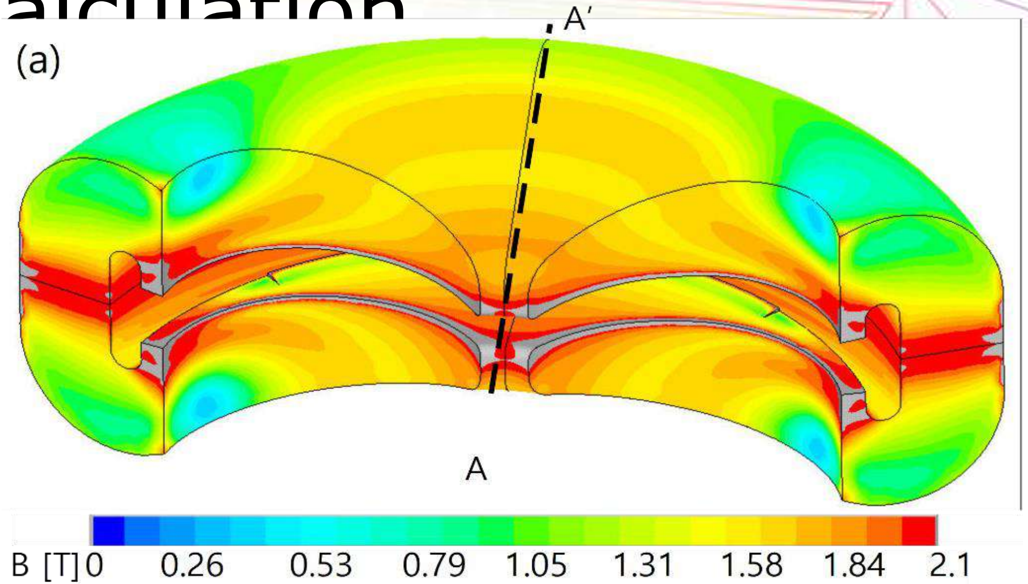
- Accuracy computational field improved.
- Simulation of ions track inside field with gas possible.

-> non-uniform magnetic fields

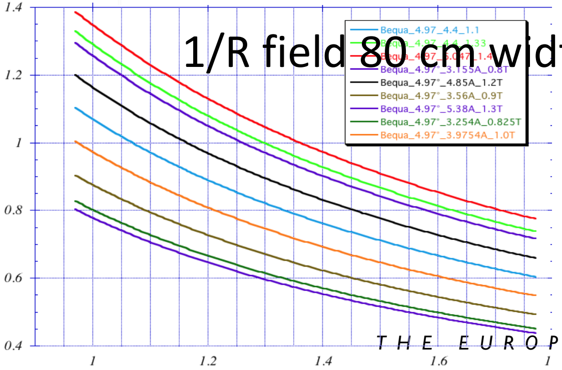
& complicated edge design becomes possible

Realistic field calculation

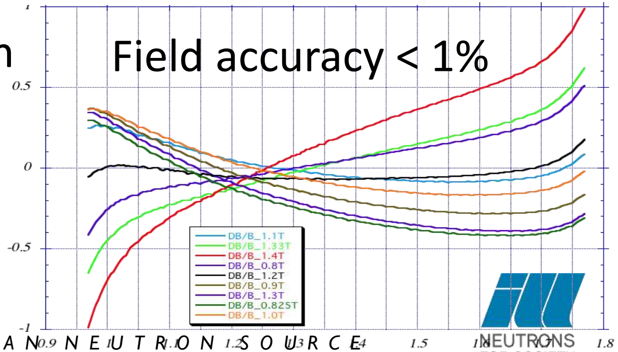




1/R field 80 cm width

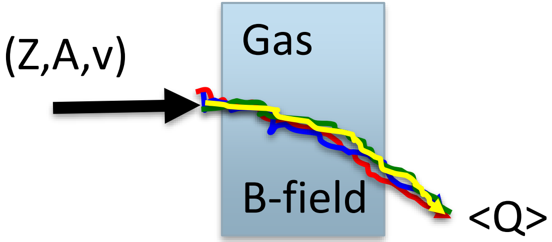


Field accuracy < 1%



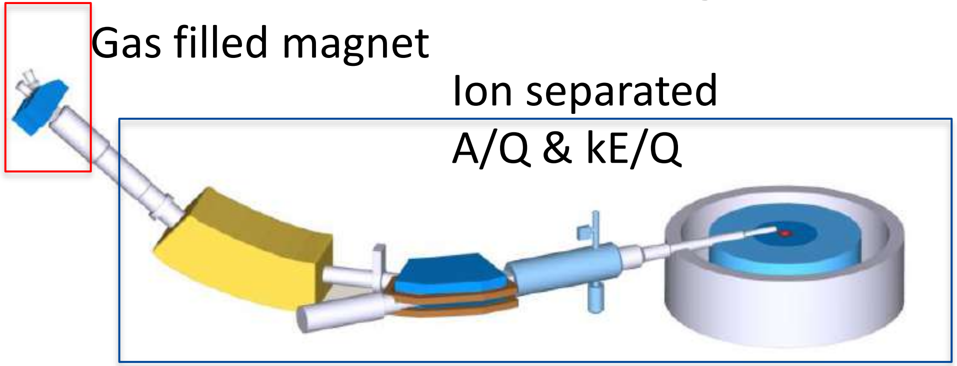
Effect of gas on fission fragment?

$$B r = \frac{M}{Q} b g \sim \frac{M}{Z^a}$$



Mean free path He gas
1 mbar 180 um
10 mbar 18 um

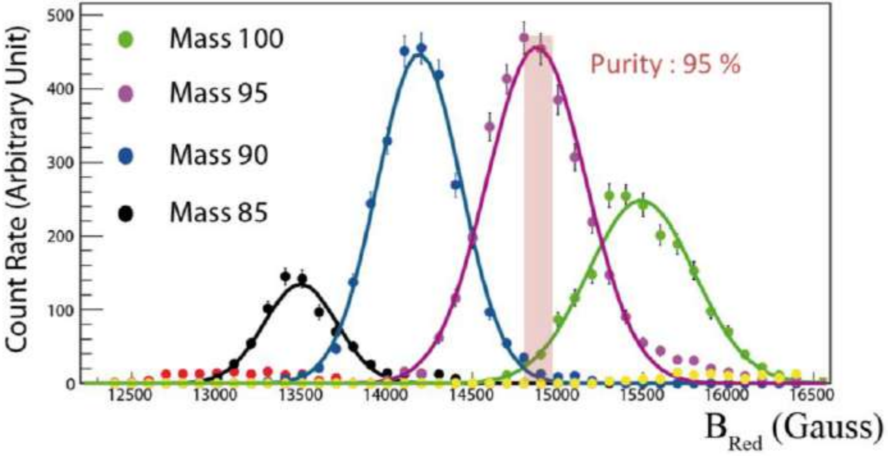
Test experiment @ Lohengrin



- Test of ion separation
- Test of $\langle Q \rangle$ & σ_Q from different gas pressure
- ^{98}Y as referece

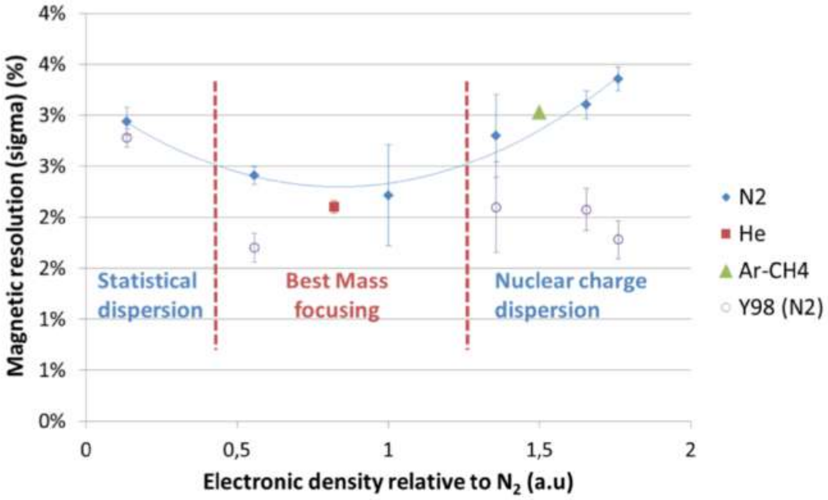
Test experiment @ Lohengrin

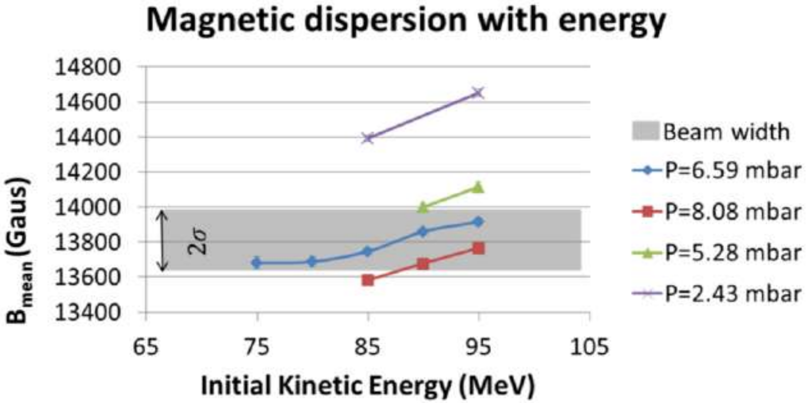
Experimental spectrum at the exit of the GFM at 40 mbar of He



Fission fragment with same A/Q separated in GFM by M/Z[a]

A. Cheboubbi PhD thesis





A. Cheboubbi PhD thesis

The ingredients for designing a magnet

FIPPS GFM

- Realistic field calculation

:ANSYS software

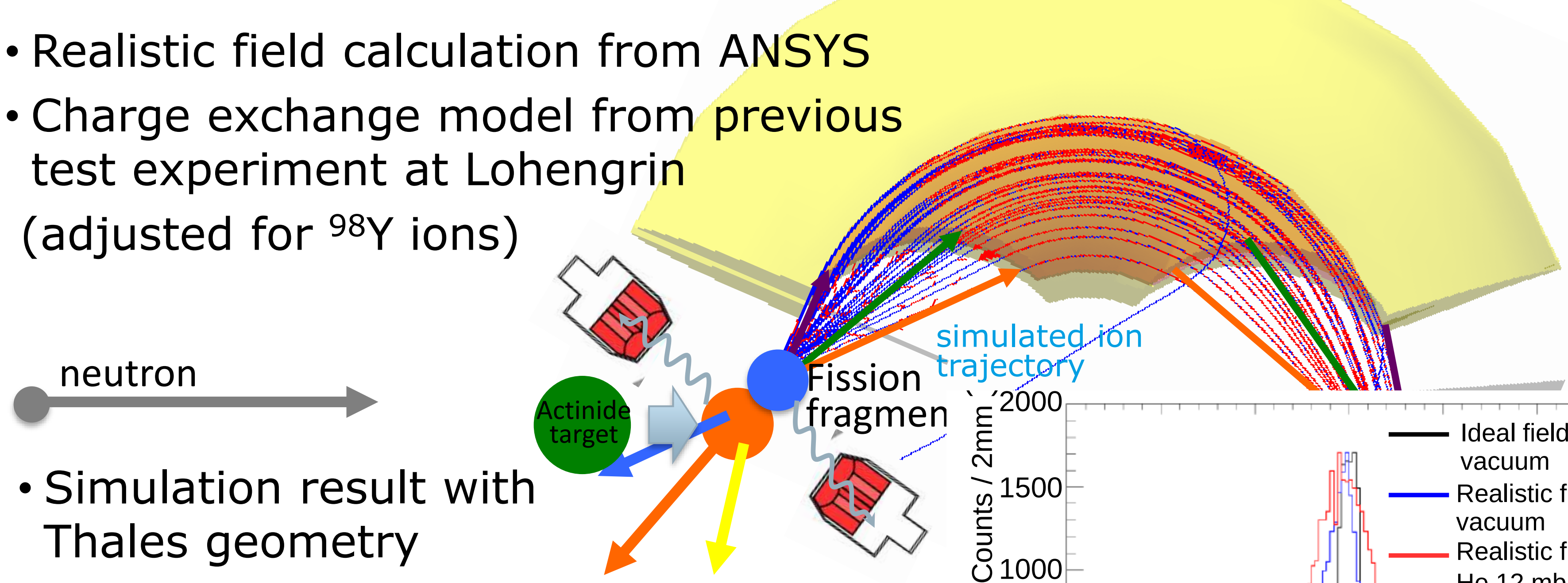
- Test of <Q> & σ_Q ->Lohengrin test experiment

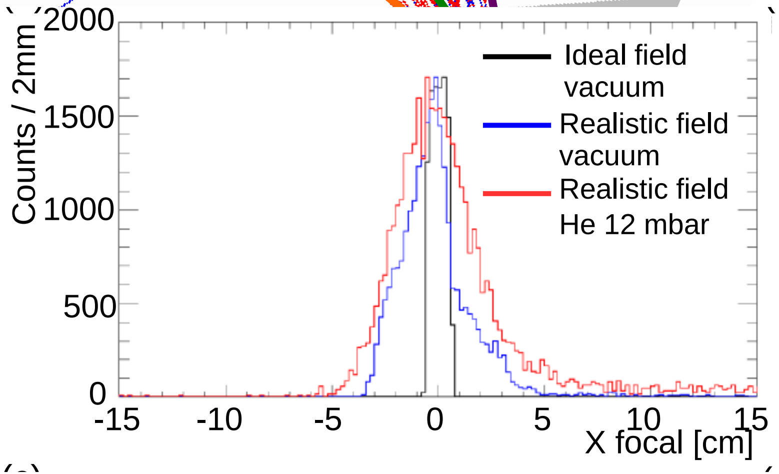
- Ion trajectory simulation: GEANT4 simulation

FIPPS GFM simulation-focus size

- Realistic field calculation from ANSYS
- Charge exchange model from previous test experiment at Lohengrin

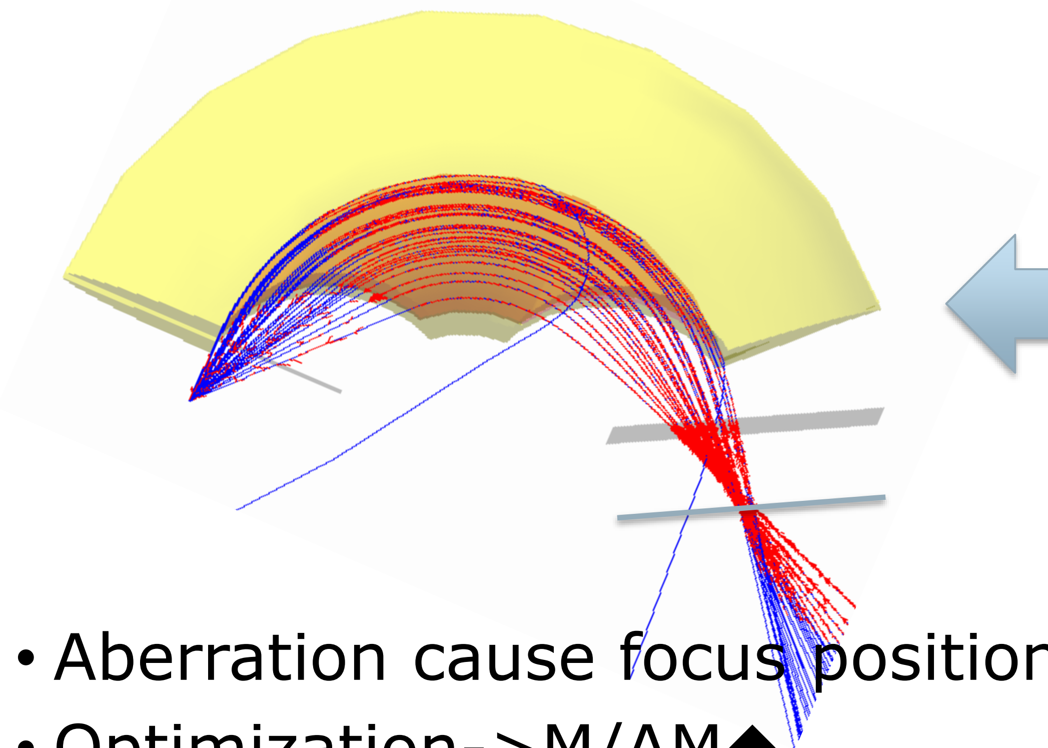
(adjusted for ^{98}Y ions)

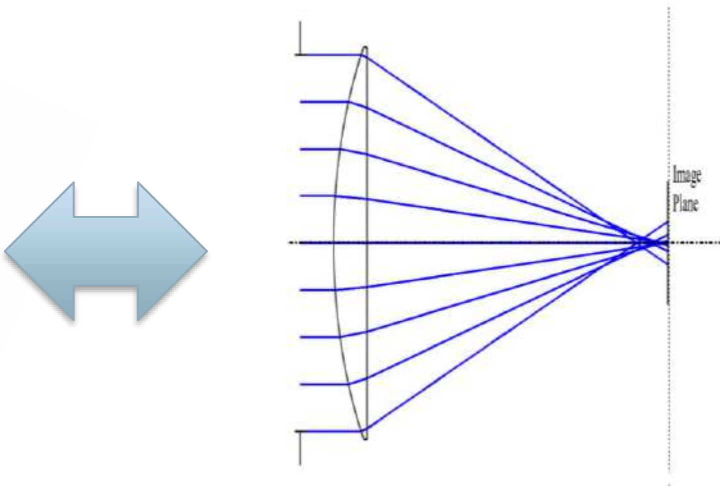




- Simulation result with Thales geometry
- Large shift of focal plane from intended position & events at the edge not focused

Optimization?

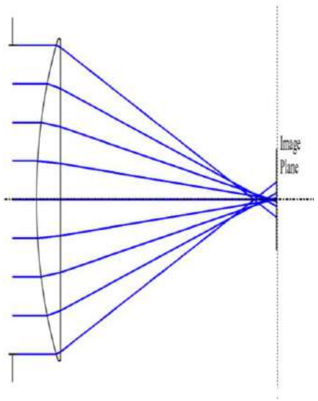


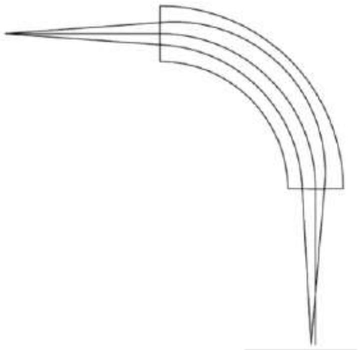


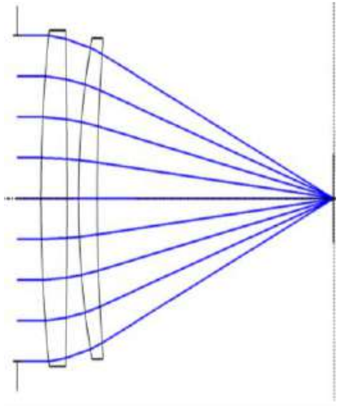
- Aberration cause focus position & focus size change
- Optimization->M/ΔM↑

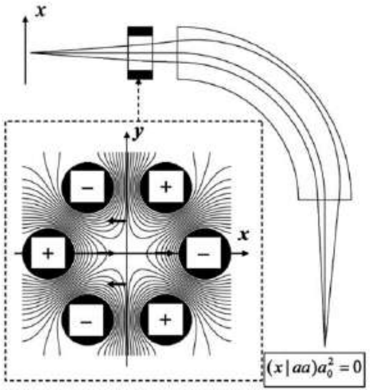
Design spectrometer

Abberation correction in optical lense

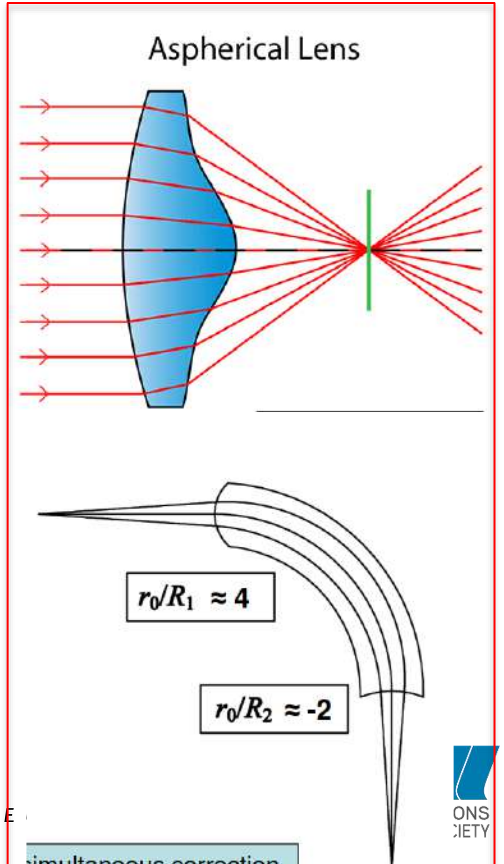




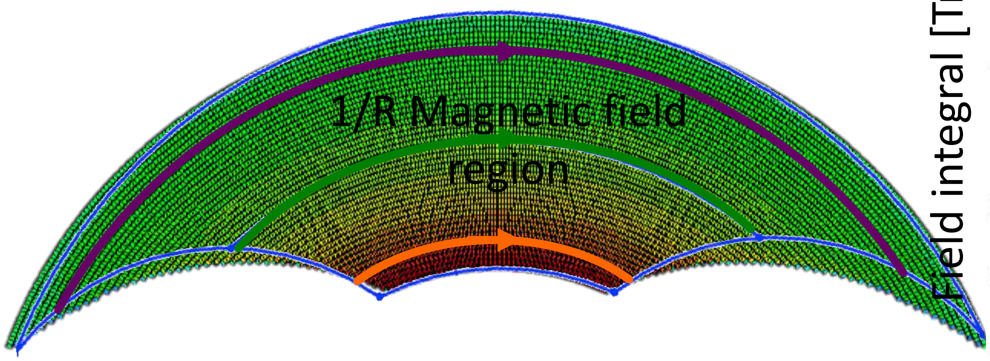


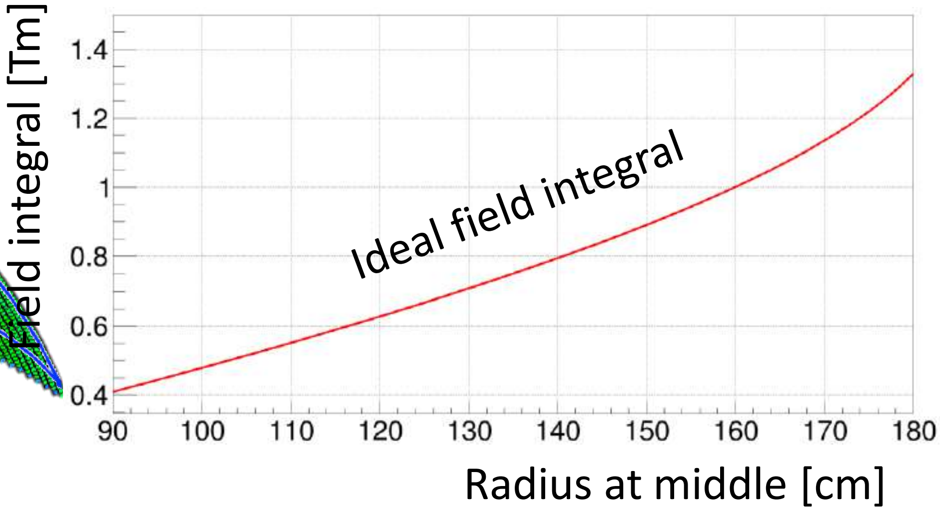


OR



Optimisation using field integral





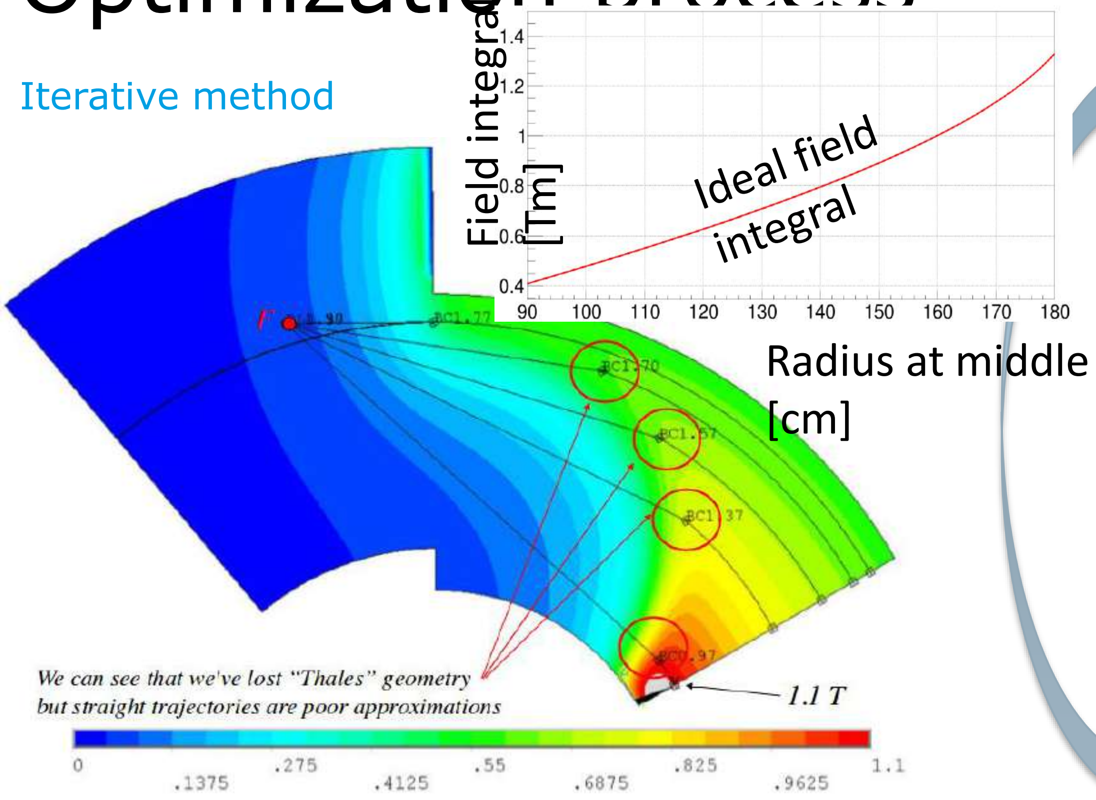
- Optimization with which value?
  - Need to be simple
  - Can be easily calculated in magnetic field simulation

$$\int \vec{B} \times d\vec{x} = \frac{\Delta \vec{P}}{Q}$$

- Field integral ~how much ion is bent through trajectory

Optimization process

Iterative method



Trial trajectory in field simulation

Calculate Field integral in trajectory

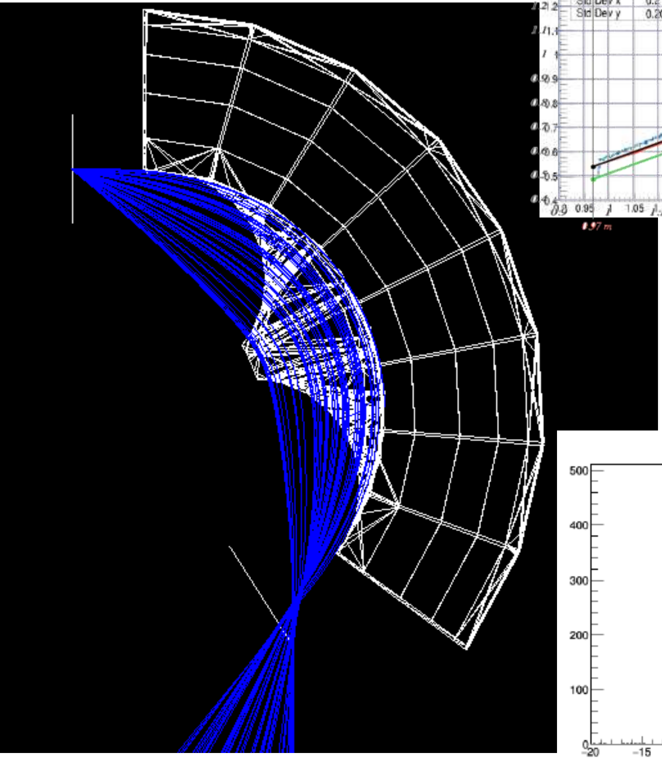
Change magnet shape to match ideal case

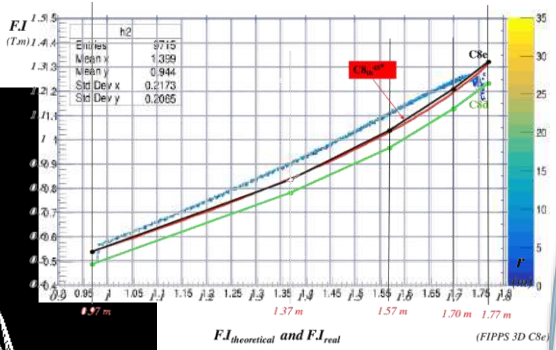
GEANT4 simulation
Check focus position/size

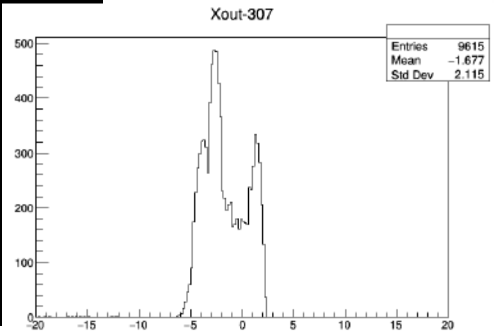
Find real trajectory

Optimization process

Iterative method







Trial trajectory in field simulation

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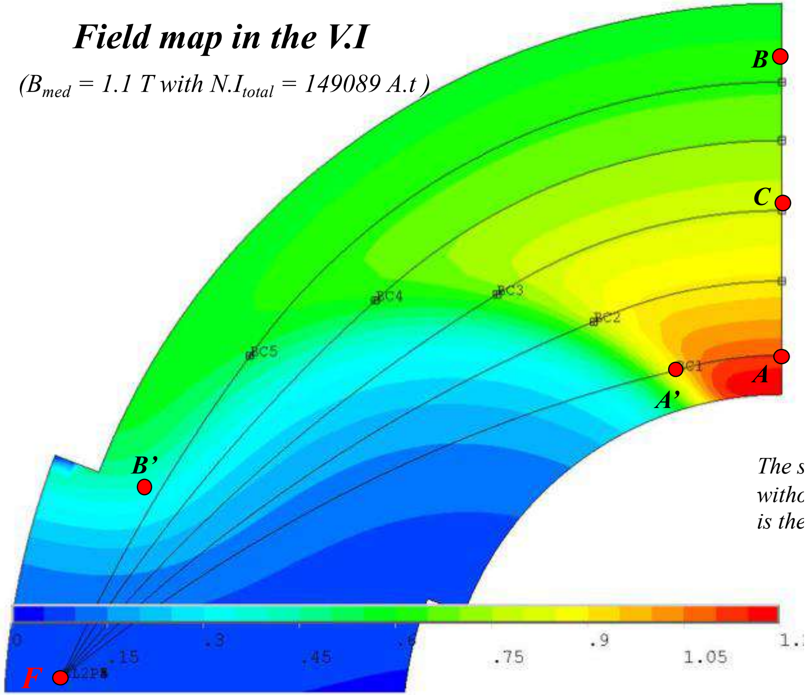
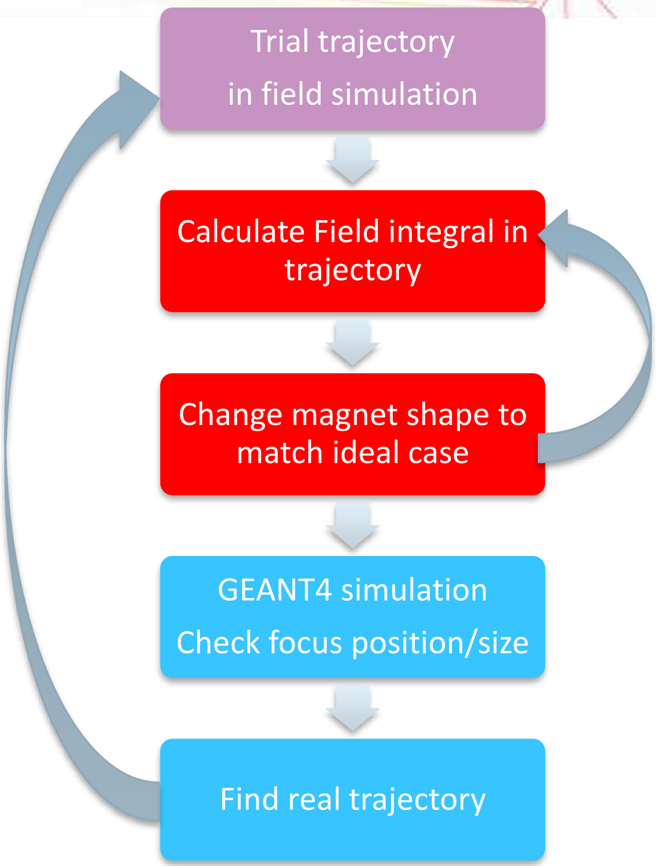
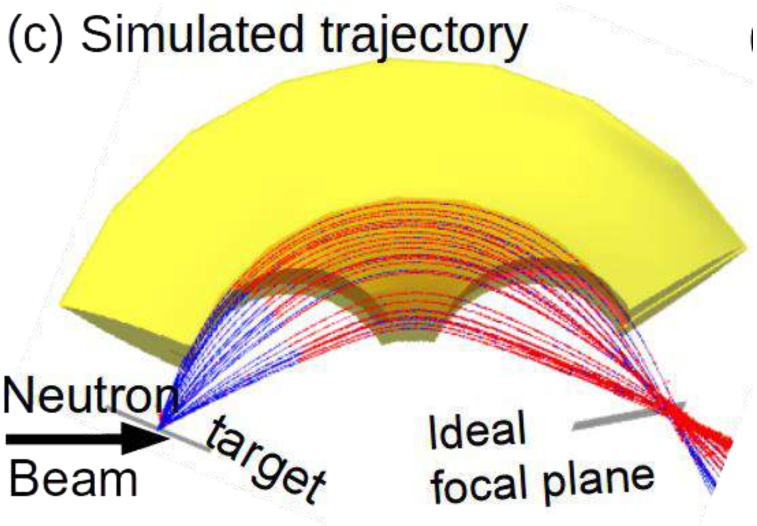
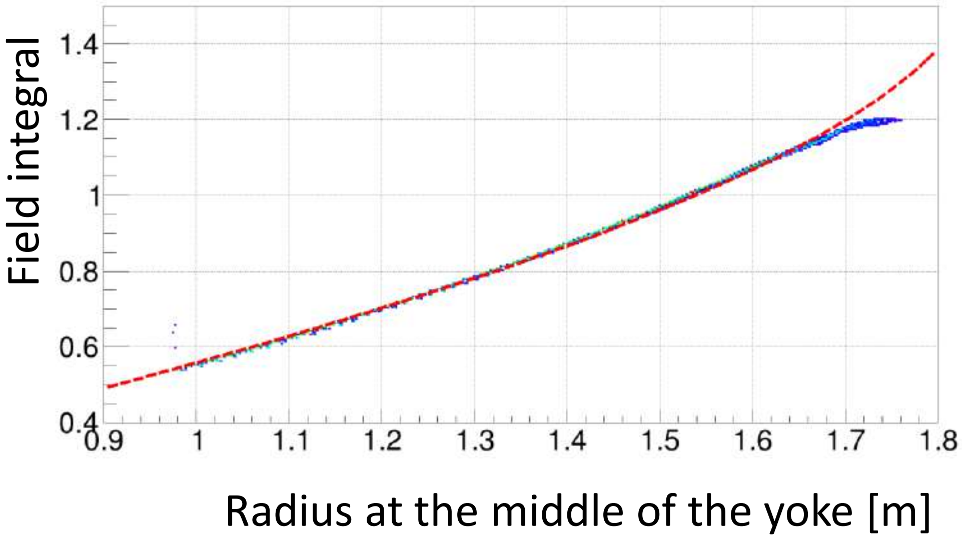
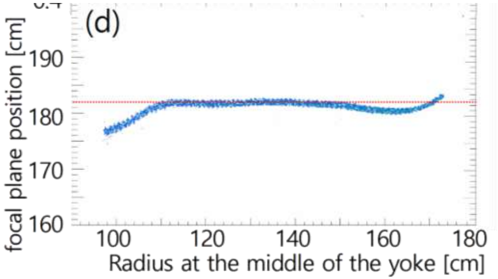




Optimisation: preliminary Result

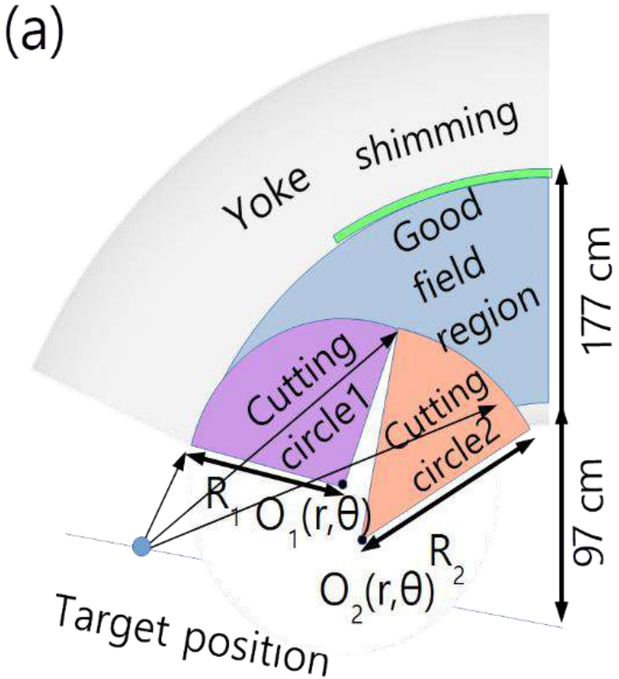


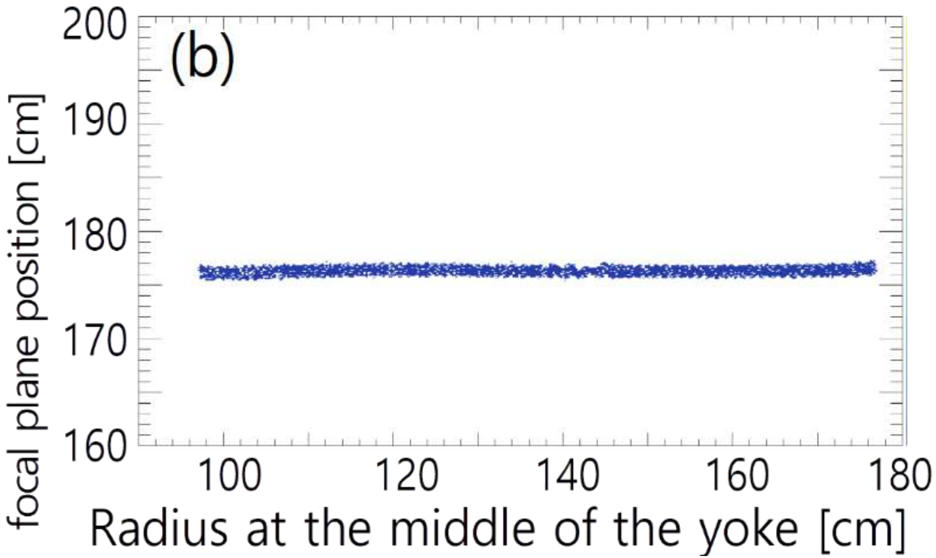




- Field integral close to ideal
- Focusing at at the intended position
- Focusing for trajectories near edge needs more work

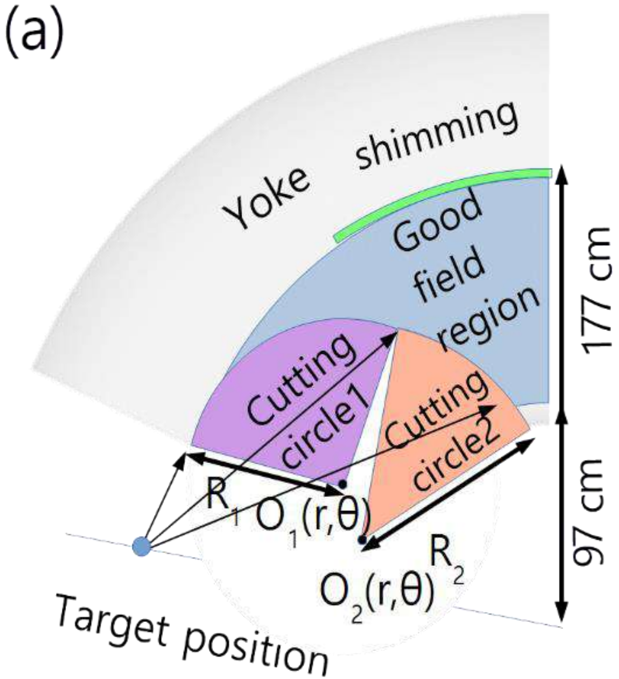
Optimisation with two cutting circle

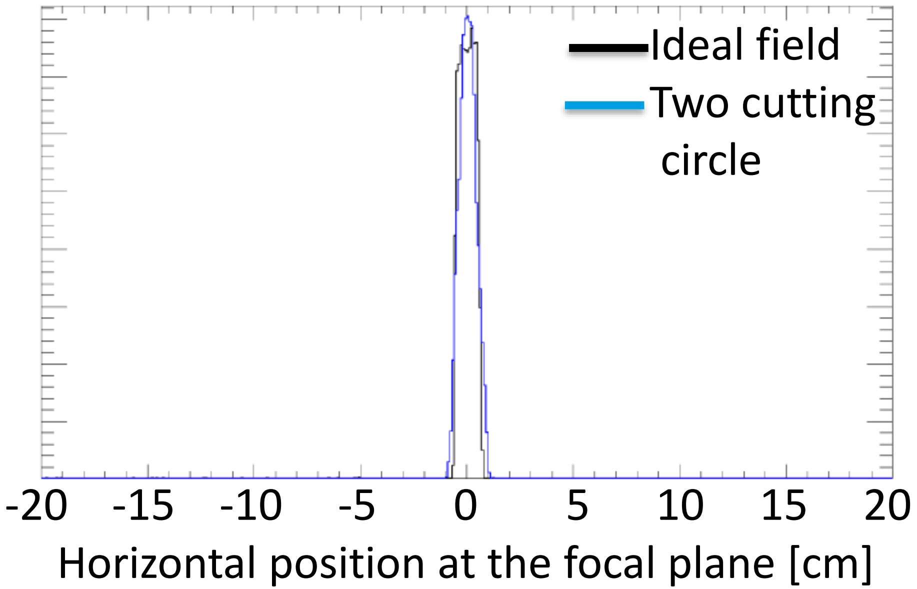




- 2nd order optimization
- Almost Perfect focus size same as ideal case

Optimisation with two cutting circle



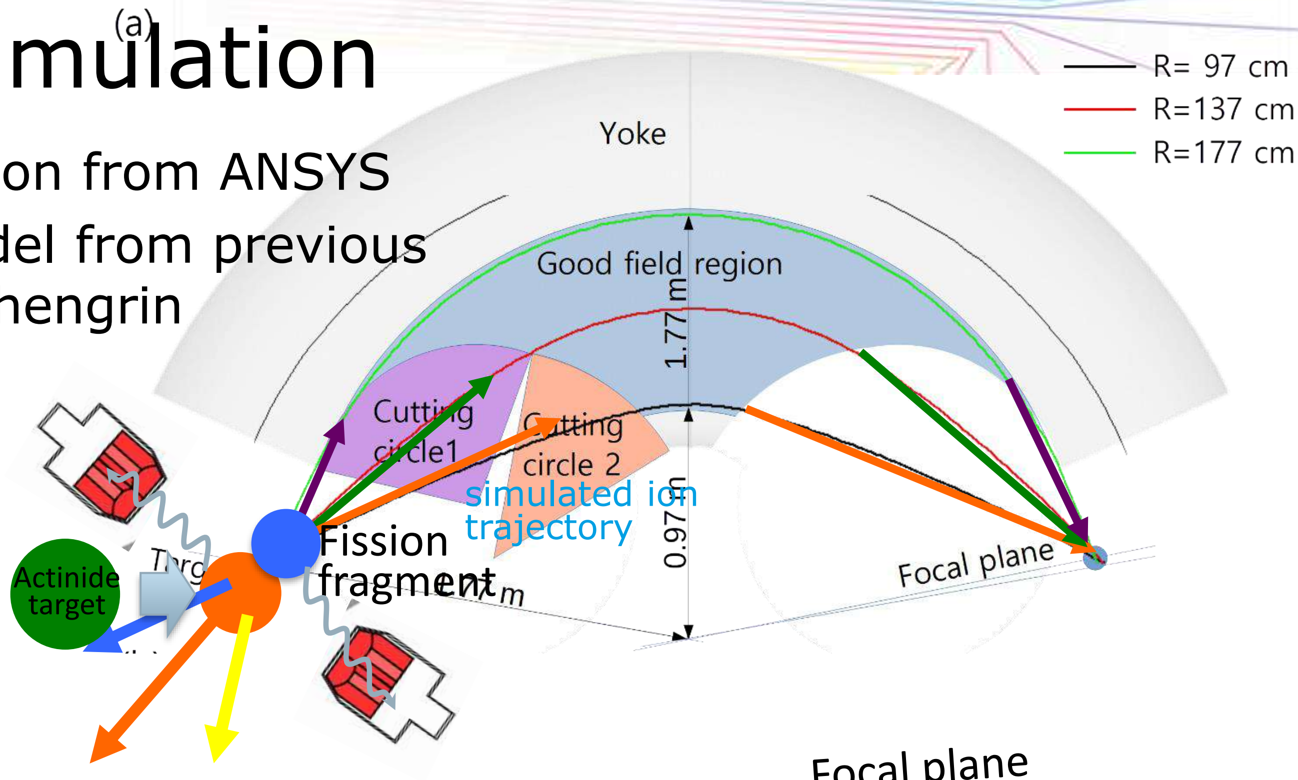


- 2nd order optimization
- Almost Perfect focus size same as ideal case

FIPPS GFM simulation

- Realistic field calculation from ANSYS
- Charge exchange model from previous test experiment at Lohengrin

(adjusted for ^{98}Y ions)



- Simulation result
  - Easy to operate
    - Point to line focusing

Focal plane

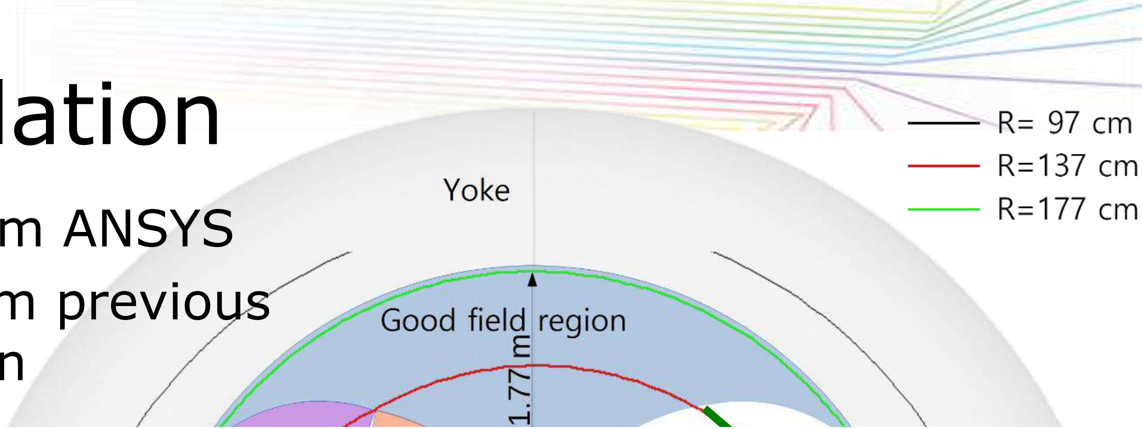
FIPPS phase 2

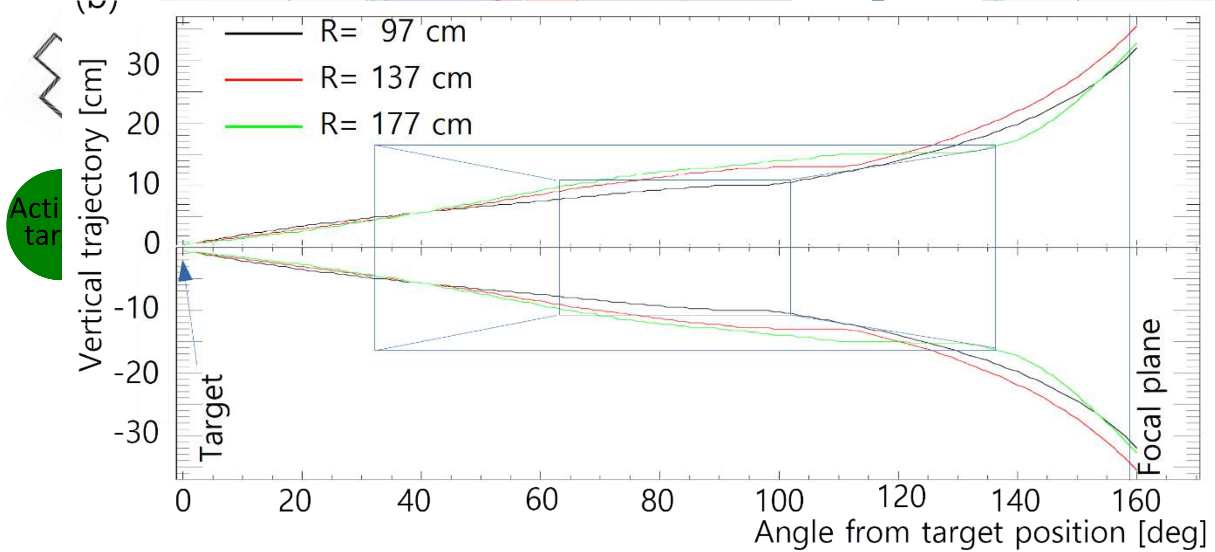
FIPPS GFM simulation

- Realistic field calculation from ANSYS
- Charge exchange model from previous test experiment at Lohengrin

(adjusted for ^{98}Y ions)

- Simulation result
  - Easy to operate
    - Point to line focusing

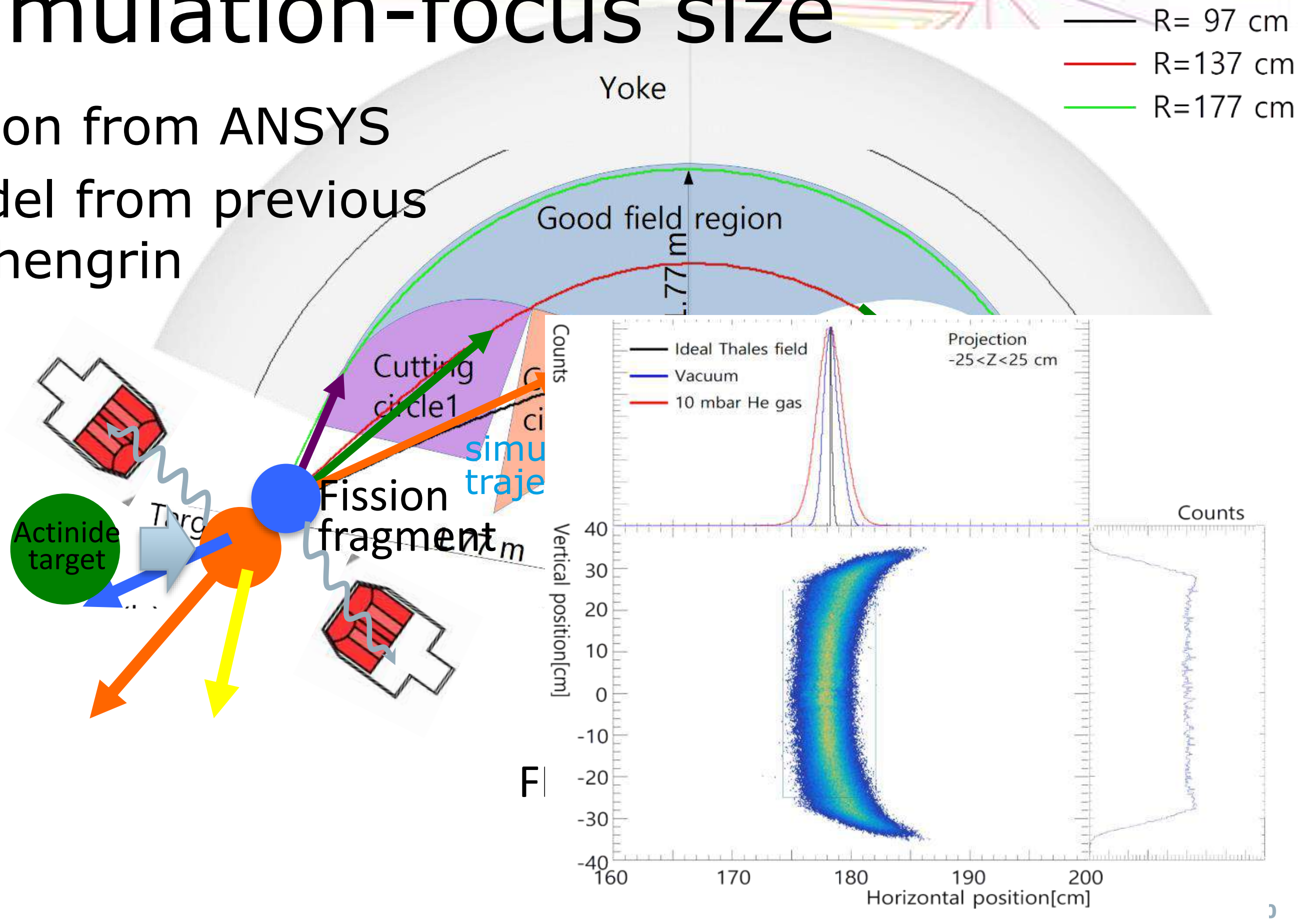




FIPPS GFM simulation-focus size

- Realistic field calculation from ANSYS
- Charge exchange model from previous test experiment at Lohengrin

(adjusted for ^{98}Y ions)



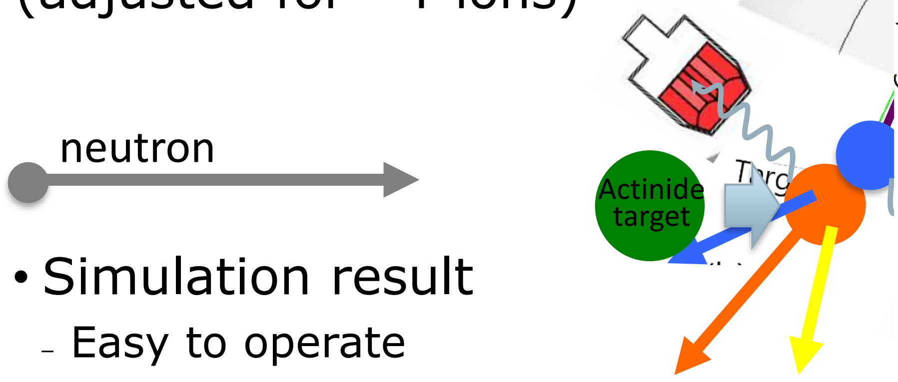
- Simulation result
  - Easy to operate
    - Point to line focusing
  - Performance

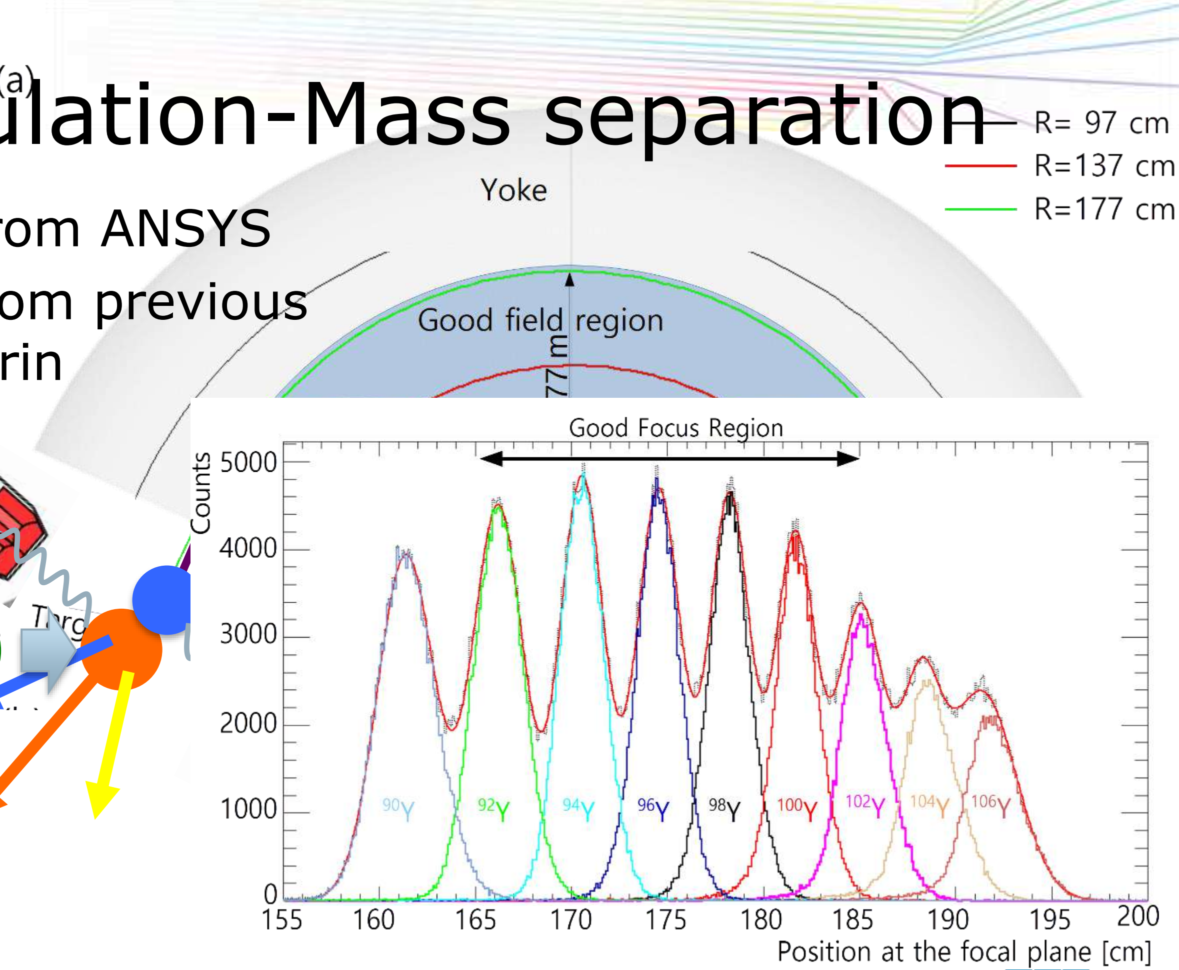
    Acceptance = 54.5 msr

FIPPS GFM simulation-Mass separation

- Realistic field calculation from ANSYS
- Charge exchange model from previous test experiment at Lohengrin

(adjusted for ^{98}Y ions)





- Simulation result
  - Easy to operate
    - Point to line focusing
  - Performance

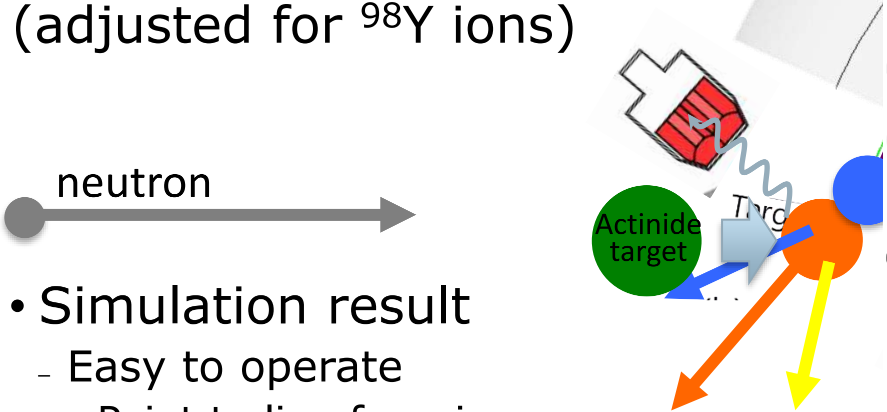
Acceptance = 54.5 msr

Mass Resolution ΔA=1.3 amu (FWHM) @ A=100 (Z=39)

FIPPS GFM simulatic

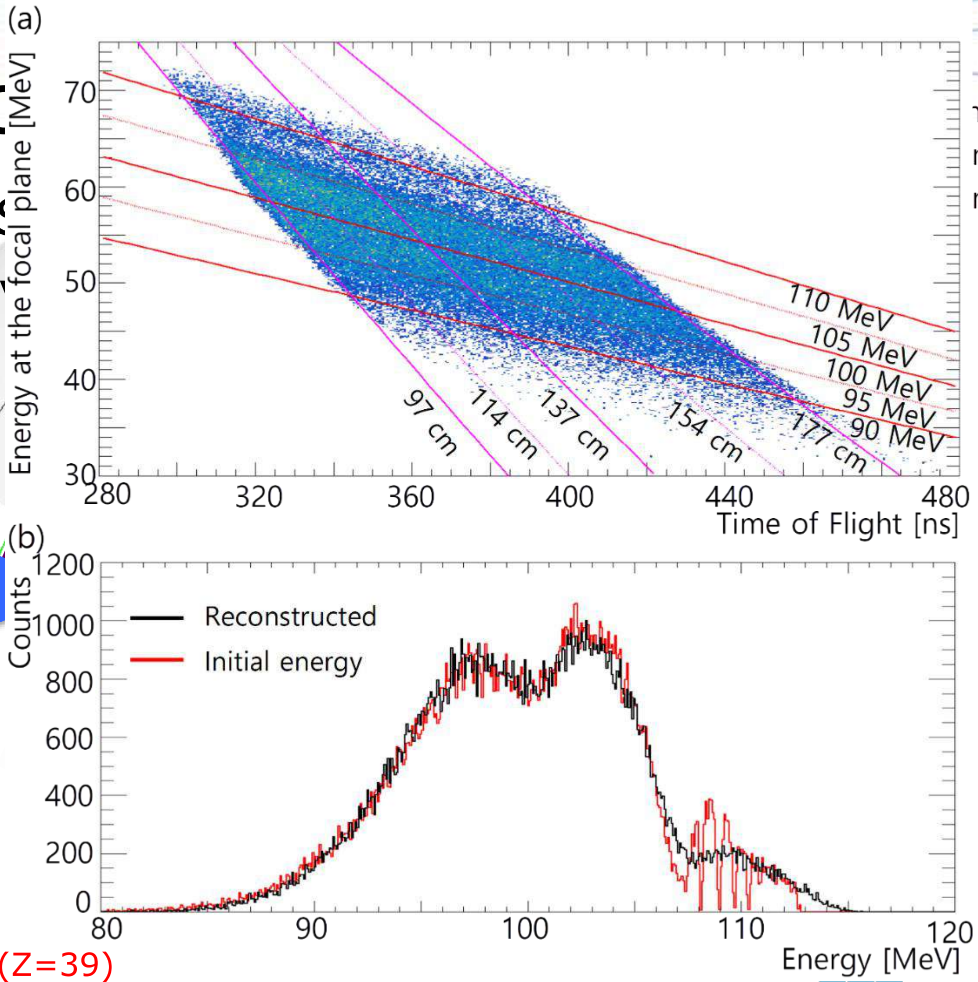
- Realistic field calculation from ANS
- Charge exchange model from prev test experiment at Lohengrin

(adjusted for ^{98}Y ions)



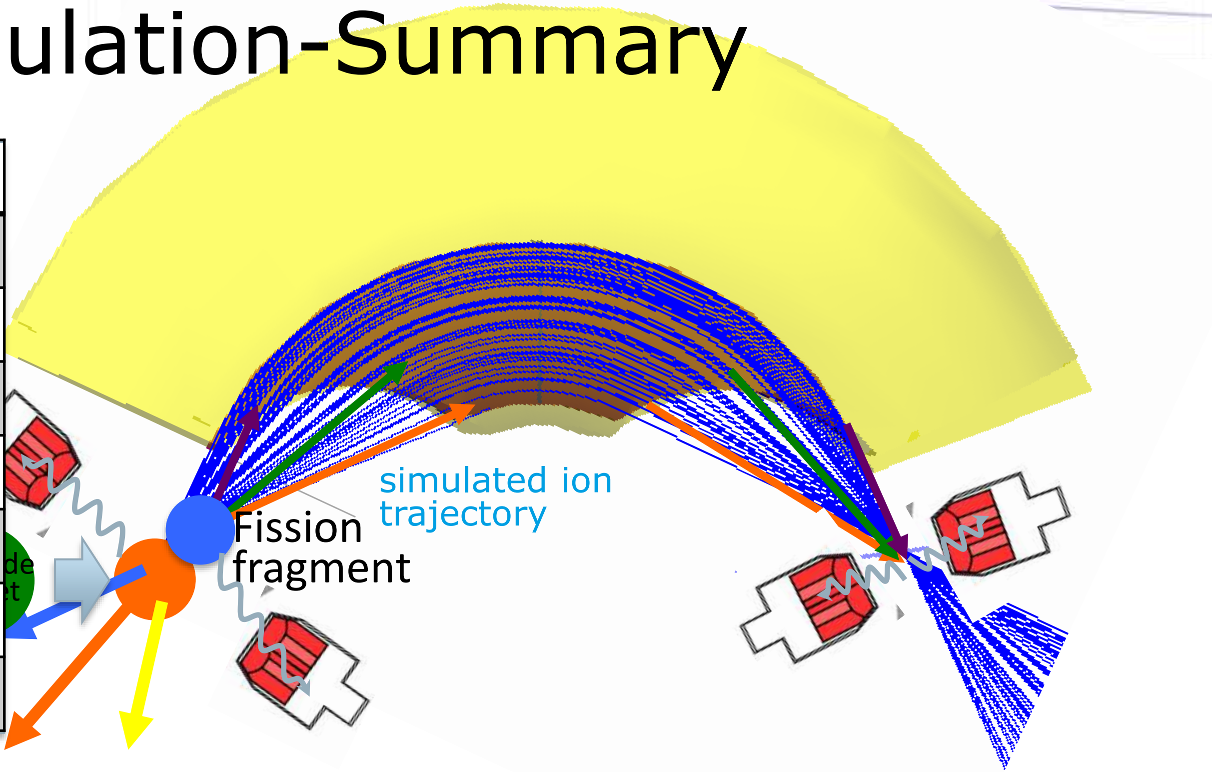
- Simulation result
  - Easy to operate
    - Point to line focusing
  - Performance

Acceptance = 54.5 msr
Mass Resolution ΔA=1.3 amu (FWHM) @ A=100 (Z=39)
Initial energy & trajectory reconstruction without tracking

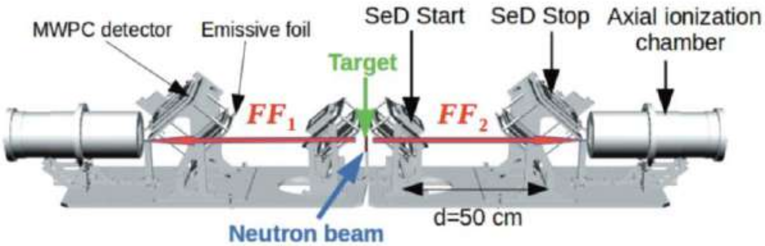
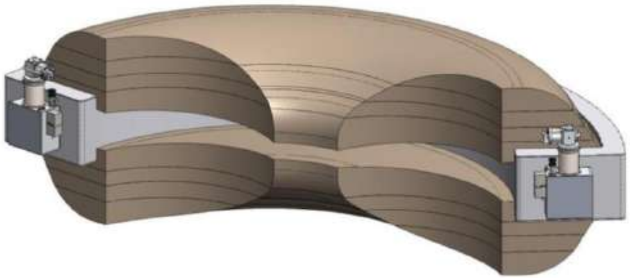


FIPPS GFM simulation-Summary

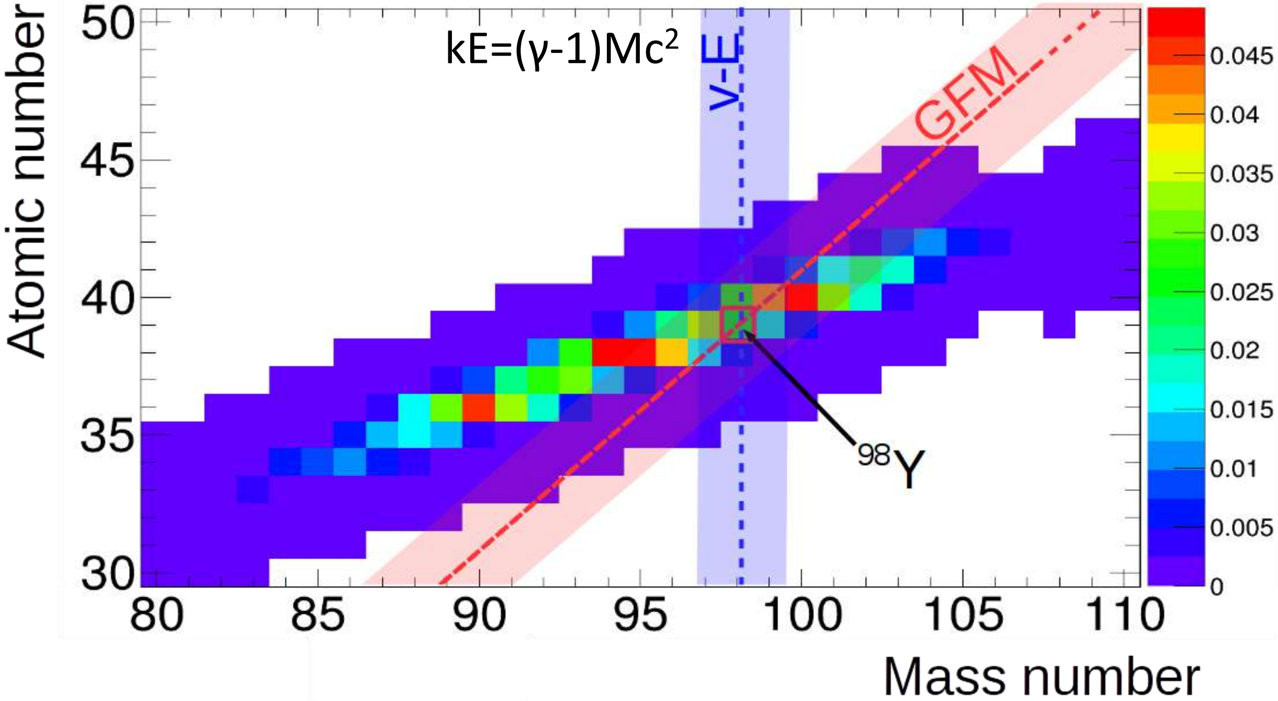
Central Radius	137 [cm]
Central Bending Angle	80 [deg]
Width good field region	80 [cm]
Maximum magnetic rigidity	1.3 [Tm]
1/r Field accuracy	1 [%]
Yoke Weight	51 [ton]
Dispersion	1.8 [cm/%]
Geometrical Acceptance	54.5 [msr]



Comparison of GFM with v-E spectrometer

	v-E spectrometer	FIPPS GFM
		
Mass resolution (1σ)	~2.0 amu	1.3 (for single Z) amu
Acceptance	50 msr (1 arm)	54.5 msr
detectors	SeD, MWPC, BRAGG IC (many ch needed)	Diamond, MWPC, IC
	Cannot place FIPPS Ge close	

Separation meth.:GFM vs v-E spectrometer

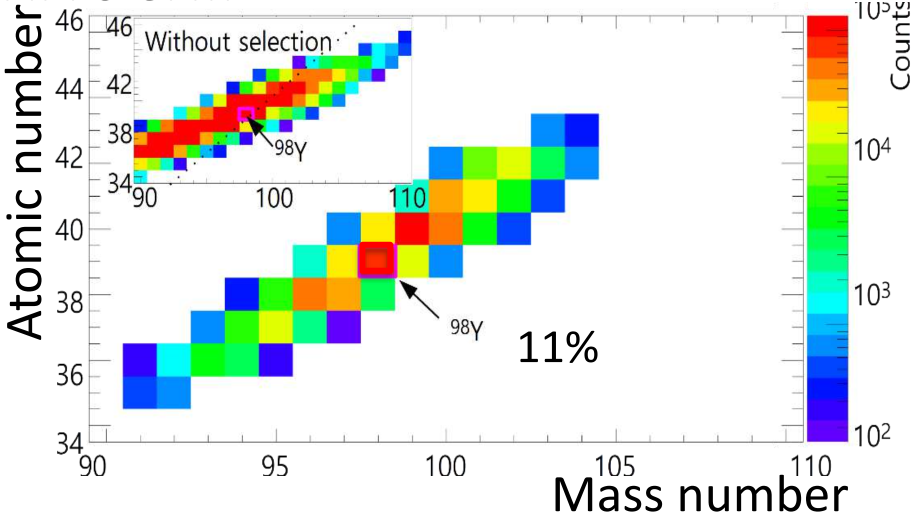


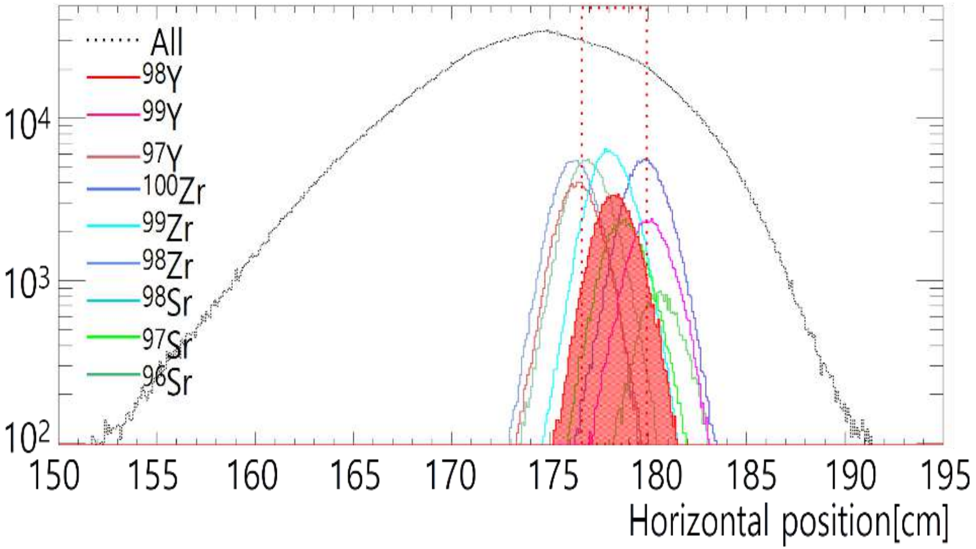
$$Br = \frac{M}{Q} bg \sim \frac{M}{Z^a}$$

- Mass distribution based on JEFF database
- Different way of selection -> Effect in purity

Separation power:GFM vs v-E spectrometer

FIPPS GFM

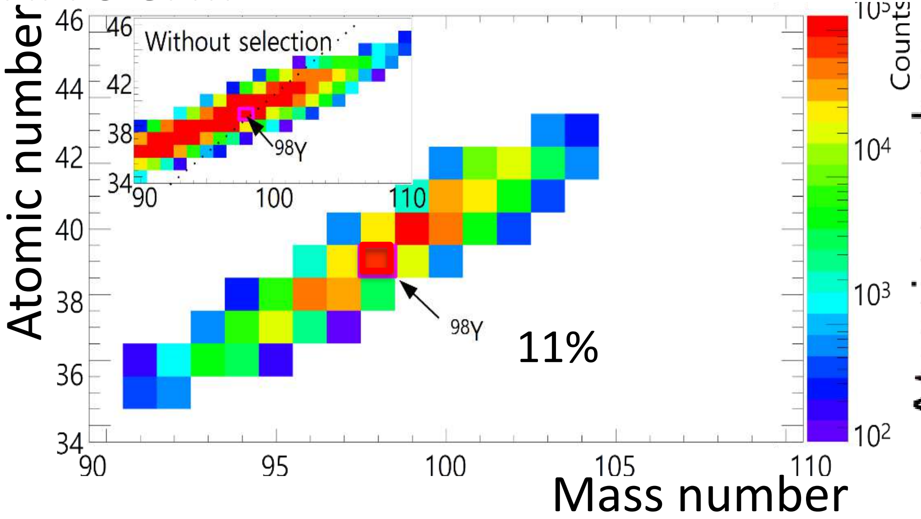




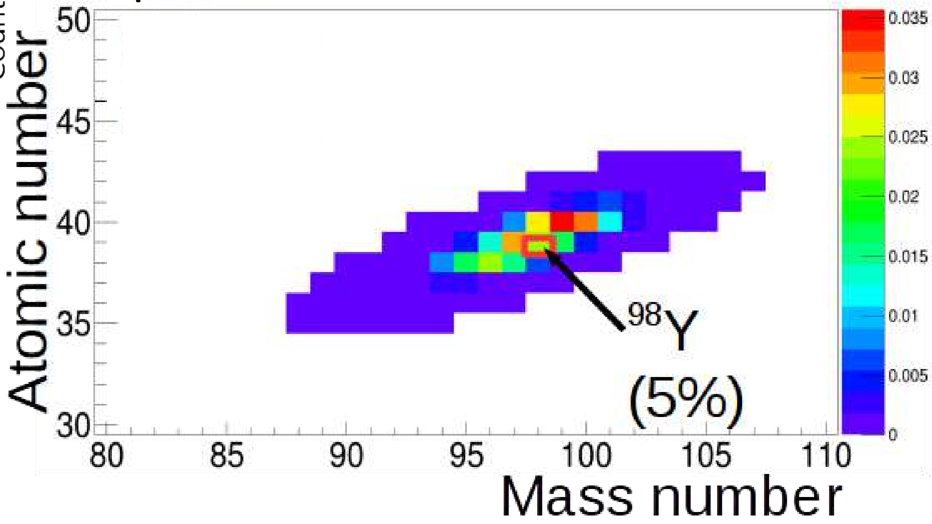
- Similar ΔA, ΔZ resolution
- Purity of $^{98\text{-}101}$Y GFM 2-3 greater in case of v-E

Separation power:GFM vs v-E spectrometer

FIPPS GFM

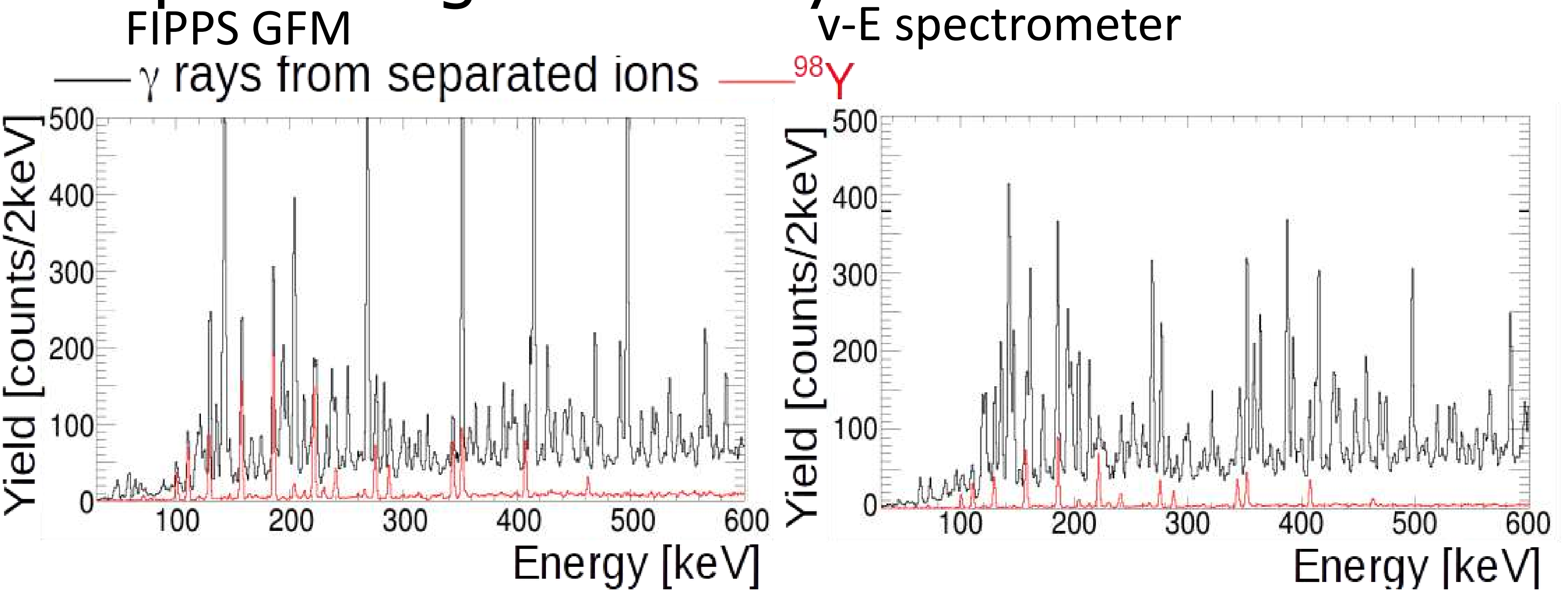


v-E spectrometer



- Similar ΔA, ΔZ resolution
- Purity of ^{98}Y GFM x2 greater in case of v-E

Impact on gamma-ray selection ^{98}Y



Prompt γ-ray simulated from FIFRELIN code

(Only light fission fragment is simulated without effect of Ge-response)