

State-of-the-art of Time-Of-Flight spectrometers used in fission, quasifission and multinucleon transfer experiments for the study of heavy and superheavy elements

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Ministry of Foreign Affairs
and International Cooperation

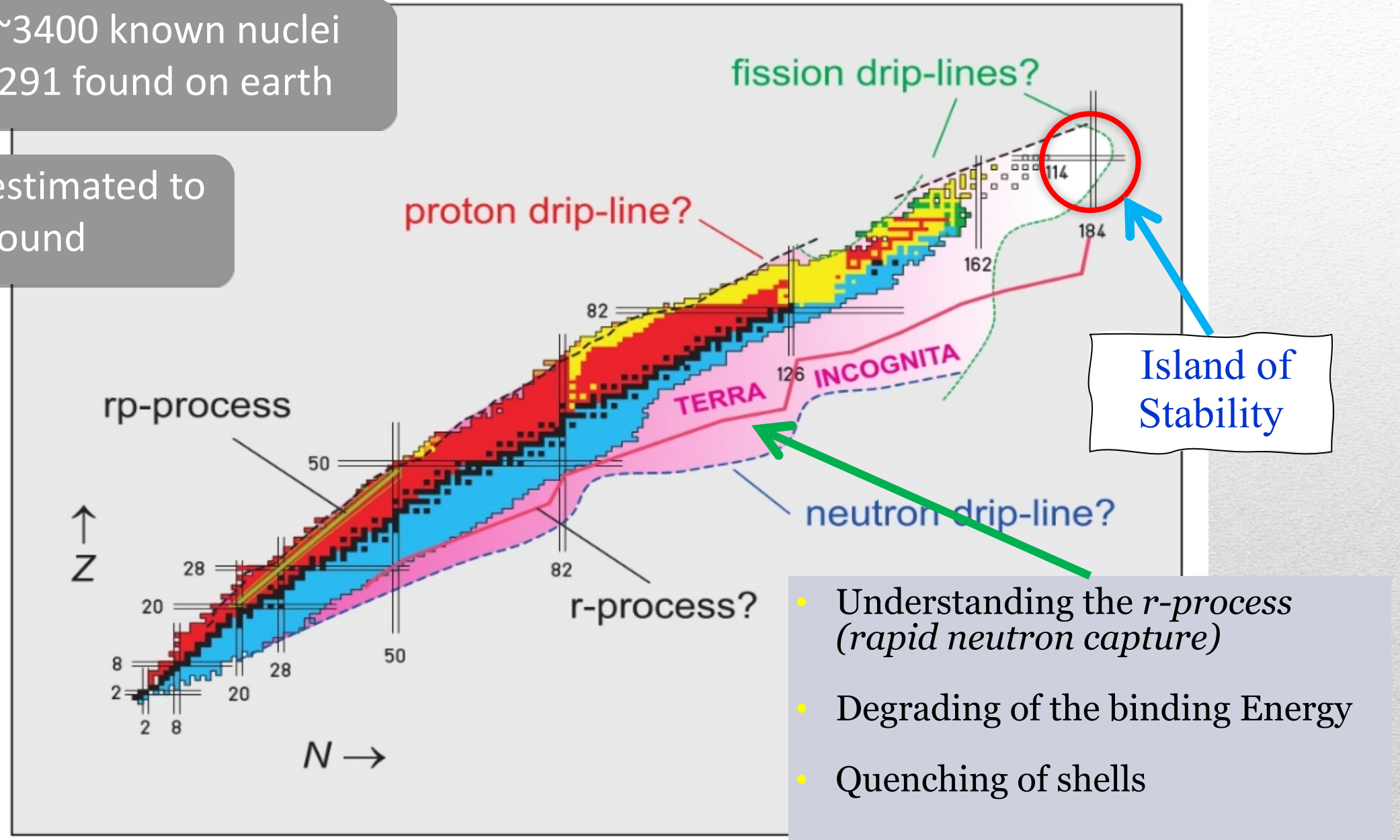


FATA 2025, Catania, October 8, 2025

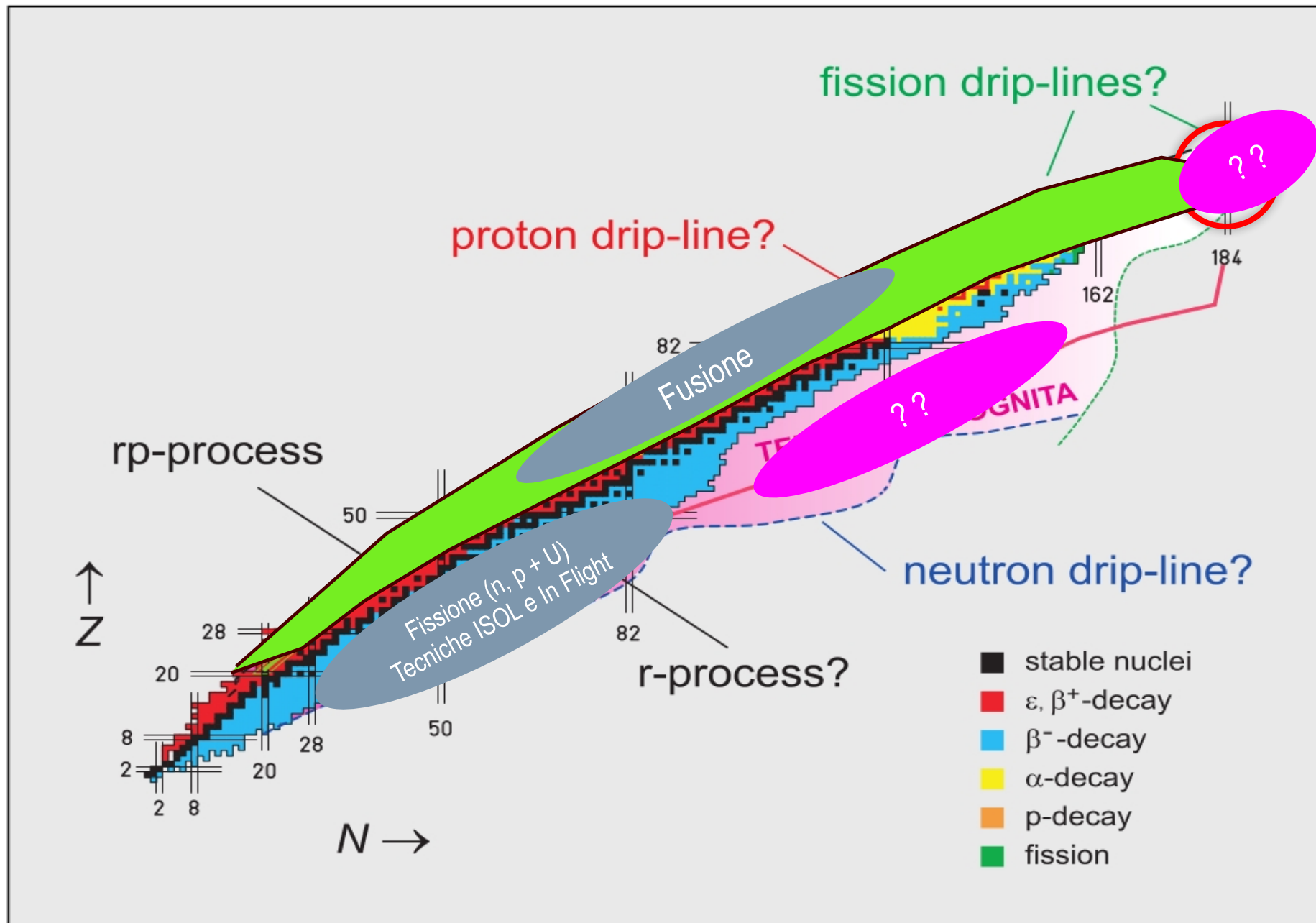
A quick look on the nuclide's chart

~3400 known nuclei
291 found on earth

~7000 are estimated to
be bound



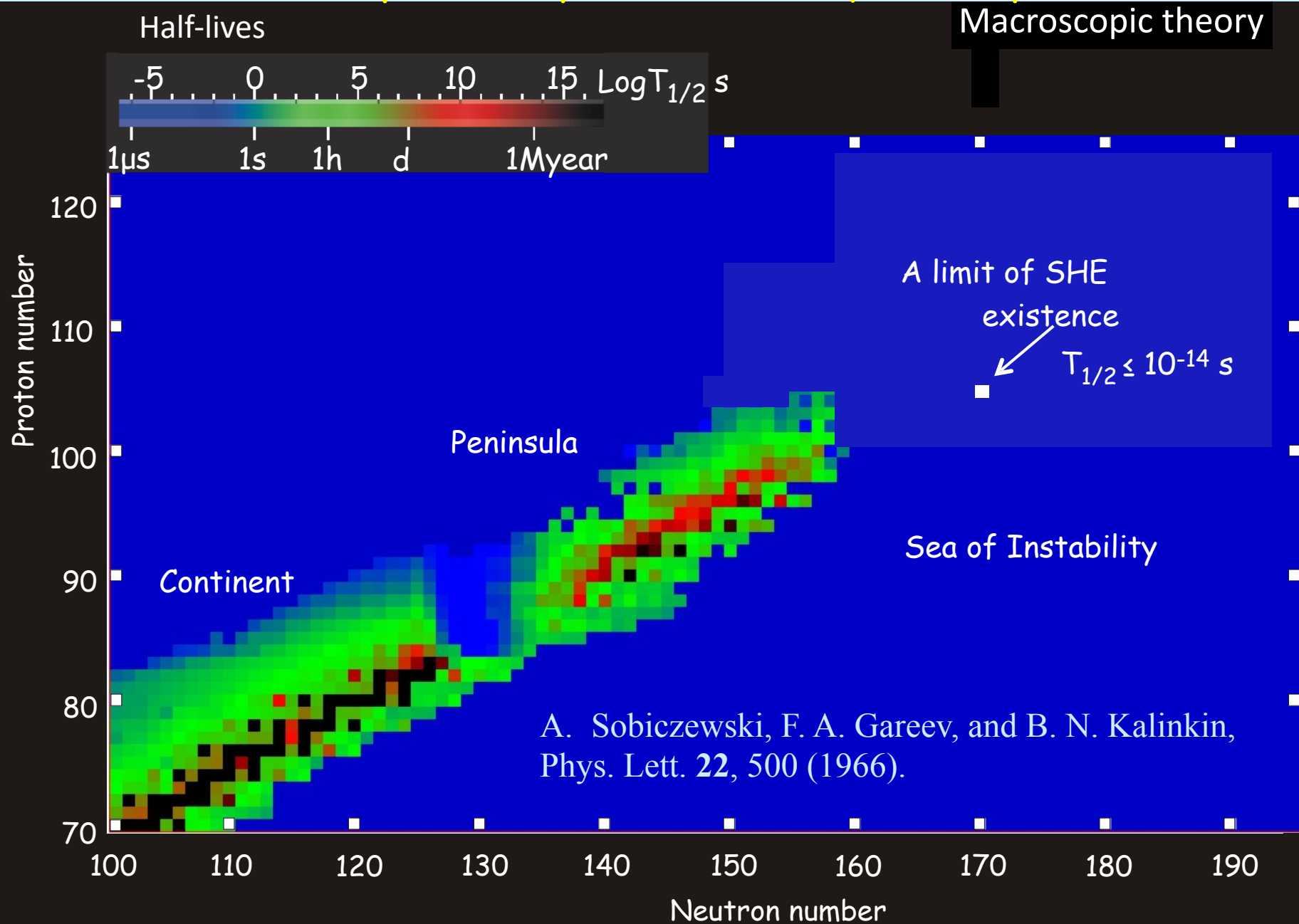
How to produce the unknown nuclei?



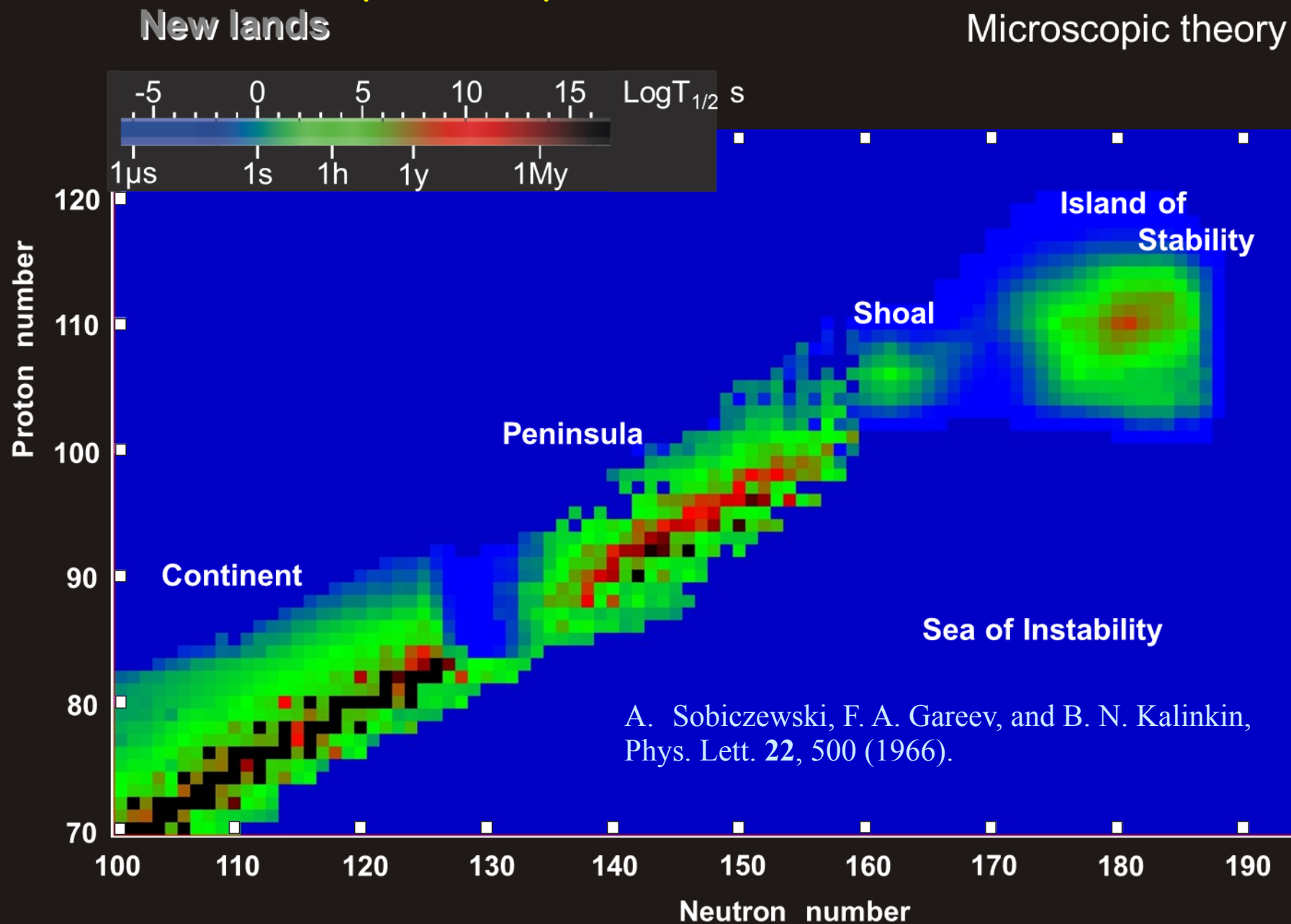
The 11 Greatest Unanswered Questions of Physics (National Research Council, NAS, USA, 2002):

1. What is dark matter?
2. What is dark energy?
- 3. How were the heavy elements from iron to uranium made?**
4. Do neutrinos have mass?
- ...

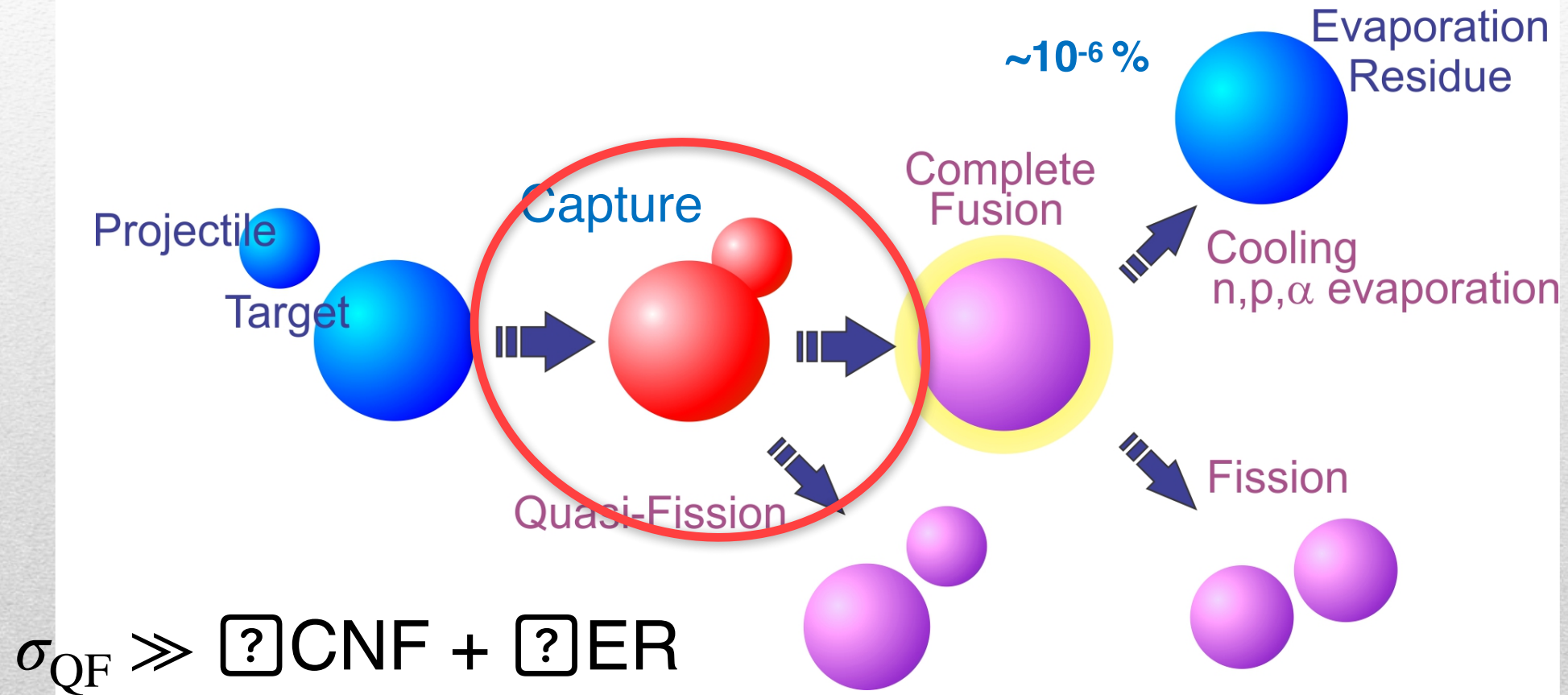
SuperHeavy elements: liquid drop



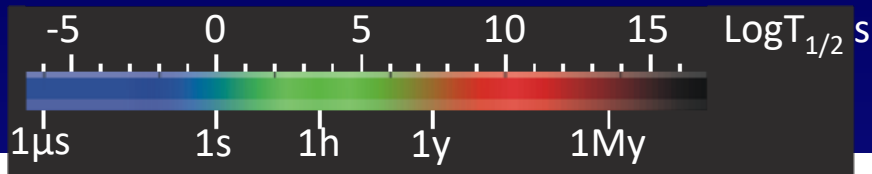
SuperHeavy elements: shell effects



Reaction channels in the collisions of heavy ions at barrier energies



$$\sigma_{\text{capture}} = \sigma_{\text{QF}} + \sigma_{\text{CNF}} + \sigma_{\text{ER}} \quad \sigma_{\text{ER}} = \sigma_{\text{capture}} \times P_{\text{CN}} \times W_{\text{survival}}$$



52 neutron-rich isotopes of the 15 heaviest elements were synthesized in ^{48}Ca -induced fusion reactions

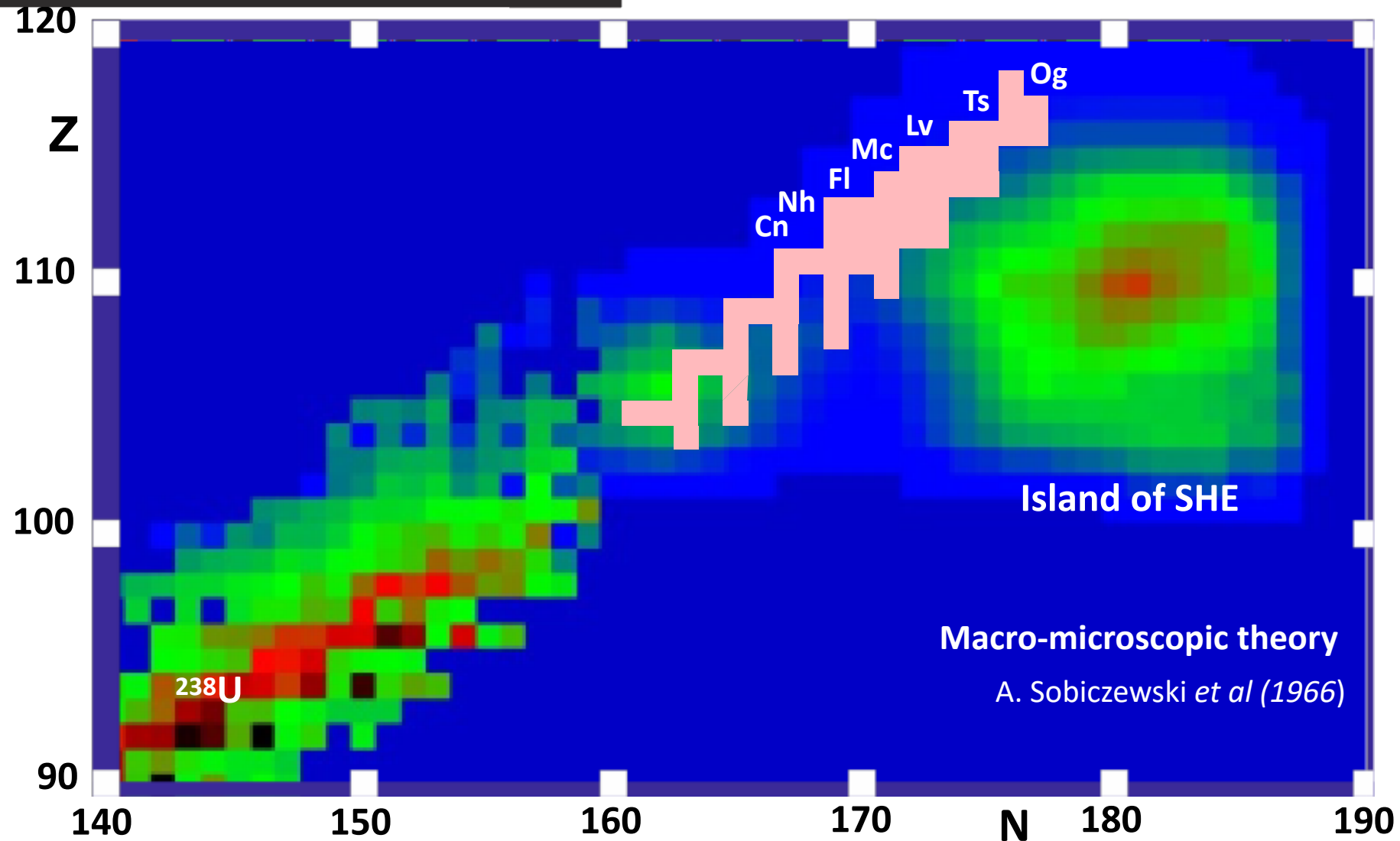
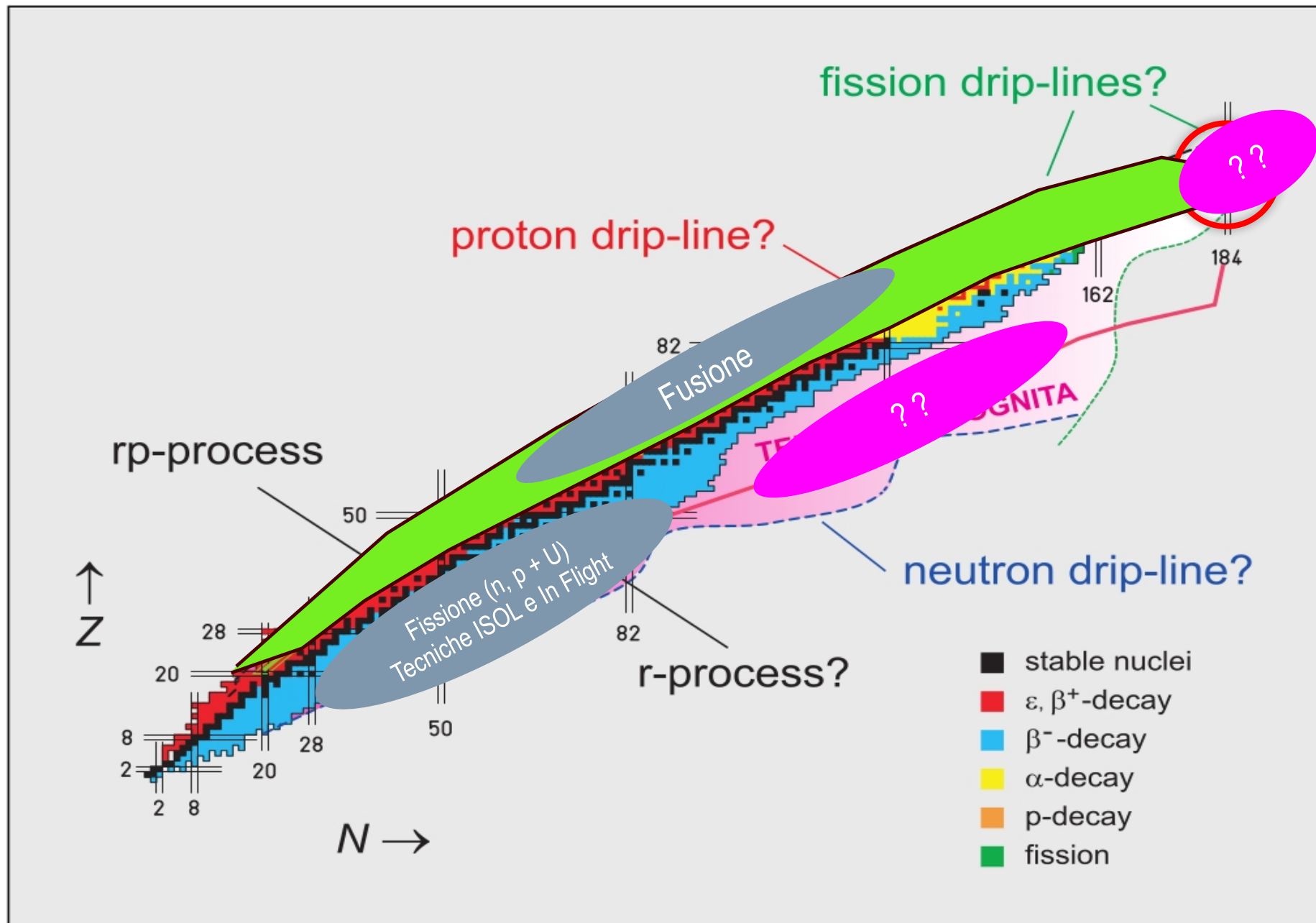


Tavola periodica (Mendeleev, 1869)

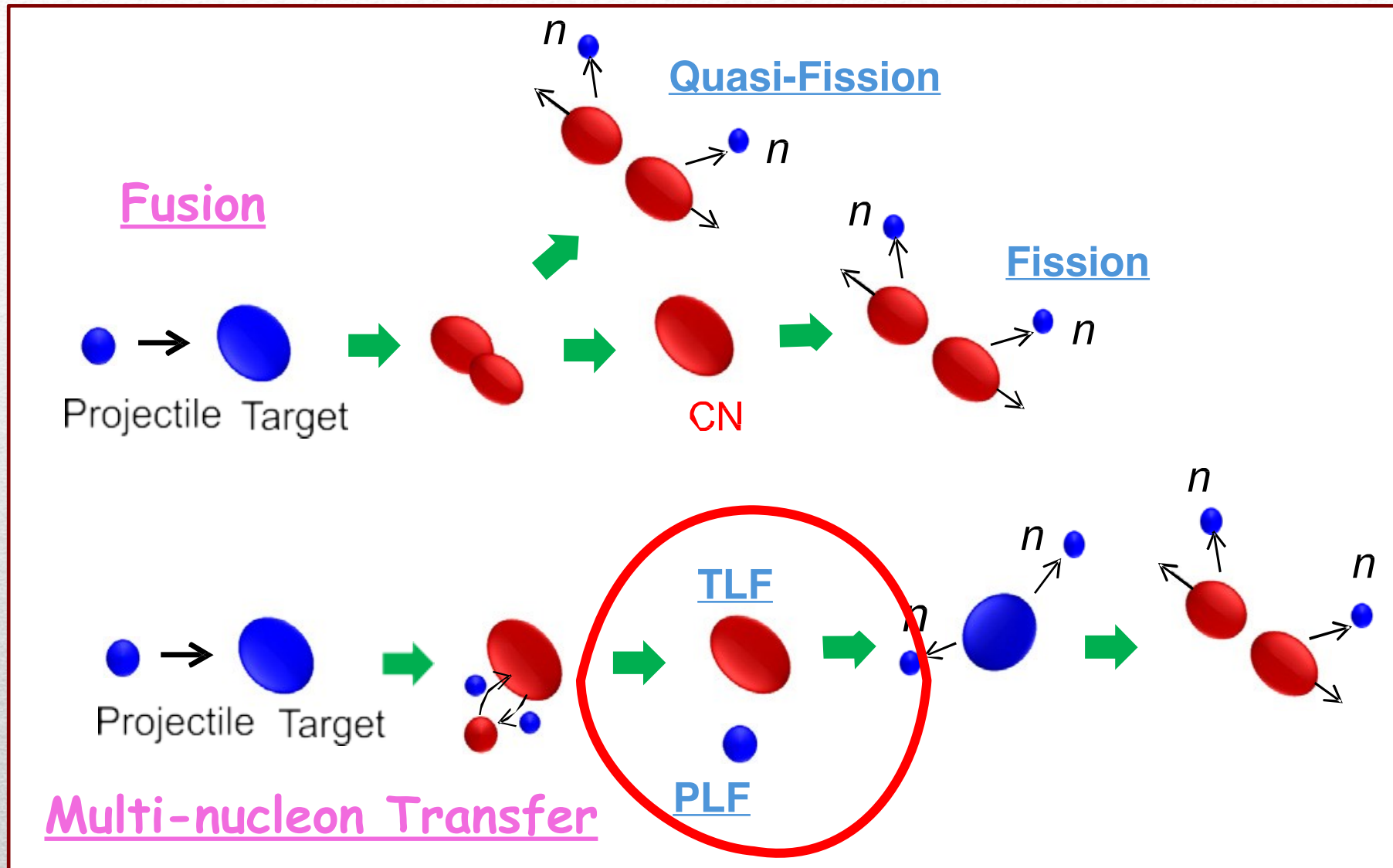
Tavola periodica (Mendeleev, 1869)

1 H Hydrogen 1.008																	2 He Helium 4.003				
3 Li Lithium 6.941	4 Be Beryllium 9.012															5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305															13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798				
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294				
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon [222]				
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium unknown	114 Fl Flerovium [289]	115 Mc Moscovium unknown	116 Lv Livermorium [293]	117 Ts Tennessine unknown	118 Og Oganesson unknown				
Alkali Metal Alkaline Earth Transition Metal Basic Metal Semimetal Nonmetal Halogen Noble Gas Lanthanide Actinide																					
57 La Lanthanum 138.905 58 Ce Cerium 140.116 59 Pr Praseodymium 140.908 60 Nd Neodymium 144.242 61 Pm Promethium 144.913 62 Sm Samarium 150.36 63 Eu Europium 151.964 64 Gd Gadolinium 157.25 65 Tb Terbium 158.925 66 Dy Dysprosium 162.500 67 Ho Holmium 164.930 68 Er Erbium 167.259 69 Tm Thulium 168.934 70 Yb Ytterbium 173.055 71 Lu Lutetium 174.967																					
89 Ac Actinium 227.028 90 Th Thorium 232.038 91 Pa Protactinium 231.036 92 U Uranium 238.029 93 Np Neptunium 237.048 94 Pu Plutonium 244.064 95 Am Americium 243.061 96 Cm Curium 247.070 97 Bk Berkelium 247.070 98 Cf Californium 251.080 99 Es Einsteinium [254] 100 Fm Fermium 257.095 101 Md Mendelevium 258.1 102 No Nobelium 259.101 103 Lr Lawrencium [262]																					

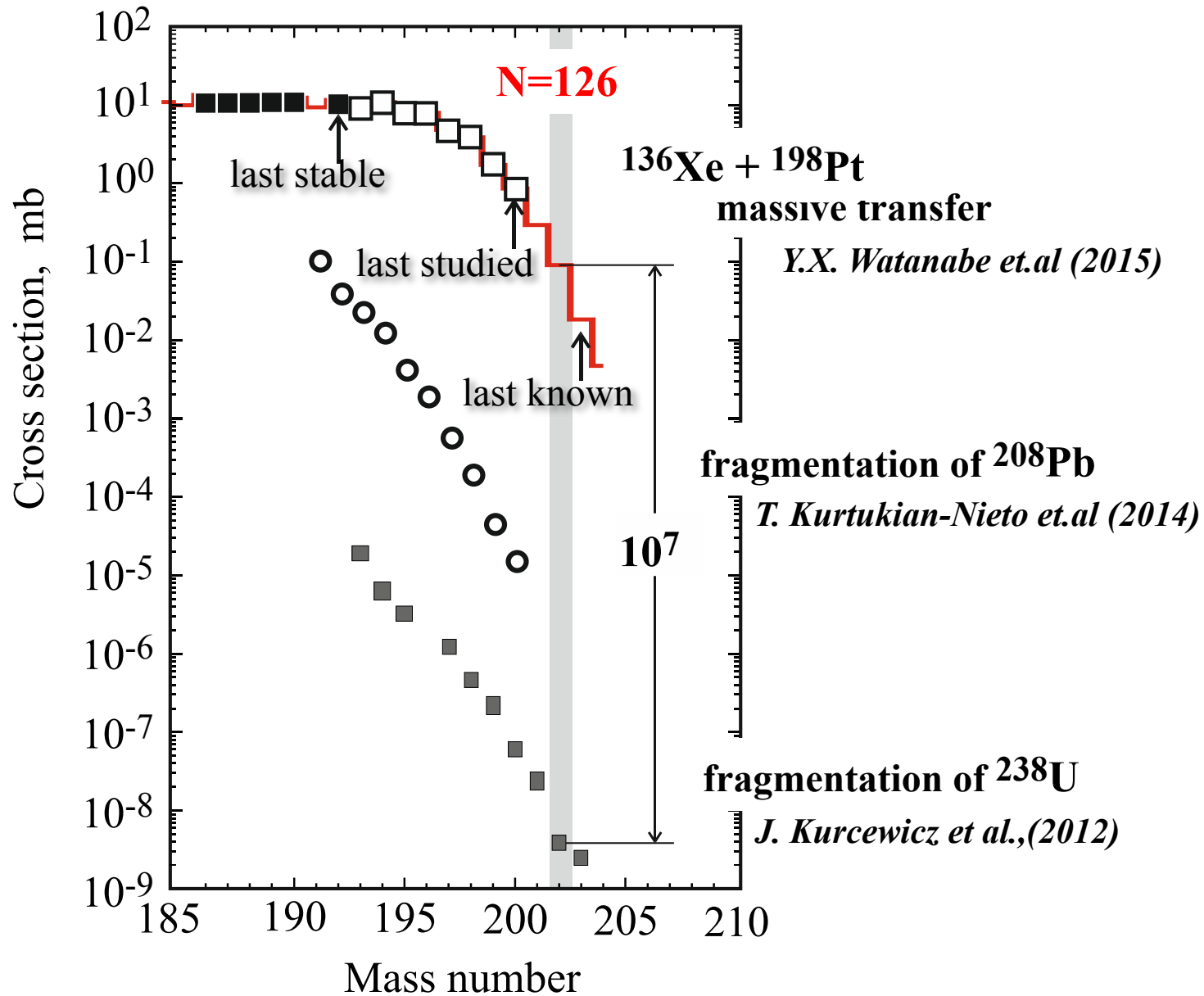
How to produce the unknown nuclei?



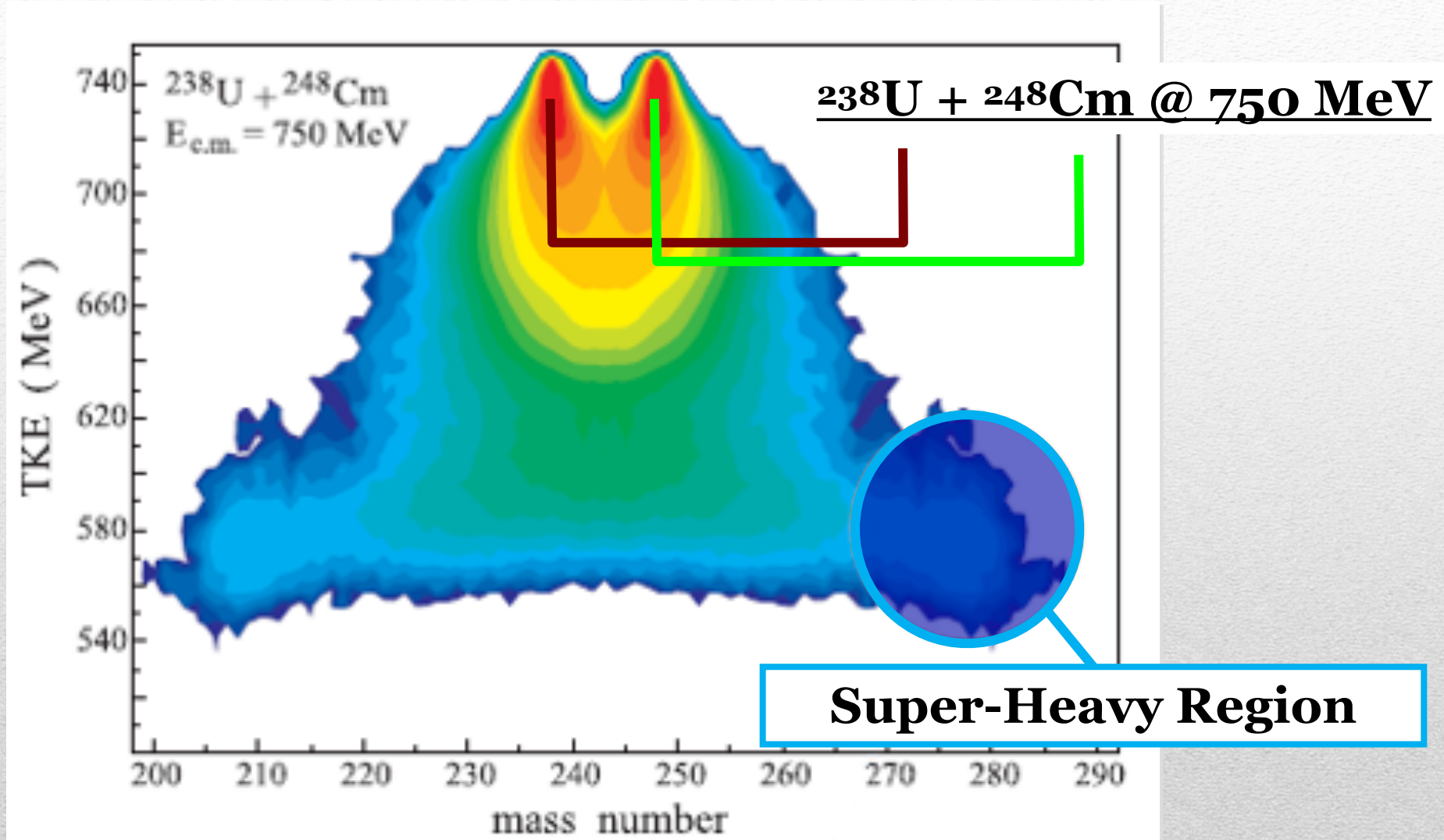
Fusion vs. Multi-Nucleon Transfer



Production of neutron-rich Os-isotopes

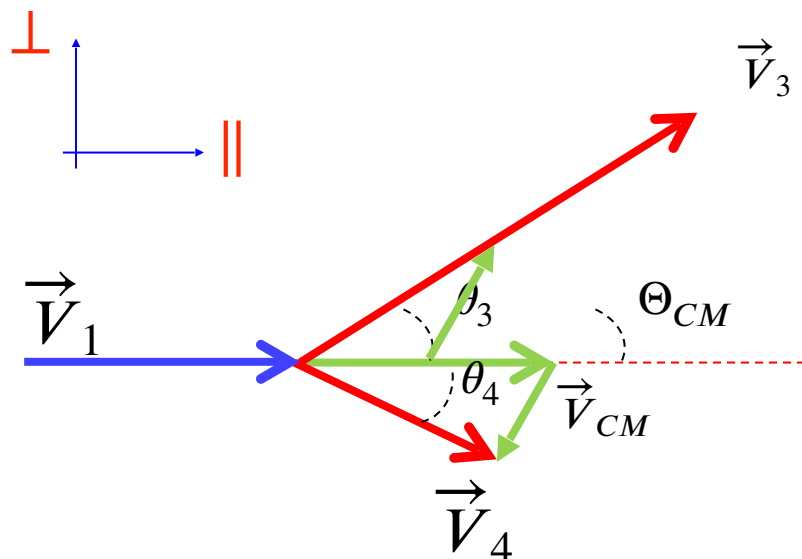


MNT as a channel for production of SHE



What is the best
tool to investigate
these reactions ?

TWO-BODY: ENERGY AND MOMENTUM CONSERVATION



$$\vec{P}_1 = \vec{P}_3 + \vec{P}_4$$

$$\left. \begin{aligned} P_1 &= P_3 \cos \theta_3 + P_4 \cos \theta_4 \\ 0 &= P_3 \sin \theta_3 - P_4 \sin \theta_4 \end{aligned} \right\}$$

$$V_3, V_4, \theta_3, \theta_4, m_3, m_4$$

$$\frac{\Delta t}{t} \approx \frac{100 \times 10^{-3} ns}{200 ns} = 5 \times 10^{-4} = 0.05\%$$

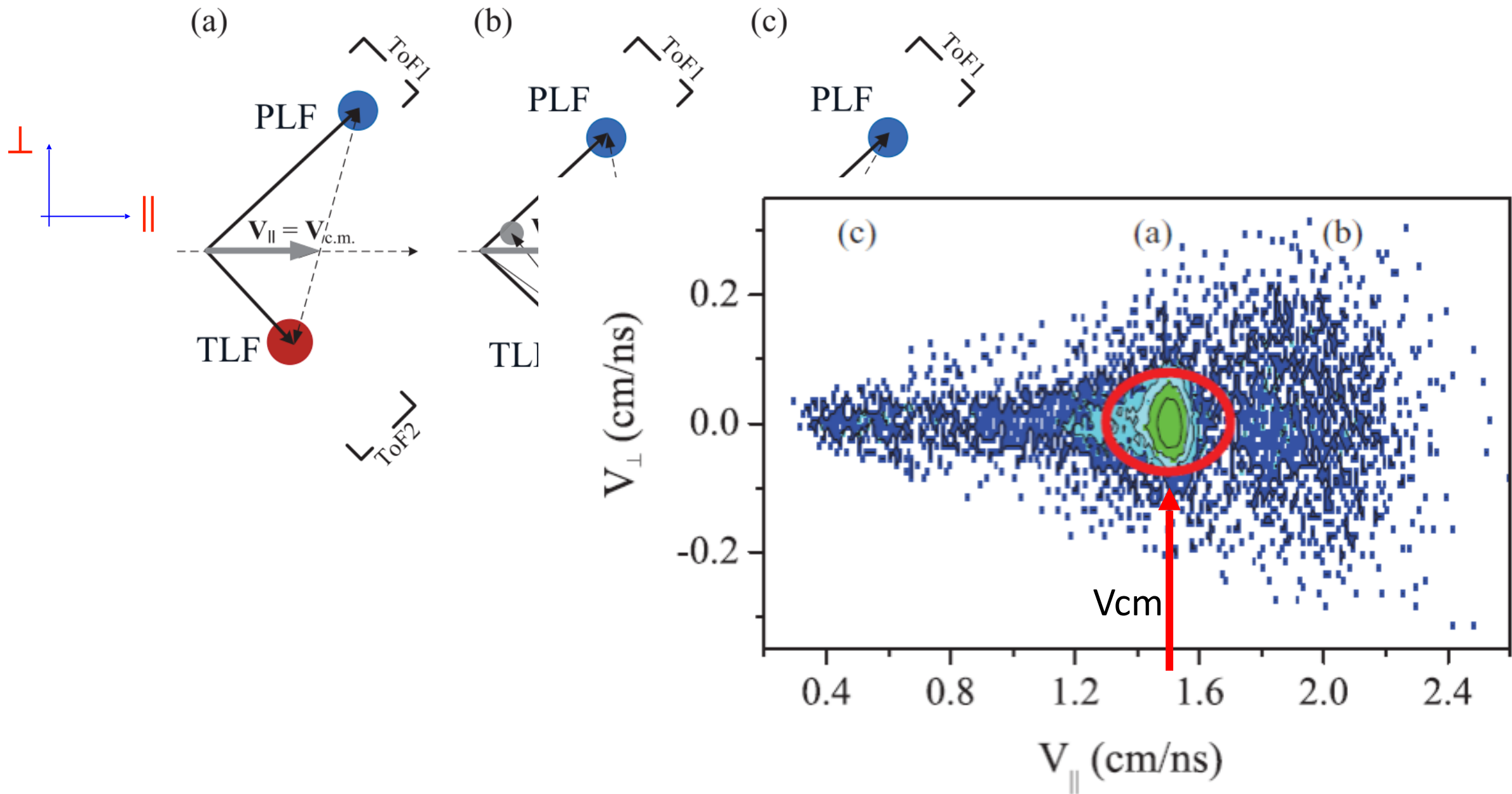
$$\frac{\Delta E}{E} = 2 \frac{\Delta t}{t} \approx \frac{200 \times 10^{-3} ns}{200 ns} = 0.1\%$$

Ranges - A: 30-250 E: 50-200 MeV

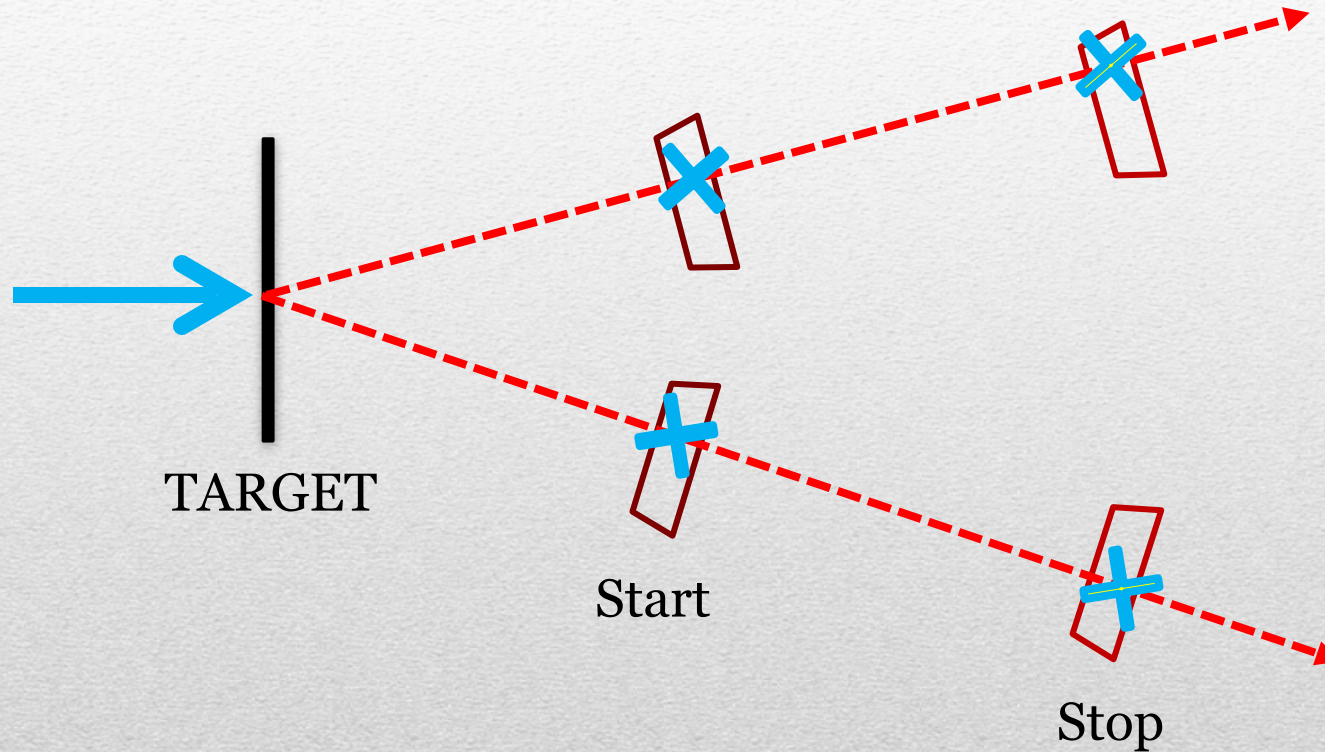
$$\begin{aligned} E^* &= E_{cm} - TKE + \\ TKE &= E_3 (CM) + E_4 (CM) \\ TKEL &= E_{CM} - TKE \end{aligned}$$

Primary A1, A2, TKE,
folding angles, Vpar,
Vper.....

TWO-BODY: FULL MOMENTUM TRANSFER



2V - TOF method: The simplest Mass Spectrometer



What do we measure:

- Time of Flight
- Hit Position



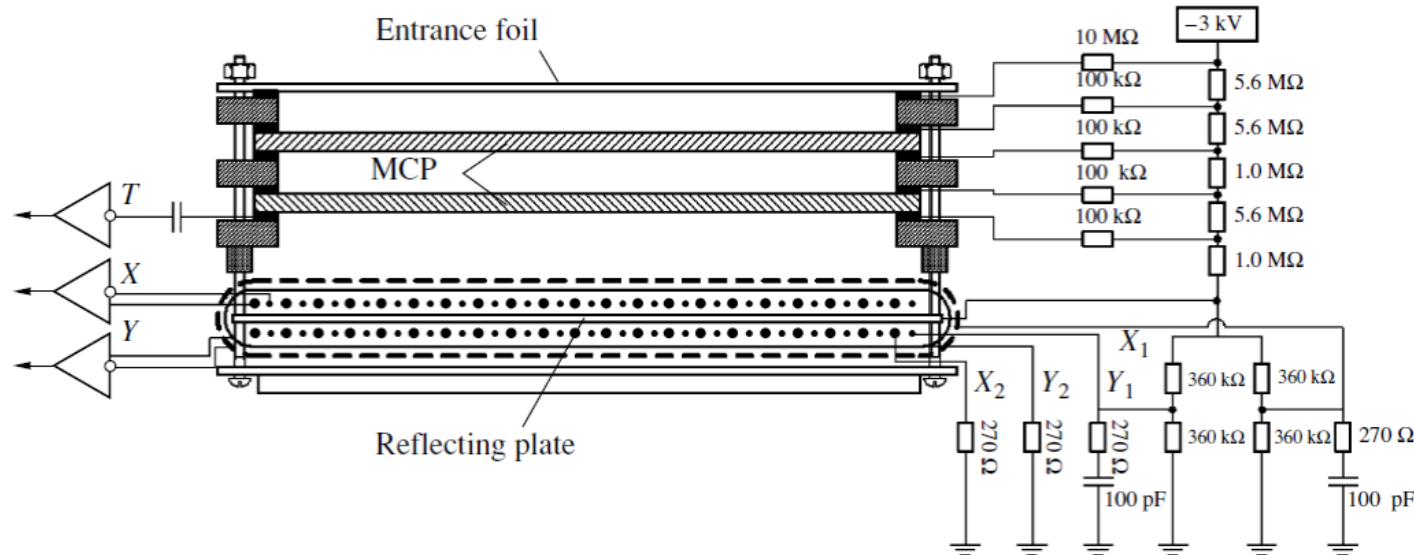
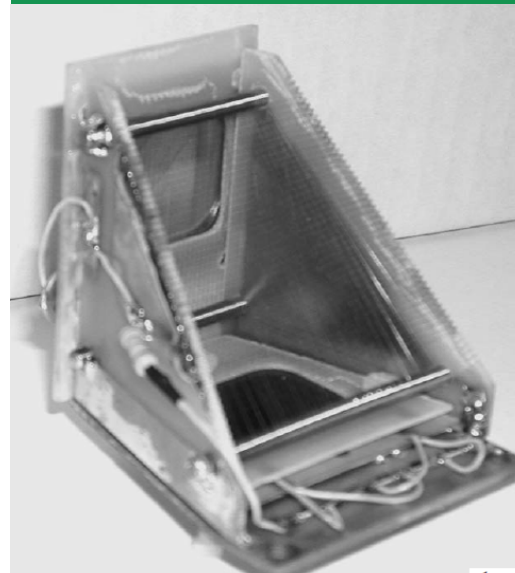
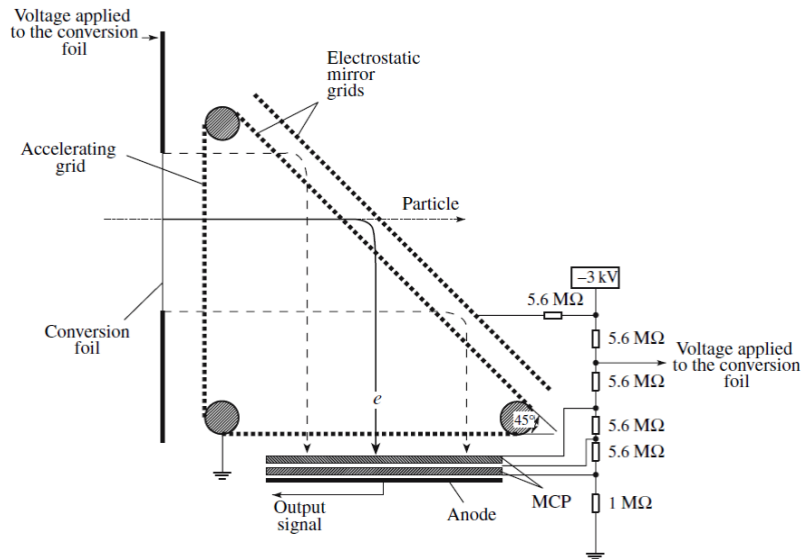
- Conservation Laws
- Corrections (non trivial)



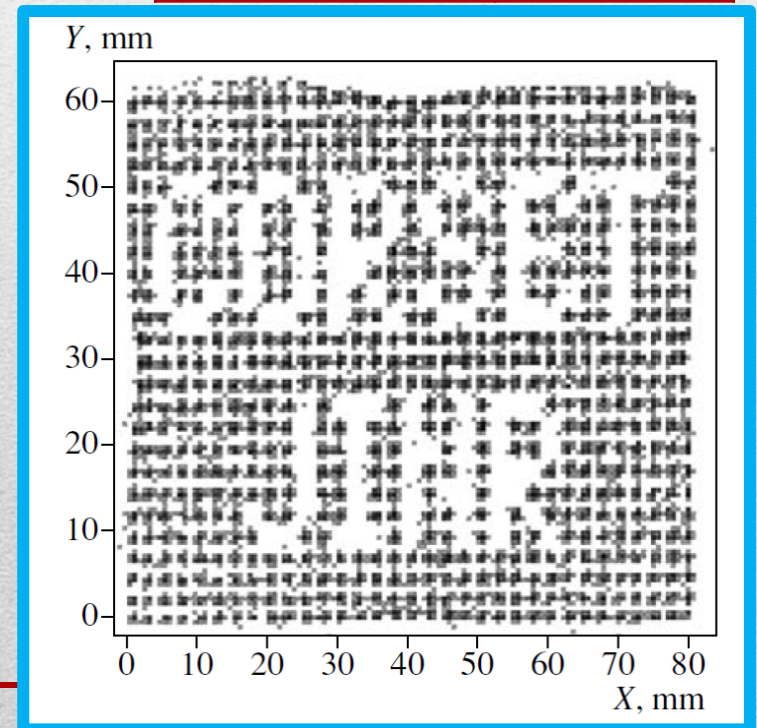
Primary A1, A2, TKE,
folding angles, Vpar,
Vper.....

- Measurement of the *primary mass* of the TLF and PLF
 - Removal of *not-FMT* events
 - Mass distribution vs. different degrees of energy dissipation (TKEL)
 - Effect of Q_{gg} values on the secondary mass distribution (after neutron evaporation)
-

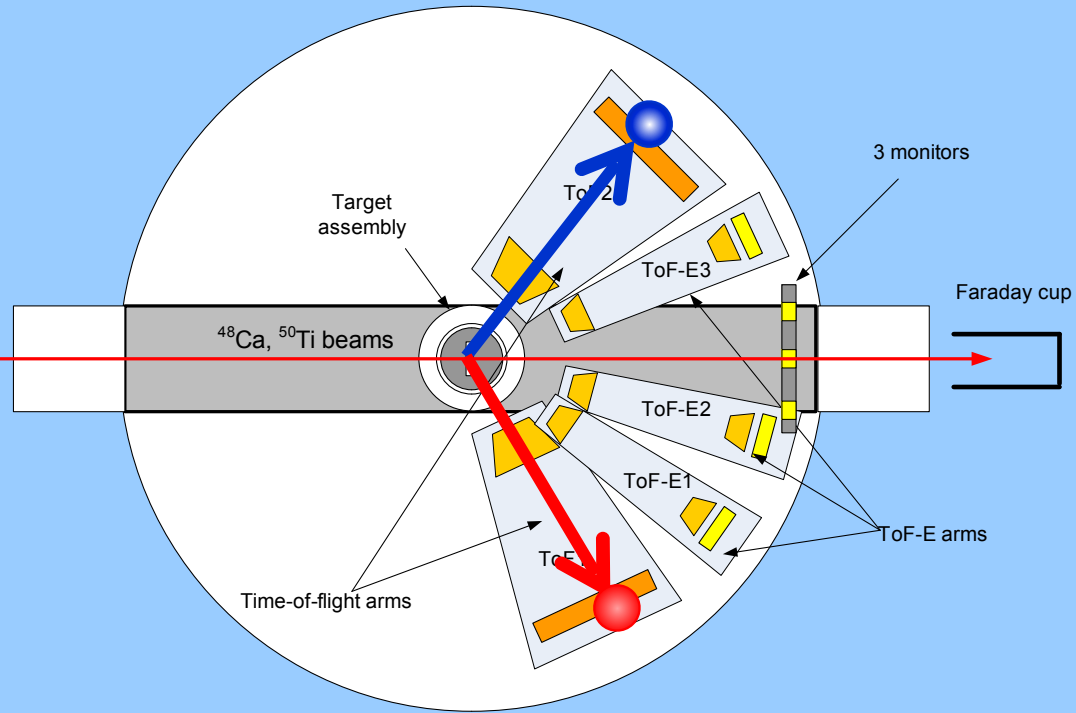
Double Arm TOF - CORSET



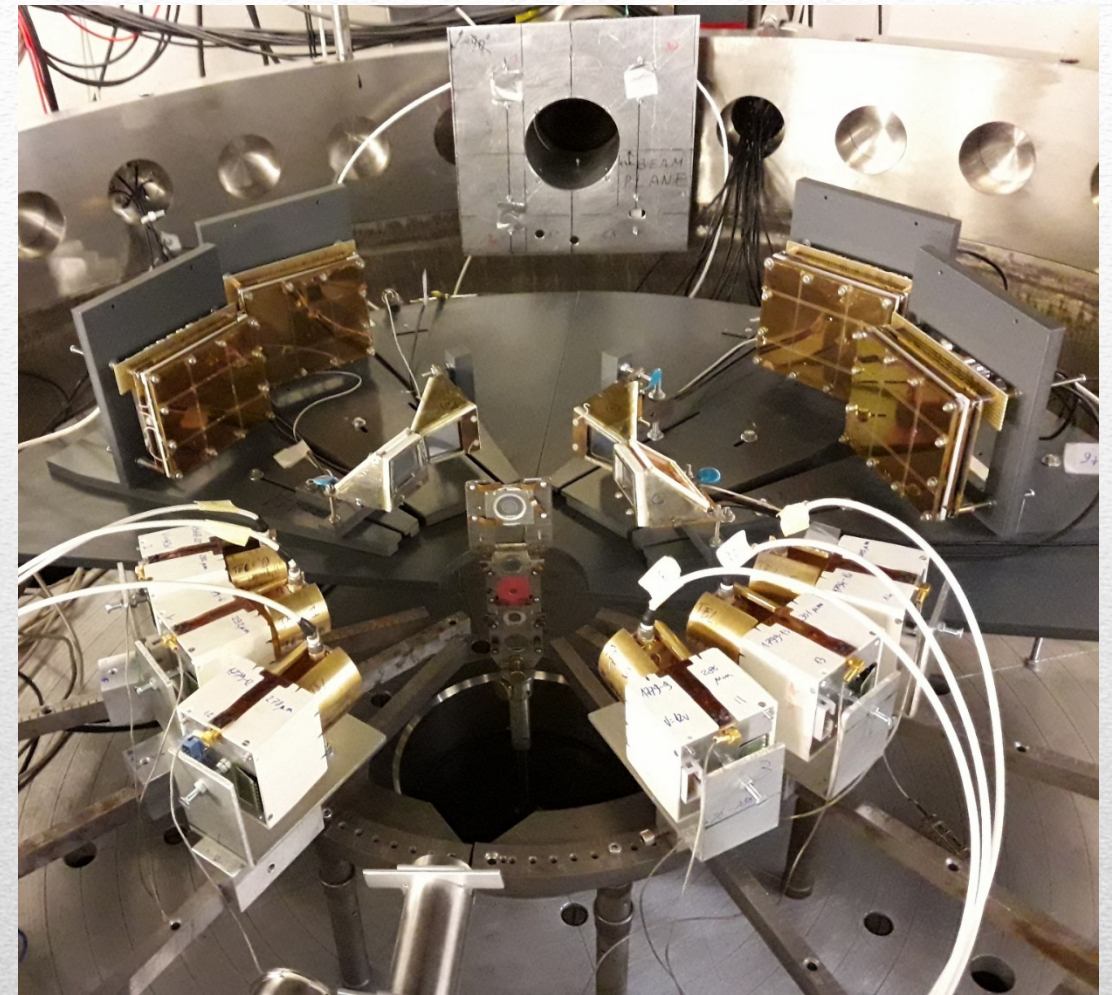
Time resolution	150-180 ps
ToF base	10-30 cm
ToF arm rotation range	15°-165°
Solid angle	100 -200 msr
Angular resolution	0.3°
Mass resolution	2-4 u
Energy resolution	1%



An extraordinary simple TOF Spectrometer: 2V - method

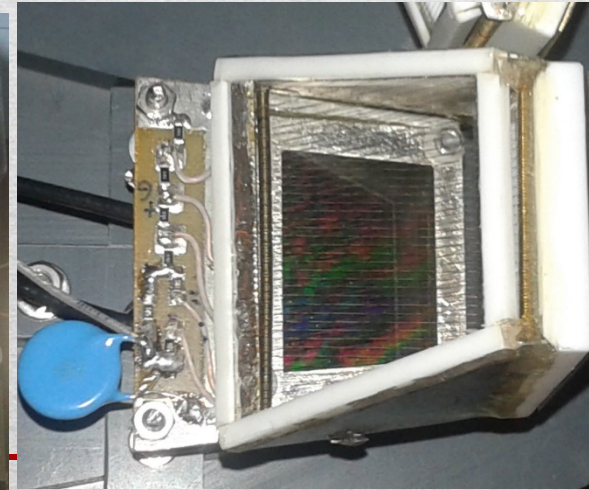
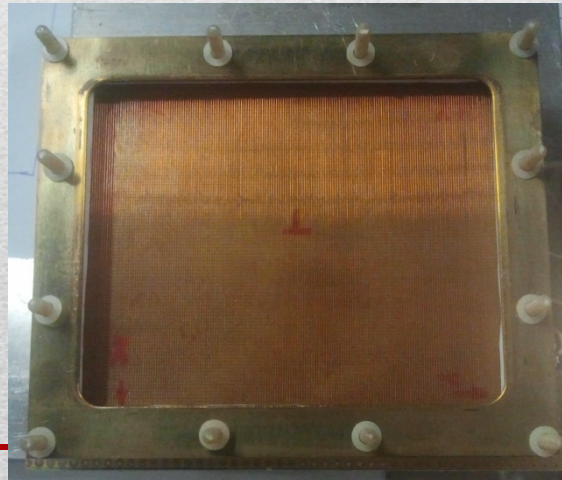
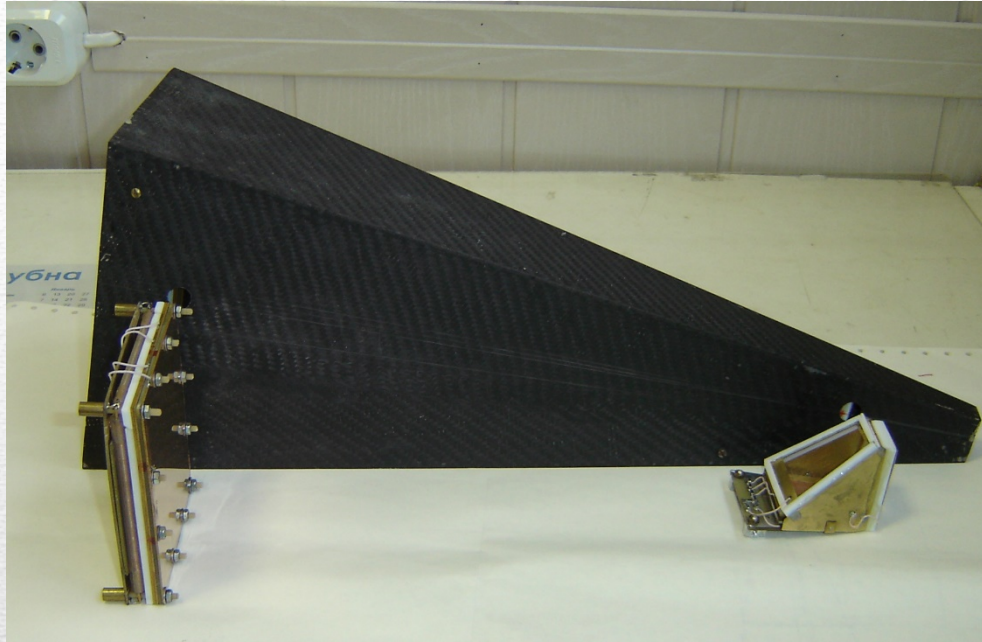


- Time of Flight
- Position
- Energy and Momentum Conservation Law
- Corrections



Primary A1, A2, TKE,
folding angles, V_{par} , V_{per}

Position Sensitive STOP



Busch-Type TOF Unit

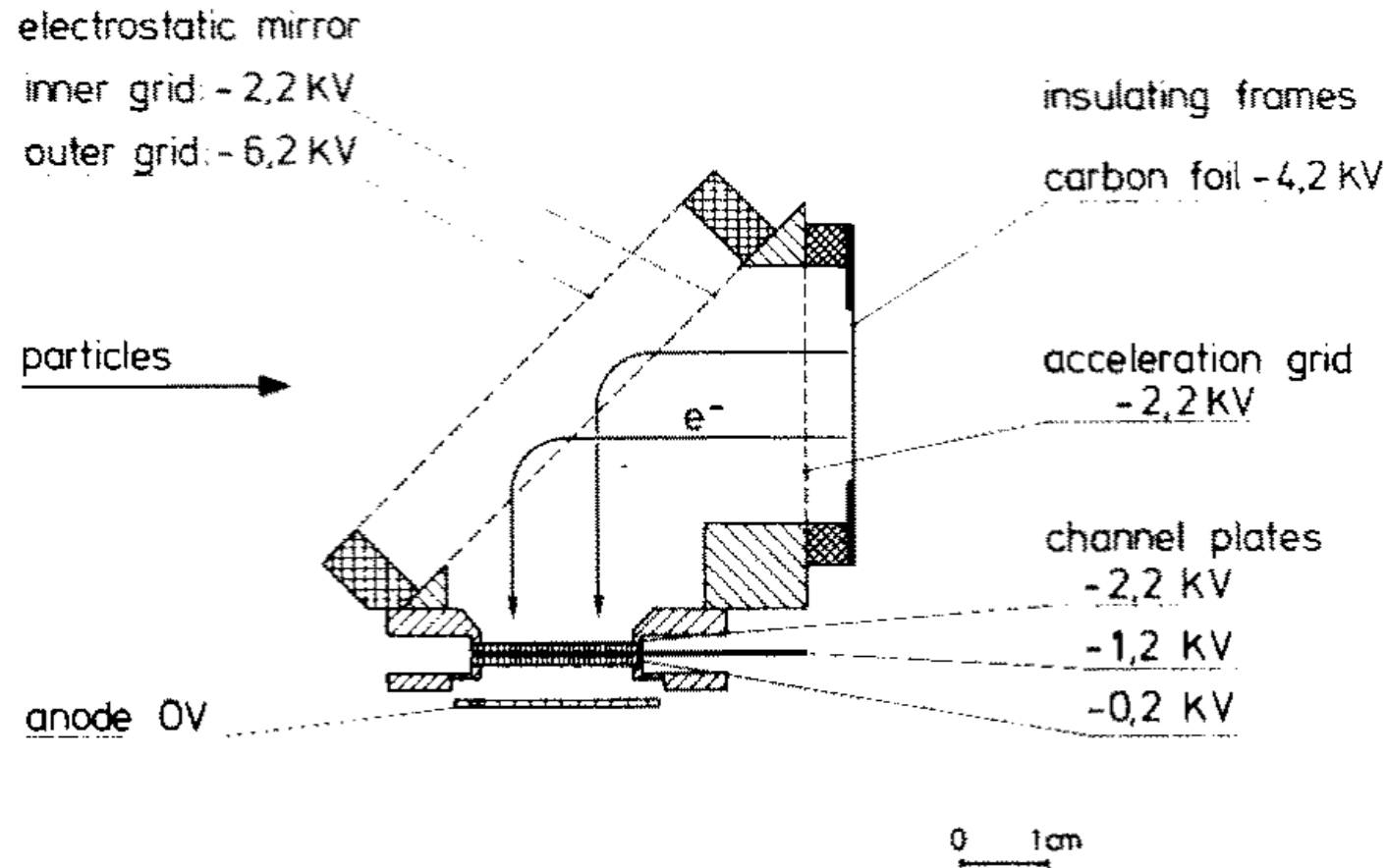


Fig. 1. Layout of the detector described in the text.

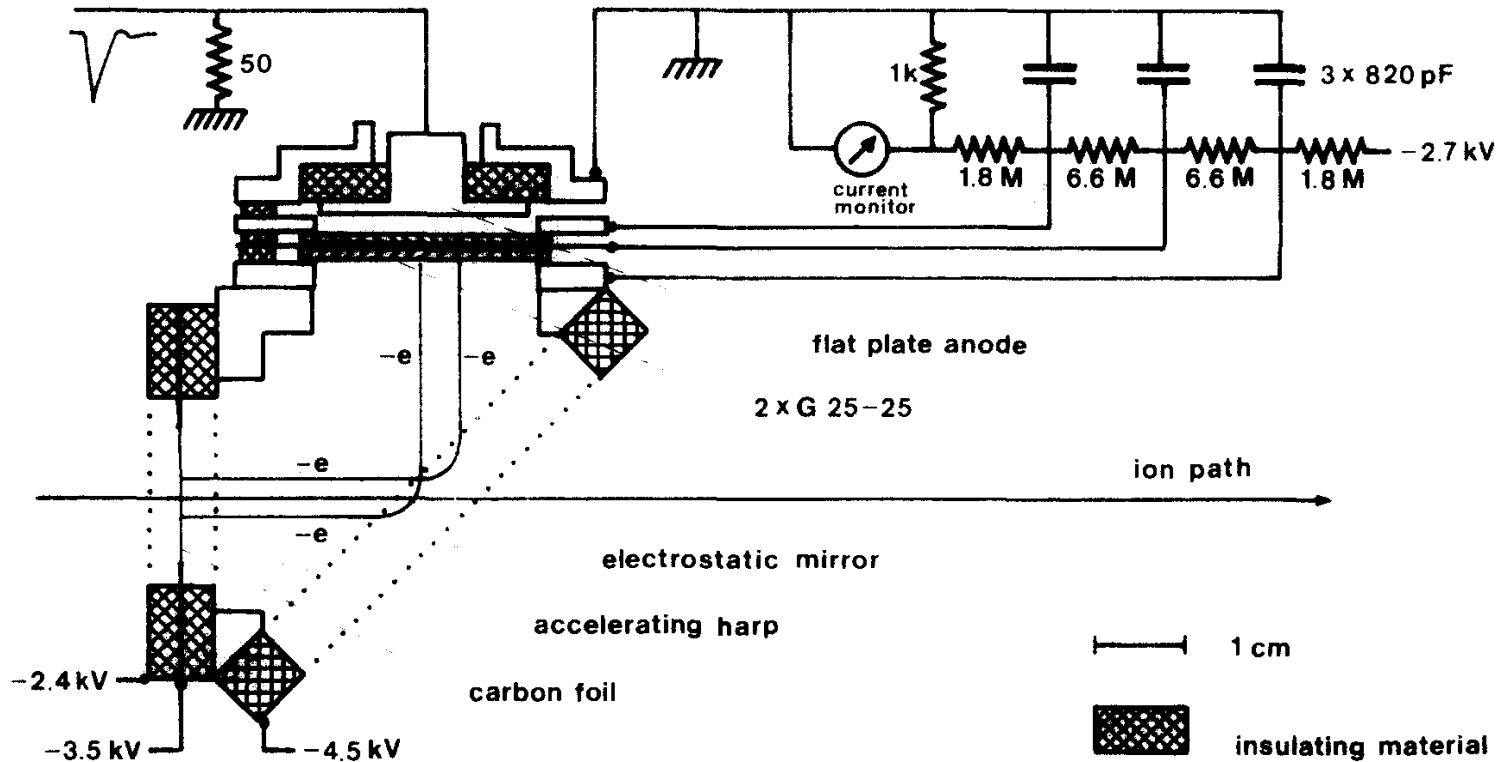
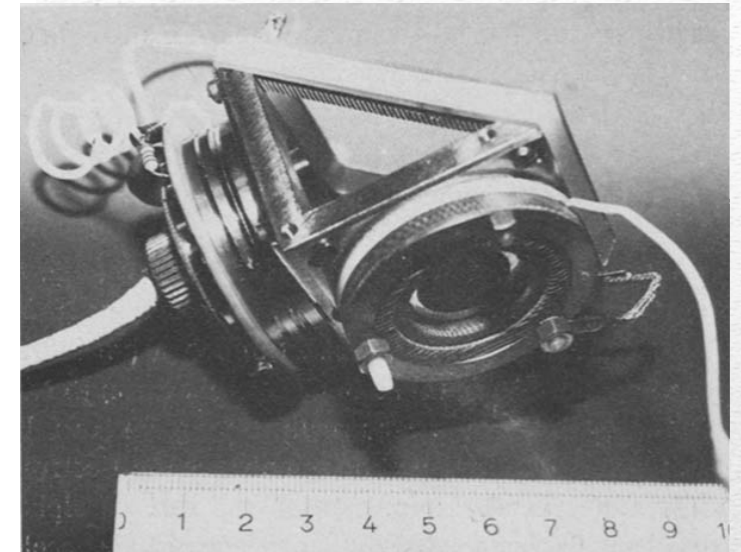
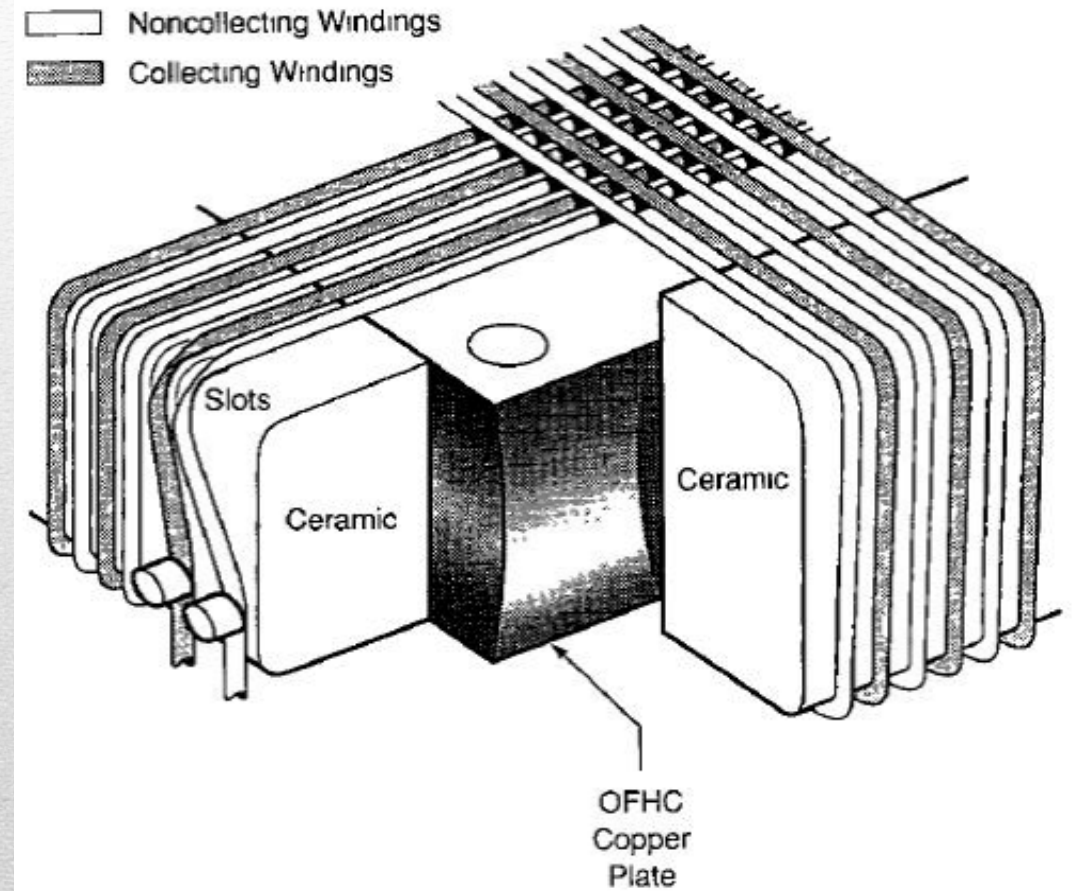
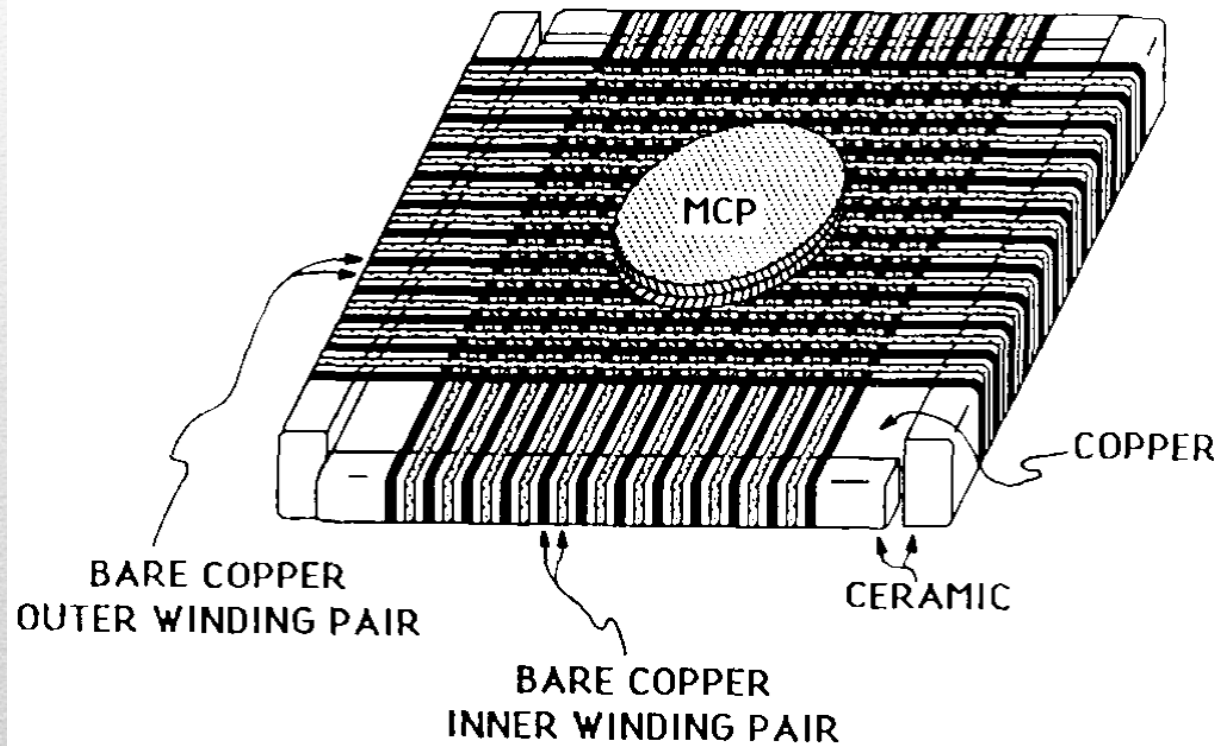
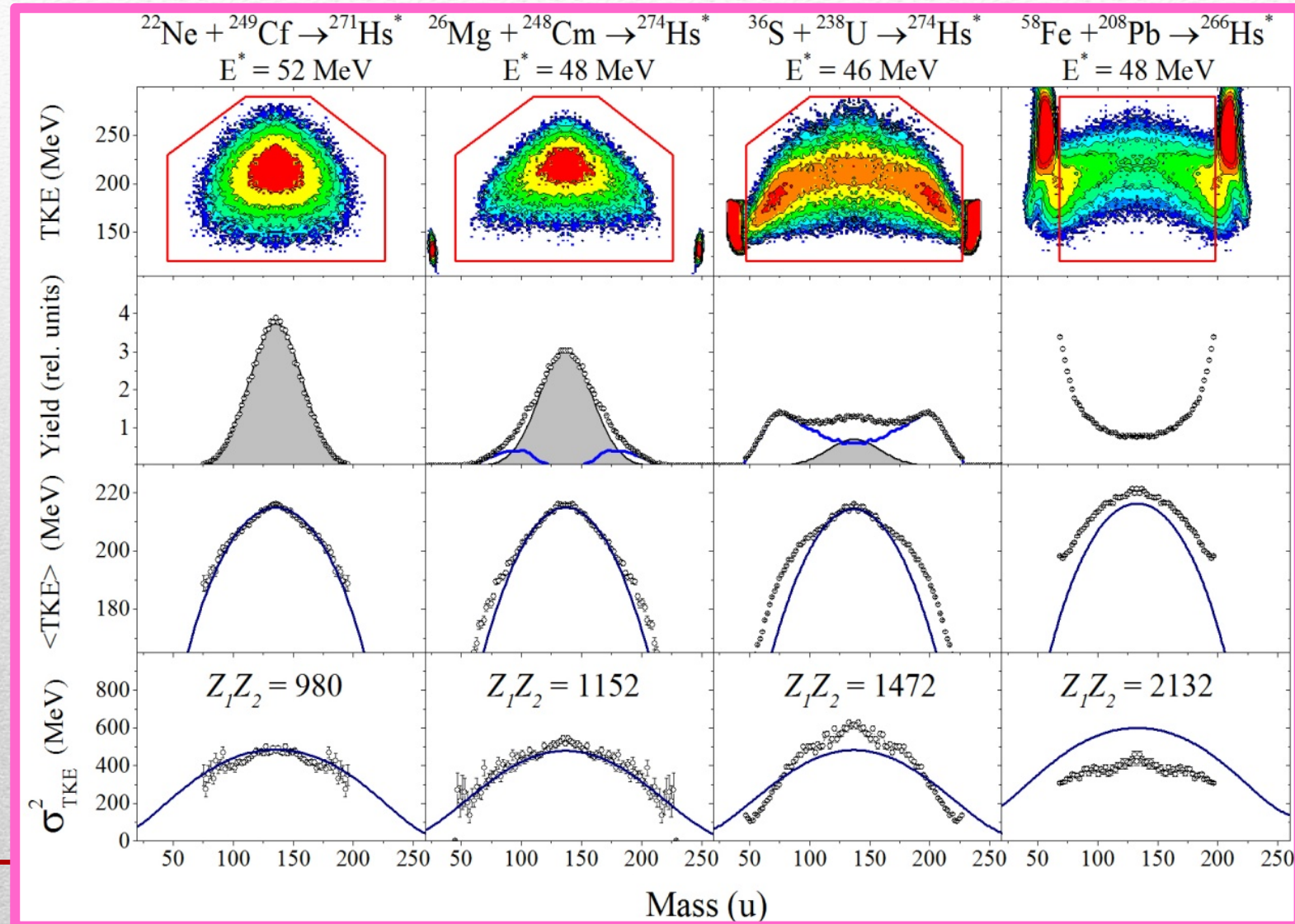


Fig. 1. Schematic view of the time-zero detector. With the potentials indicated here the reflection of the electrons occurs 1.5 mm inside the mirror.

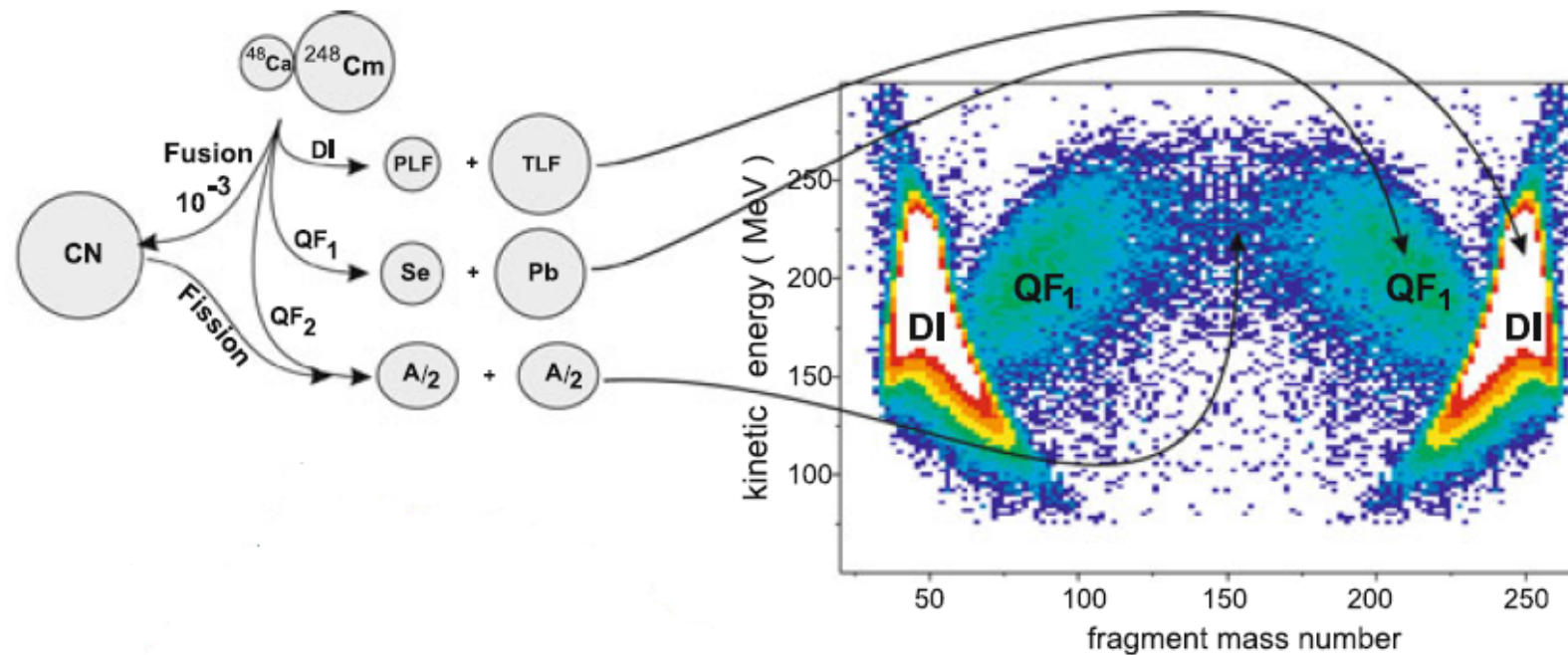
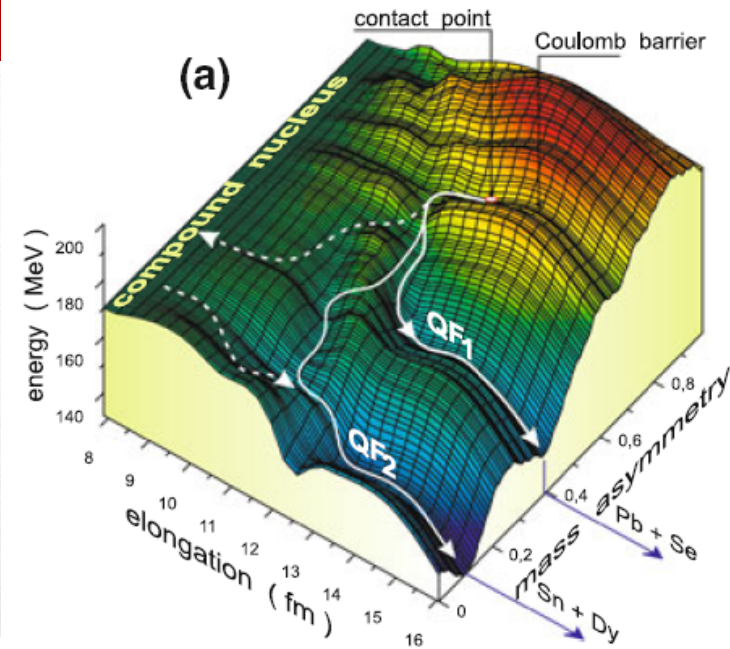




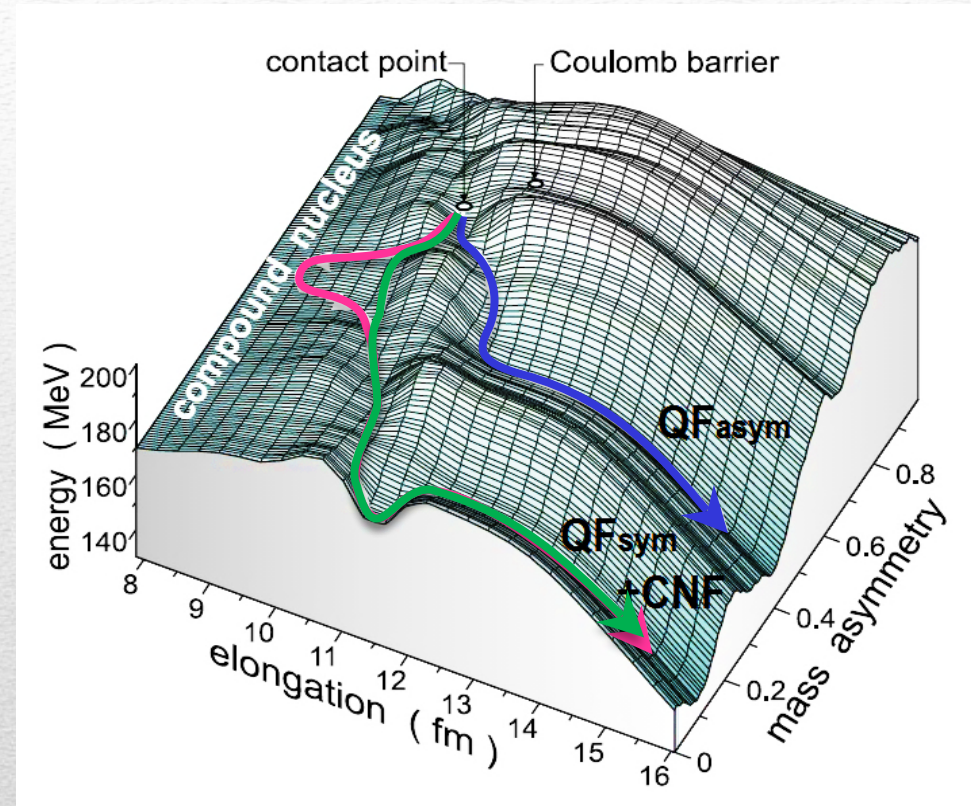
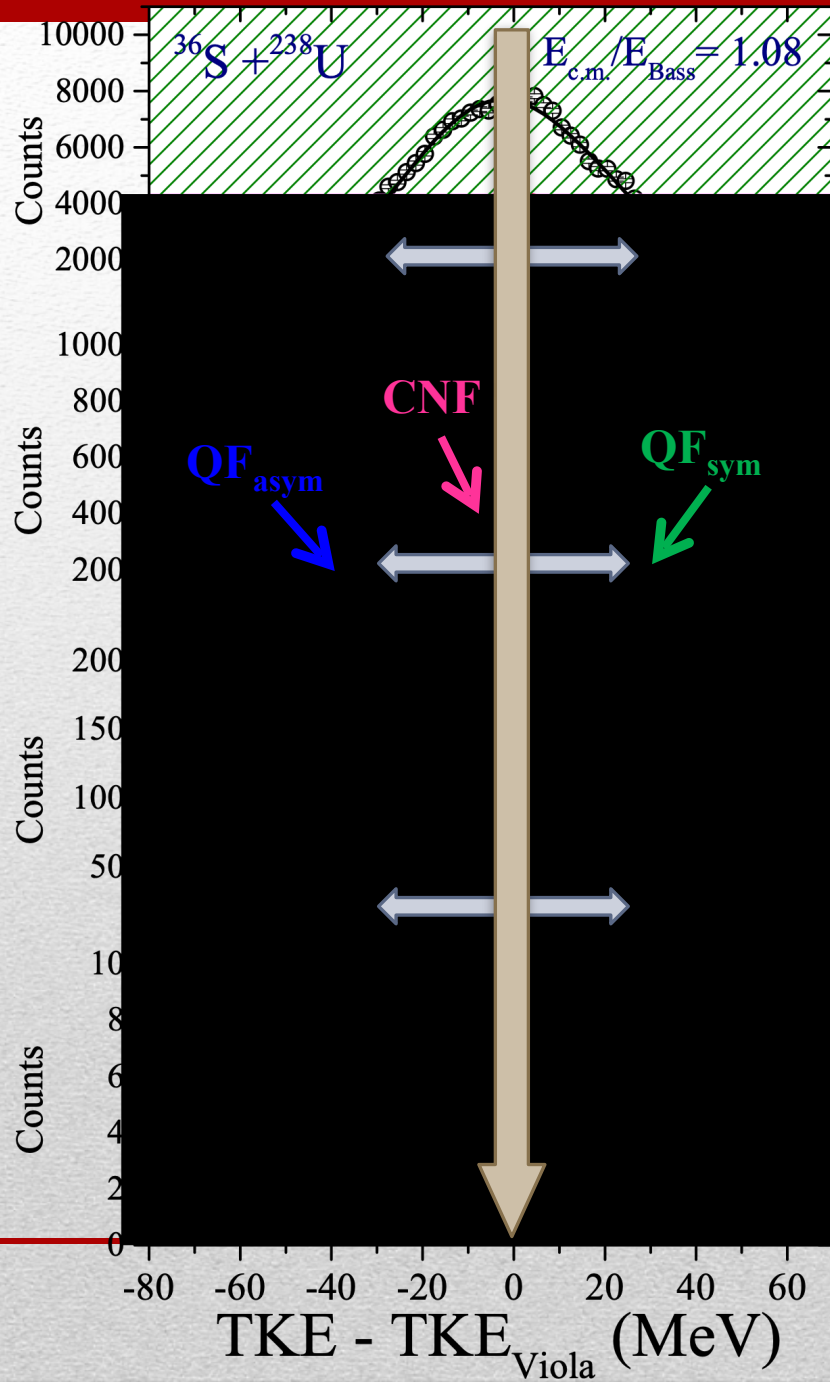
Fission and Quasi Fission: Hs (Z=108)



Shell manifestation: Potential Energy Landscape and FF/QF Paths



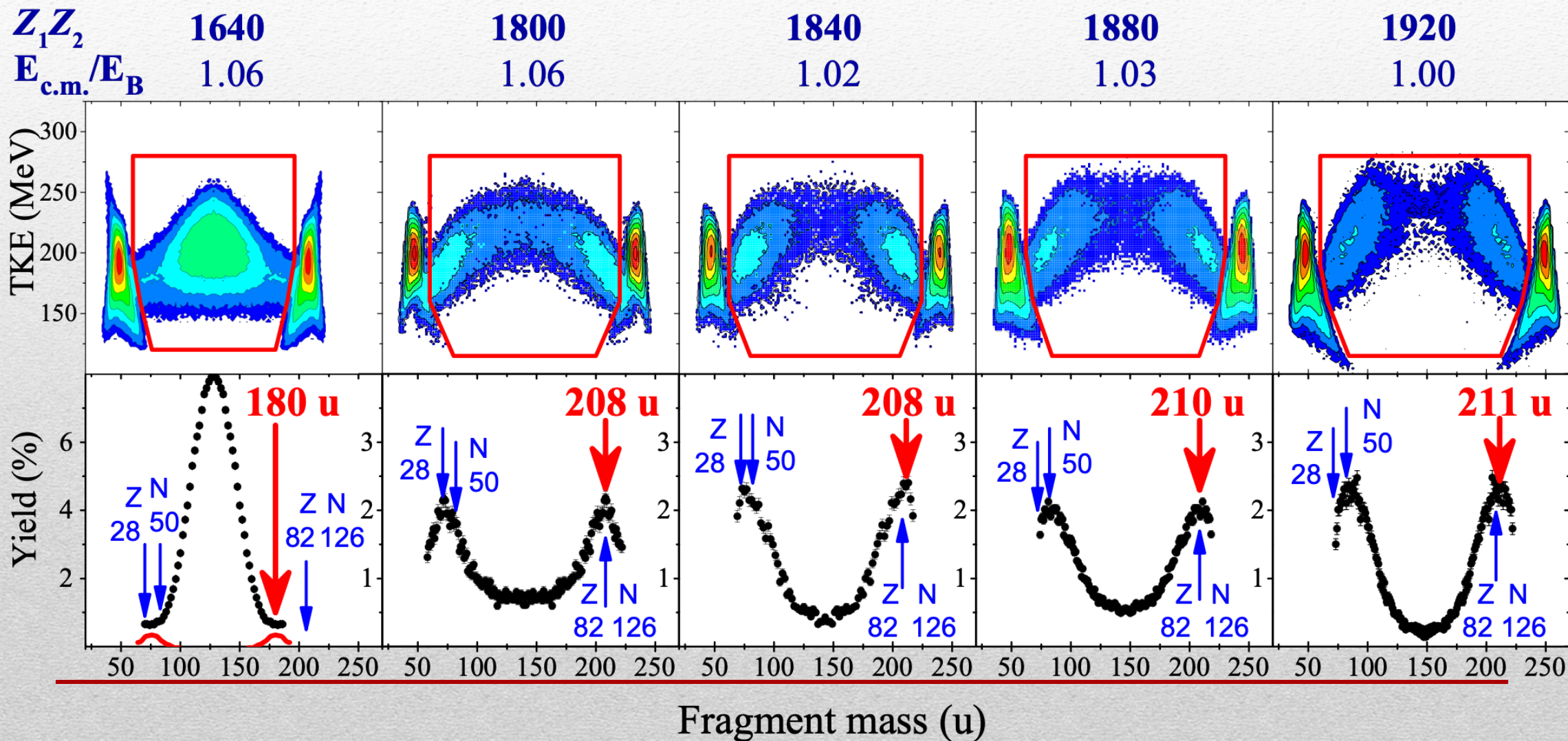
TKE deconvolution



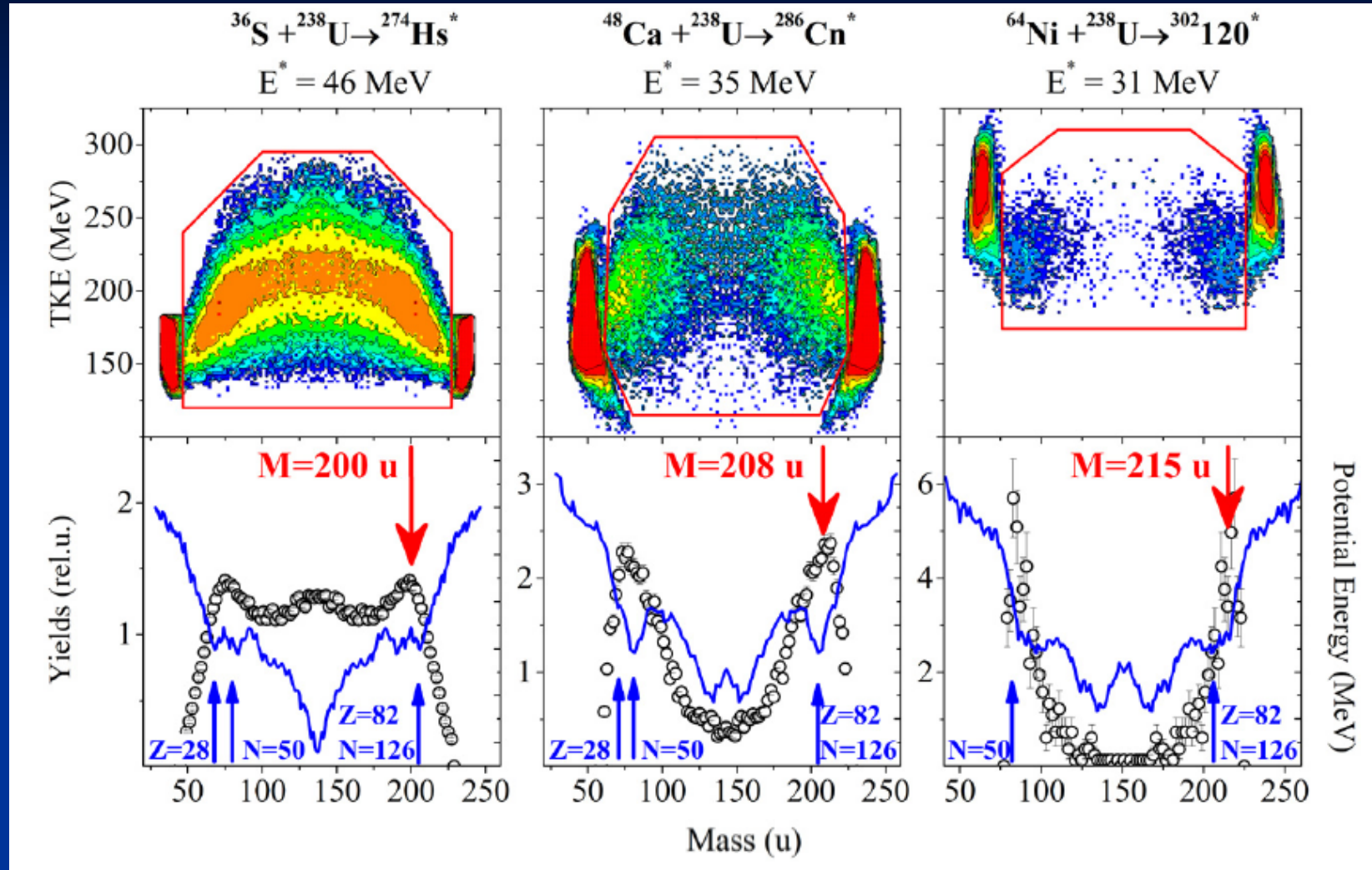
$$A_{CN}/2 \pm 20 \text{ u}$$

*Courtesy of Iulia Itkis
Workshop on Fission of SHN, ECT*, Trento, 2018*

Mass and Energy distributions in the Ca-induced reactions

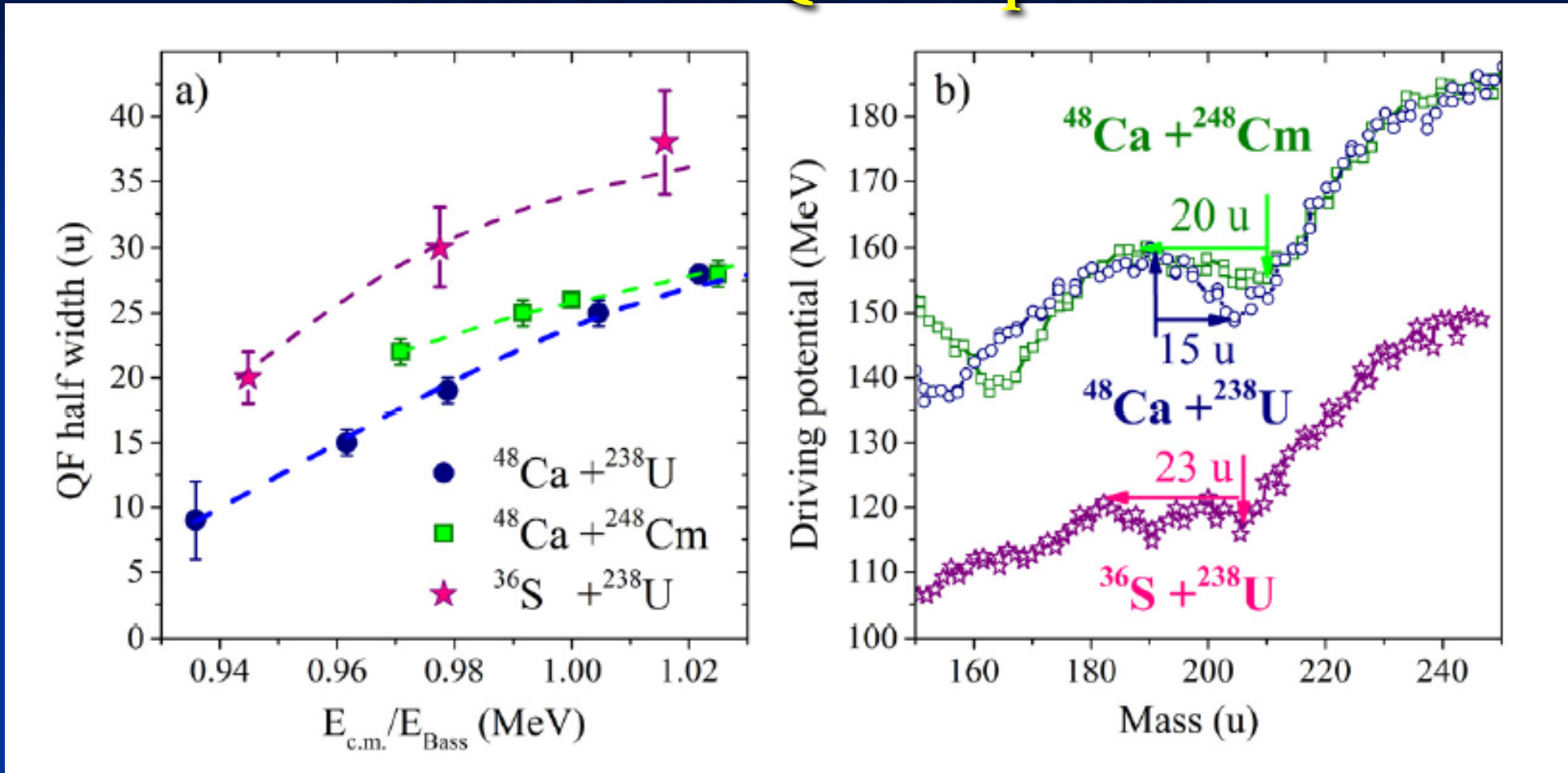


Shell effects - 1



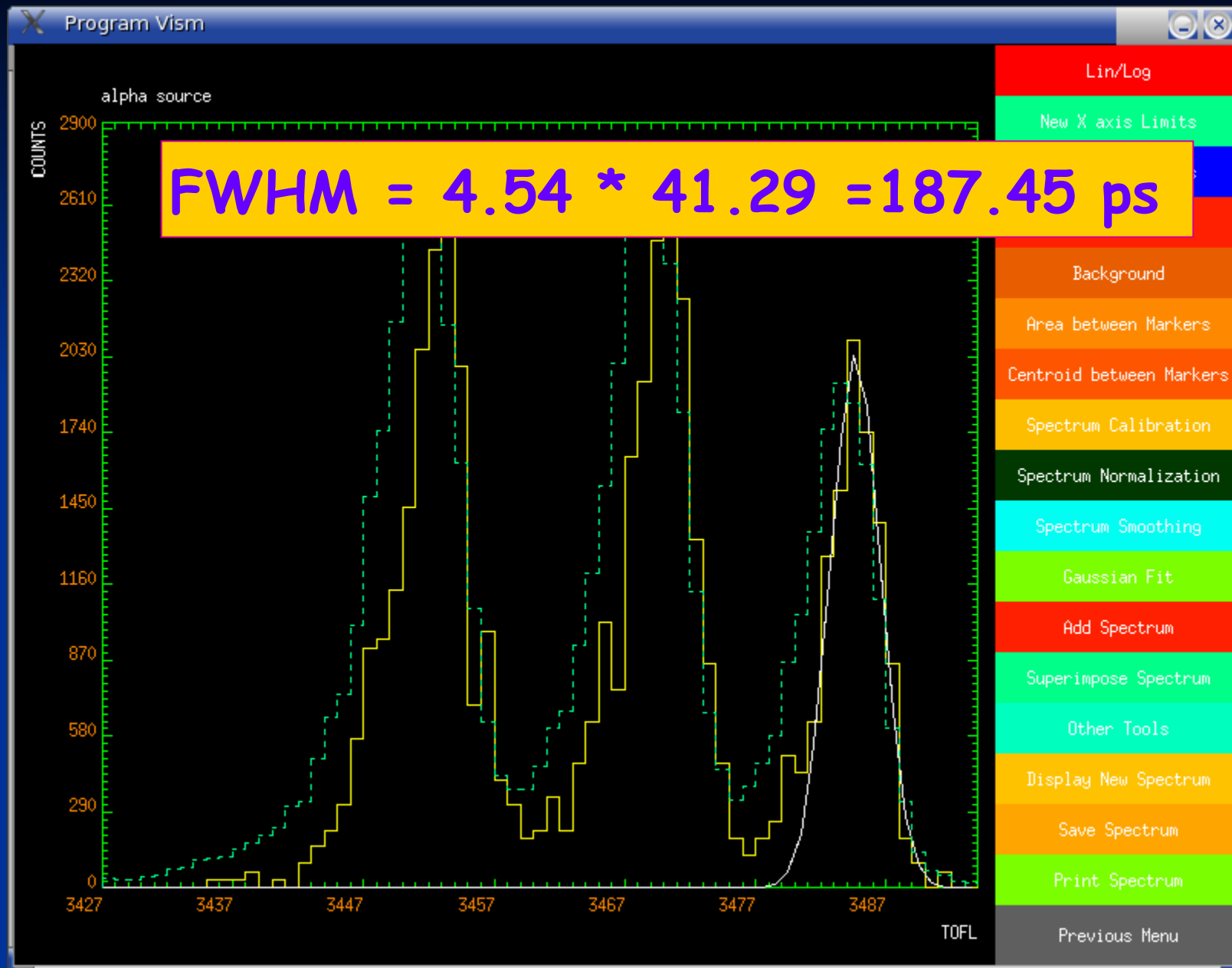
Shell effects-2

Width of the QF component



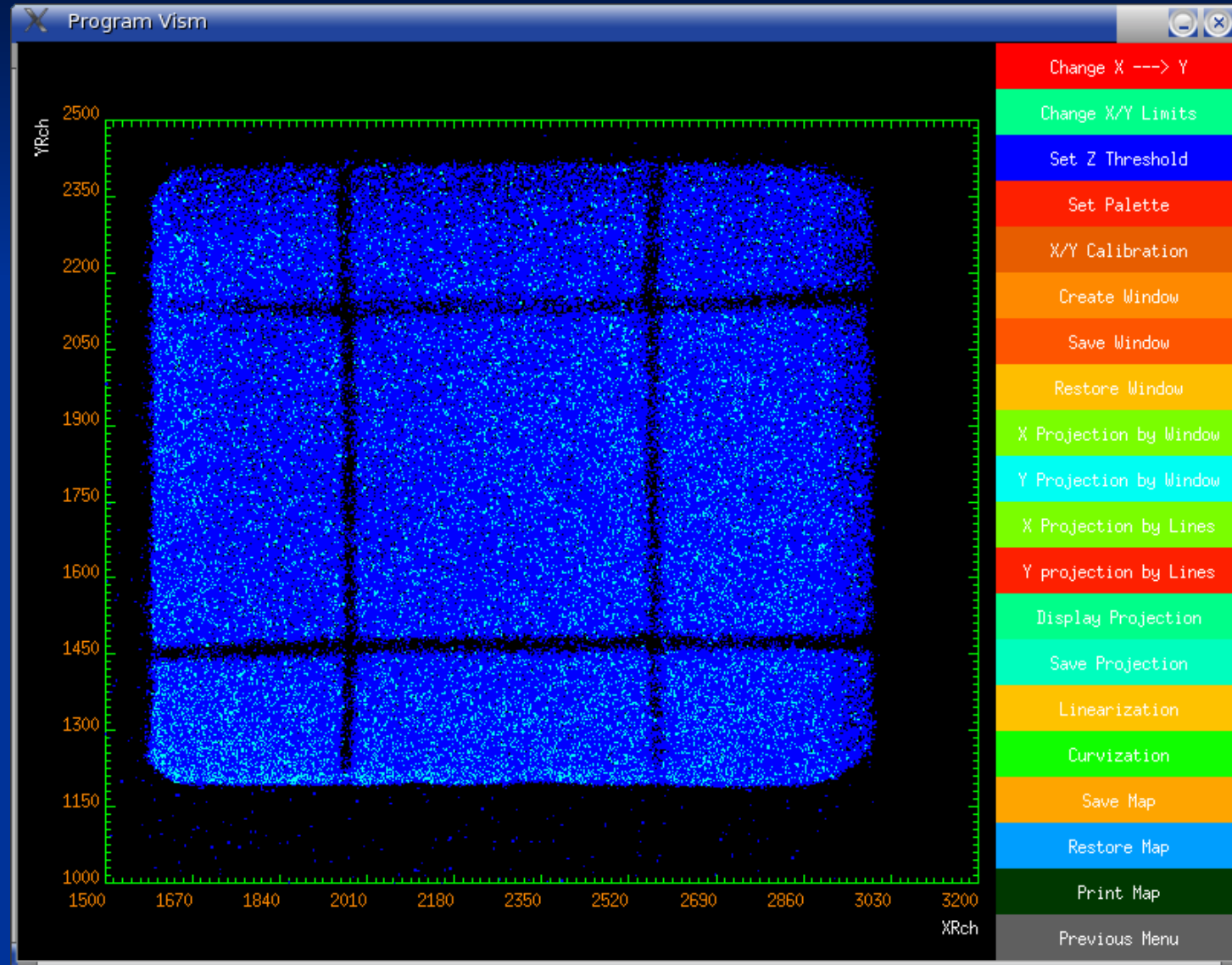
8π LP & CORSET @ LNL

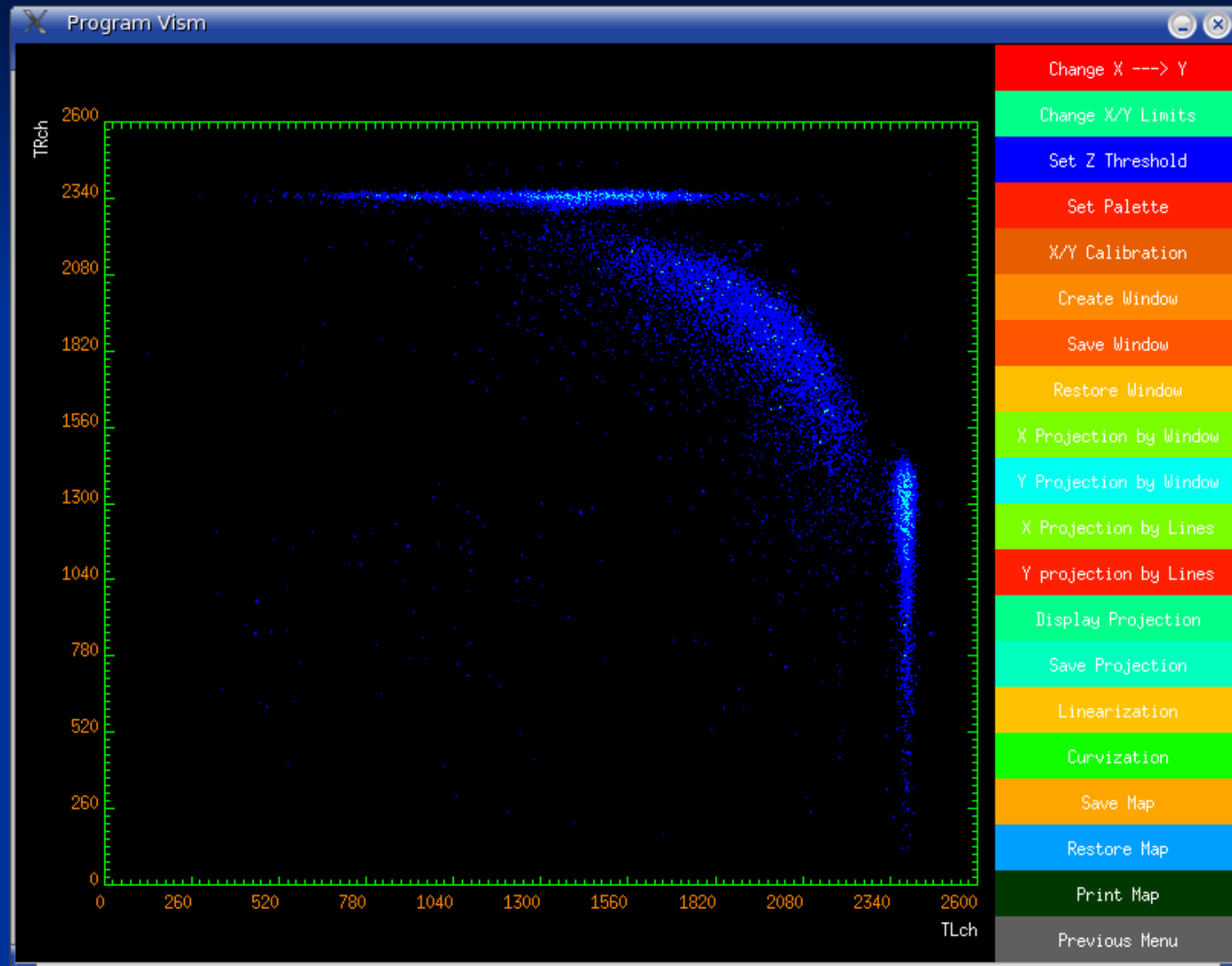






F- LEFT





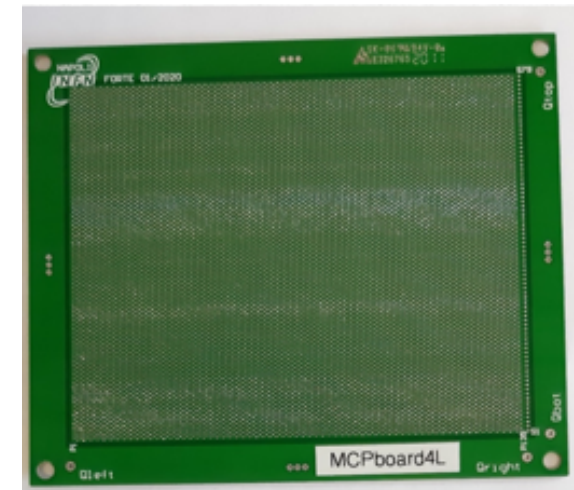
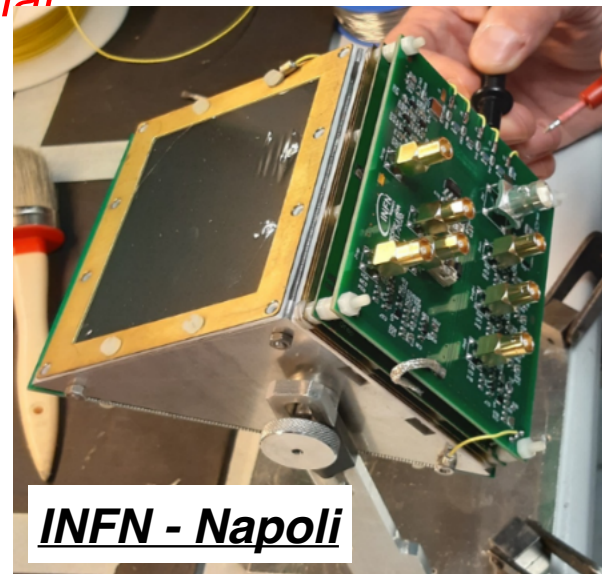
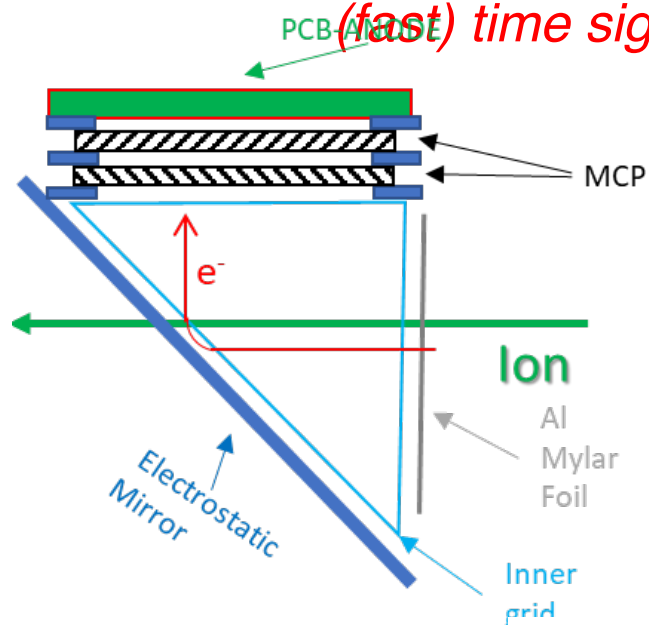
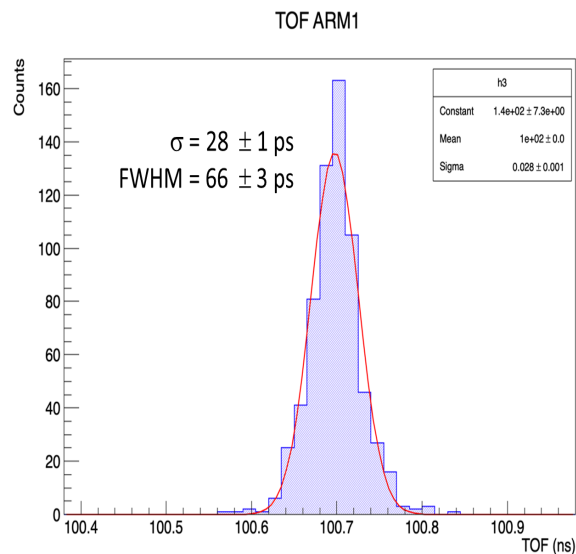


Ministero degli Affari Esteri
e della Cooperazione Internazionale

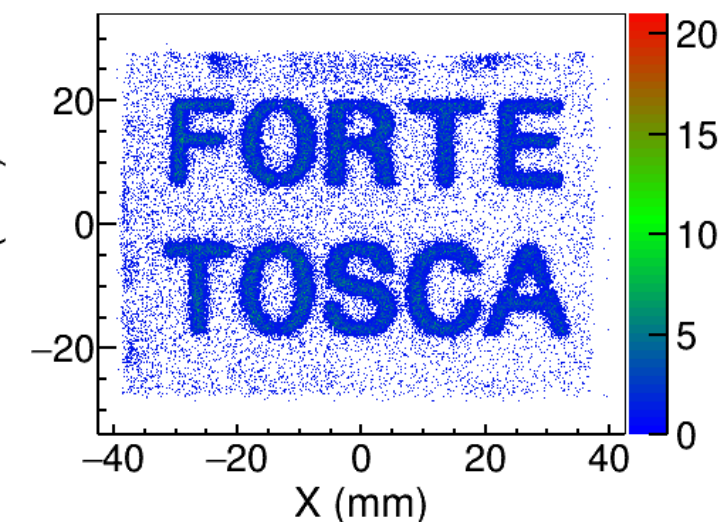
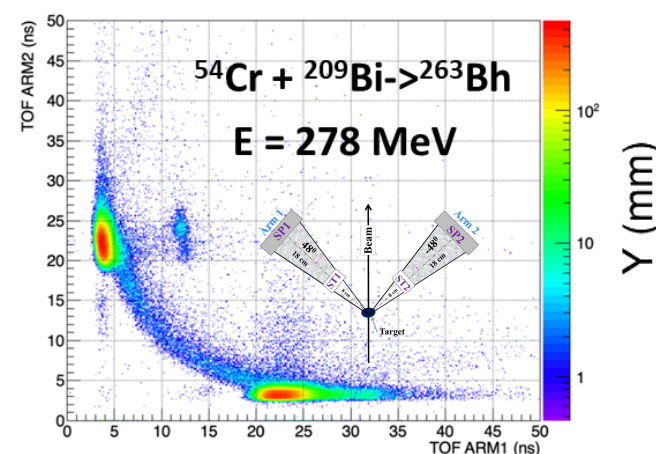
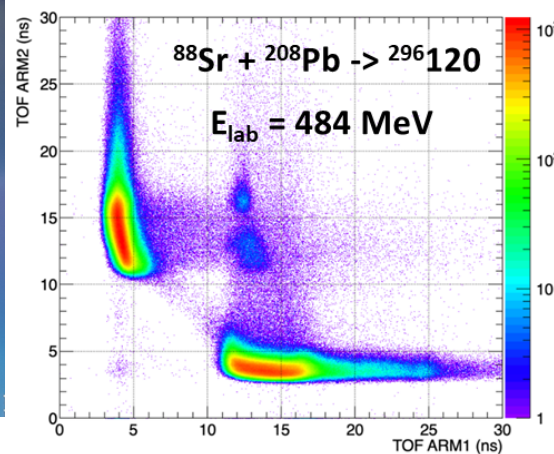
A new passing through detector – TOSCA unit

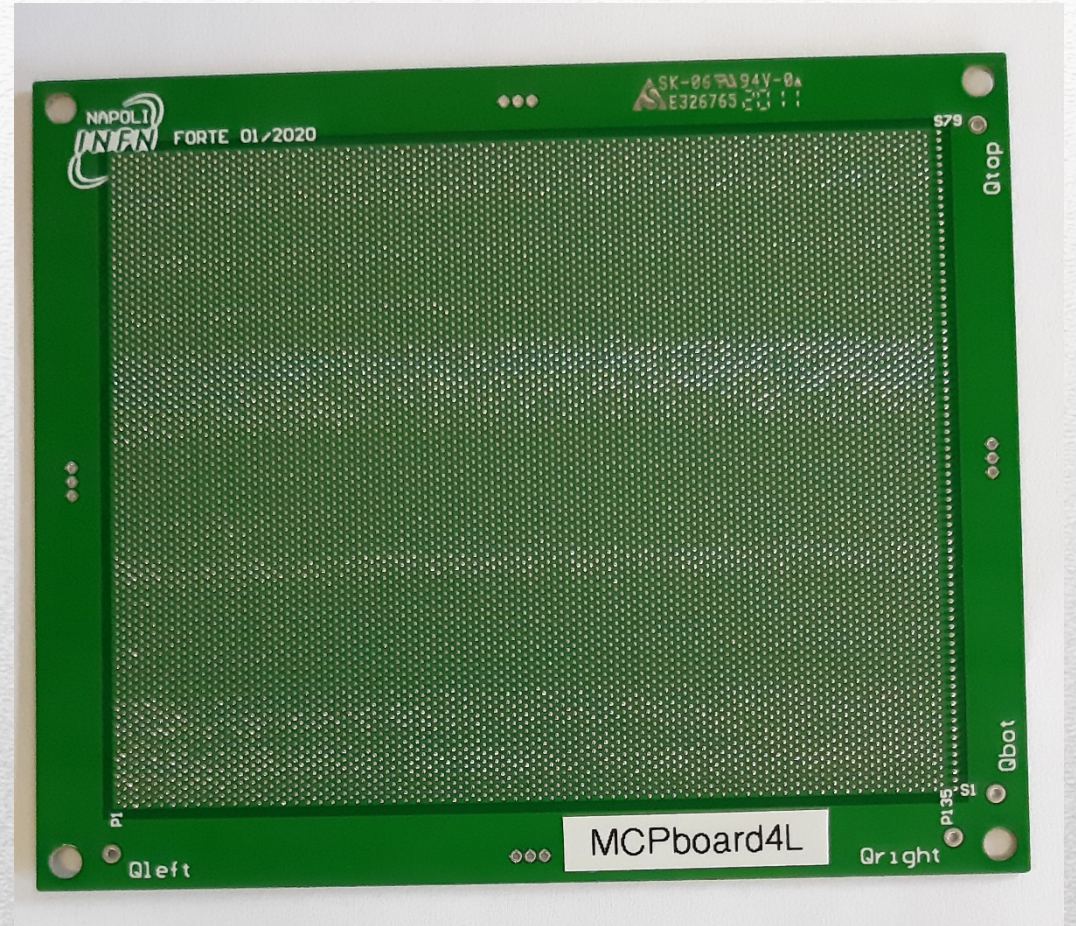
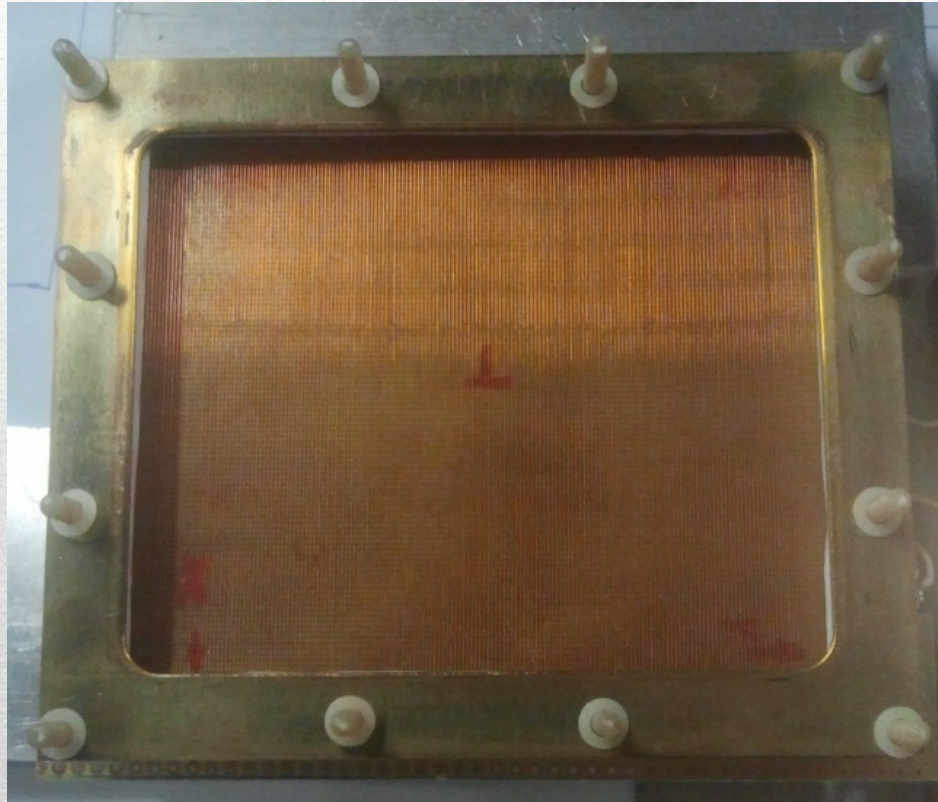
Time-Of-flight-sub-nano-second Spectrometer for Charged radiation Applications

- Position sensitive based on MCP: X,Y position and (fast) time signal

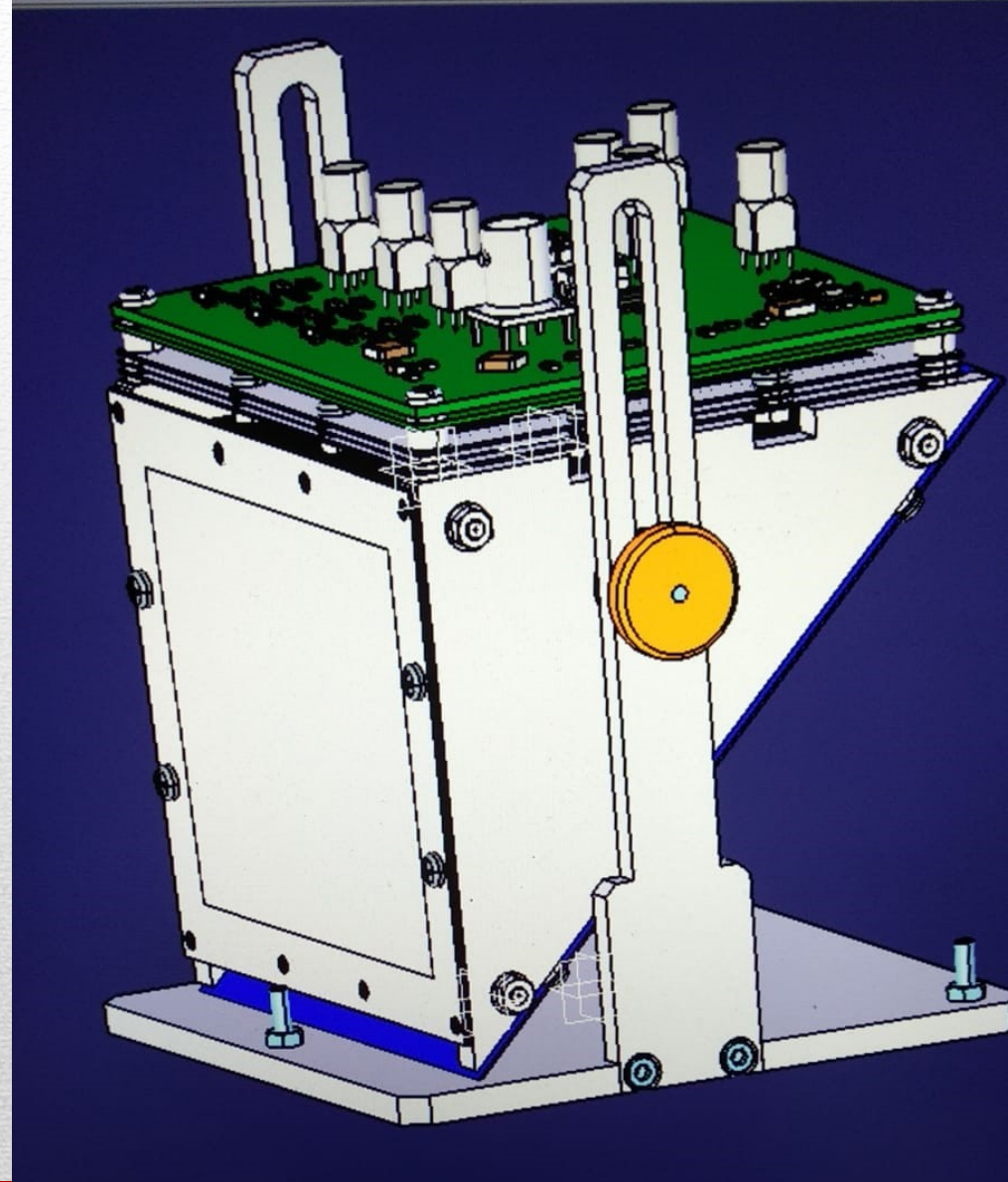
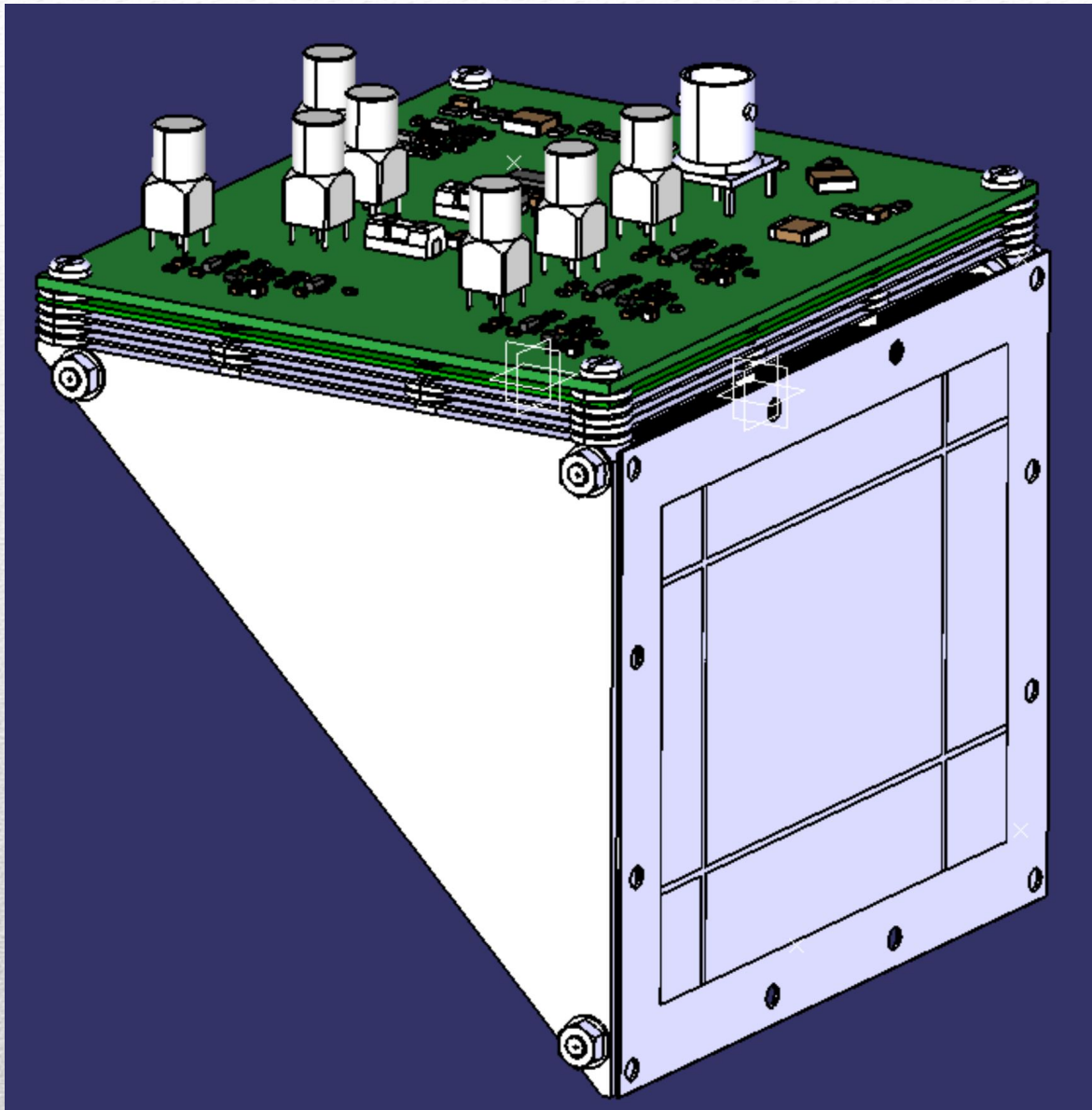


(X,Y) Position Grid on PCB



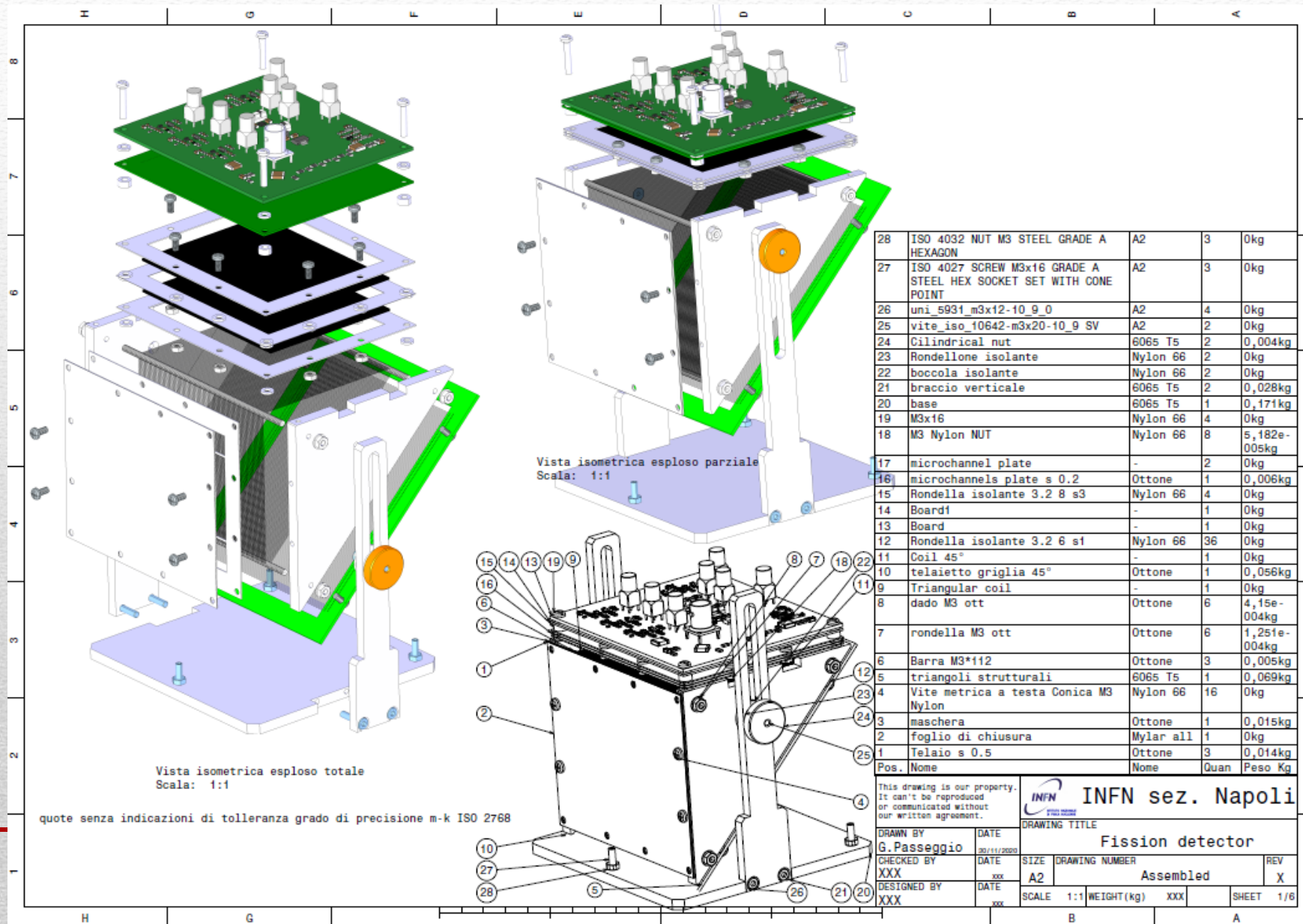


TOSCA unit

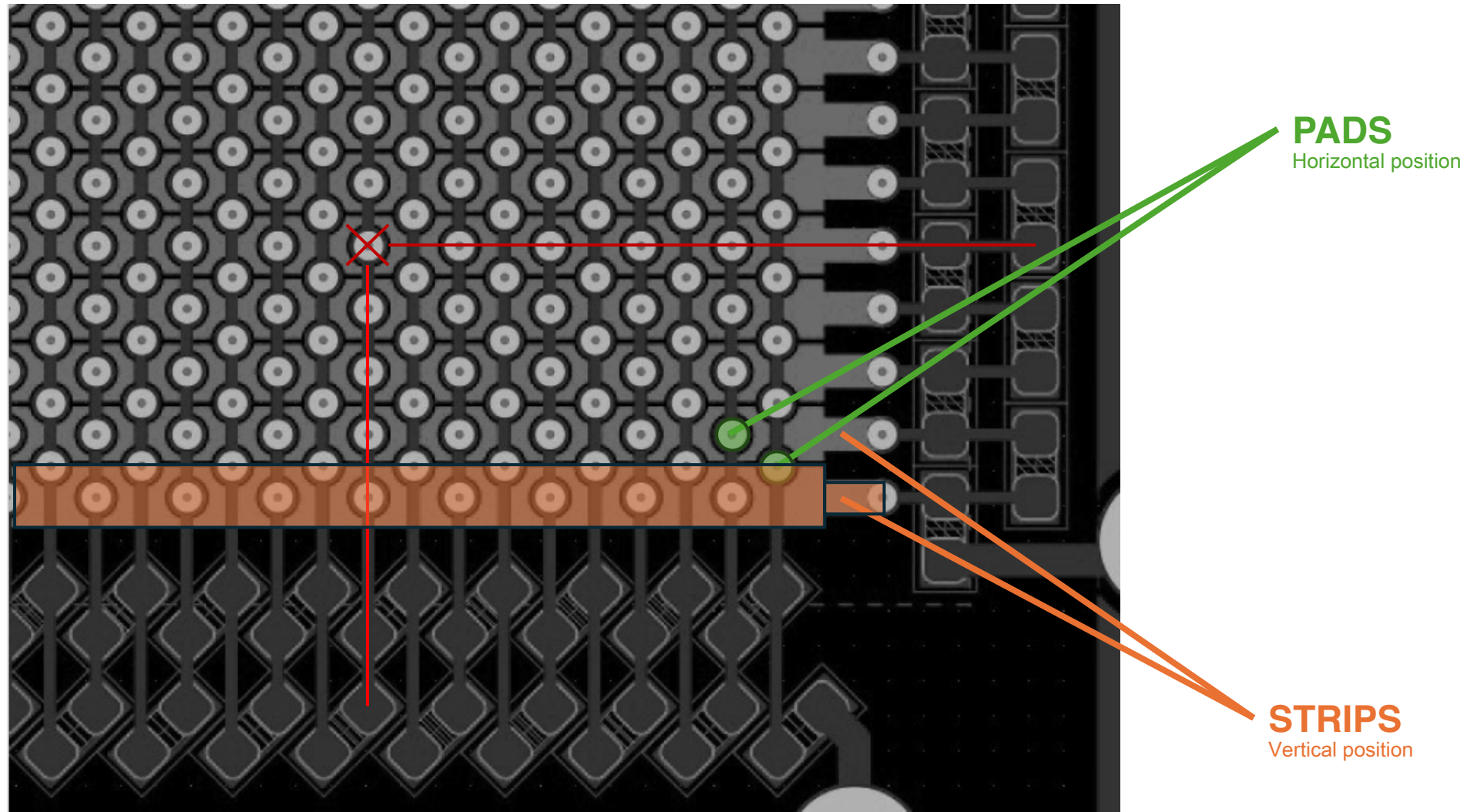


TOSCA unit

Time-Of-flight-sub-nano-second Spectrometer for Charged radiation Applications



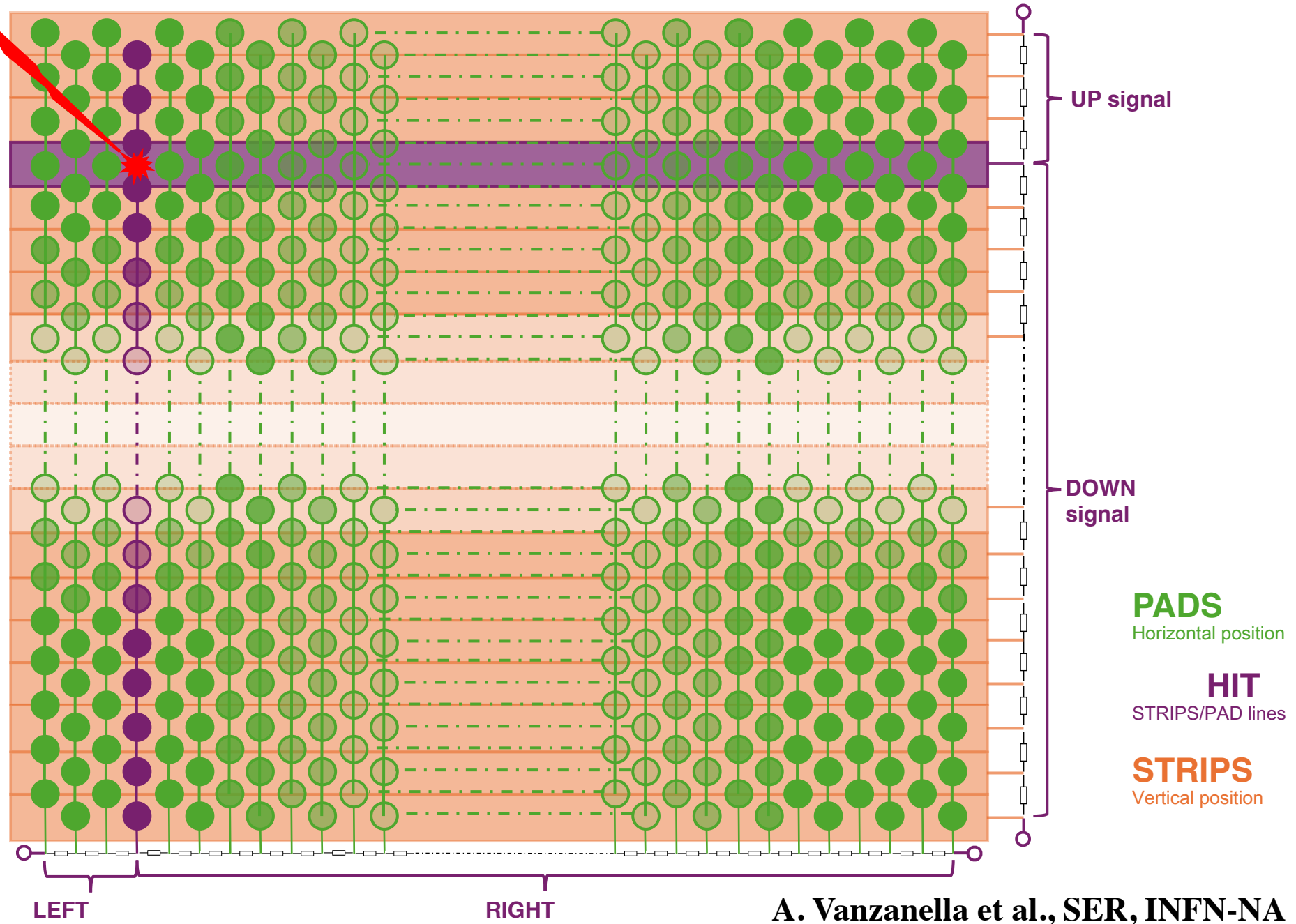
XY grid detail



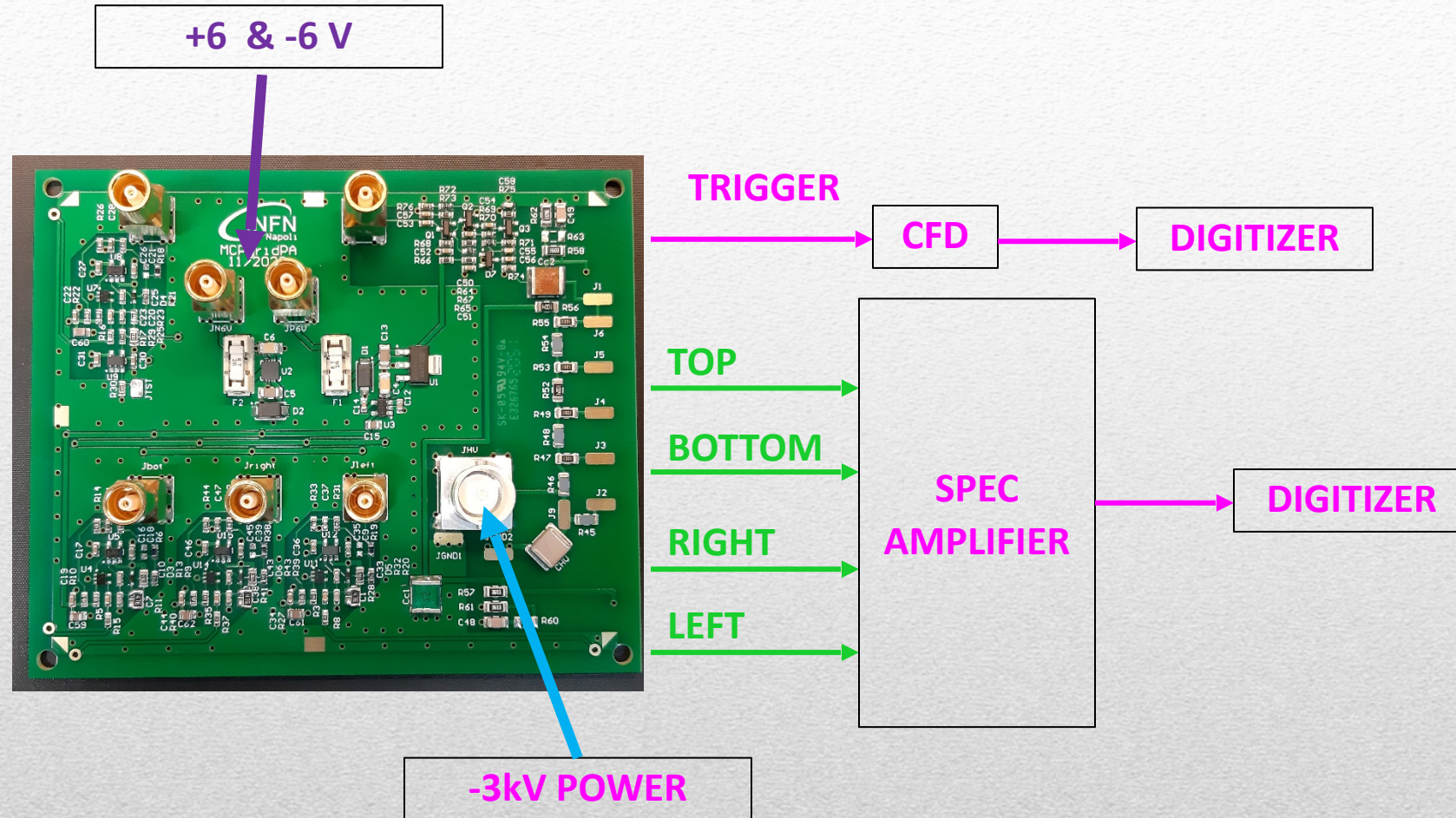
Signals production

$$X = \frac{R - L}{R + L}$$

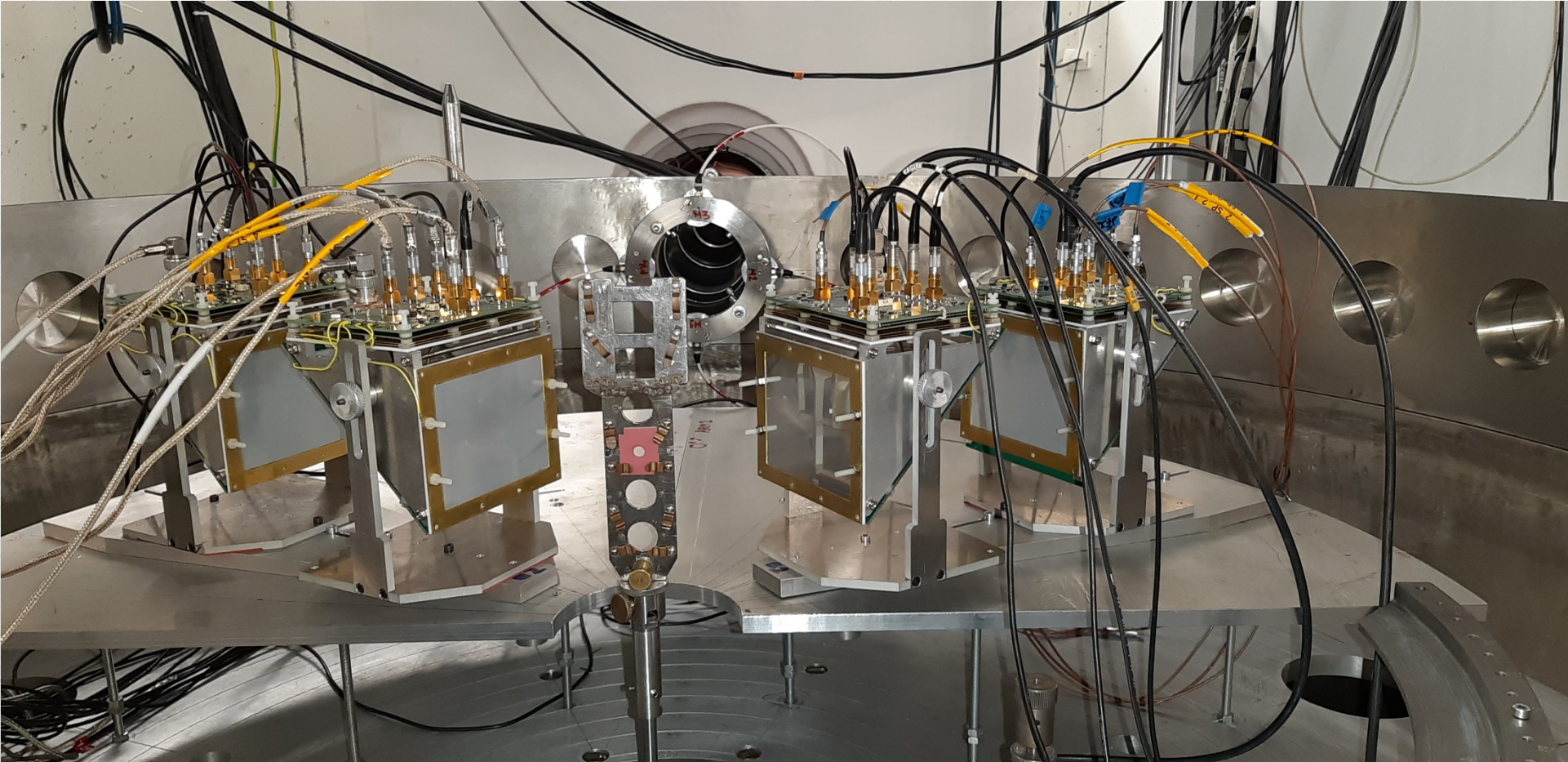
$$Y = \frac{T - B}{T + B}$$



TOSCA electronics

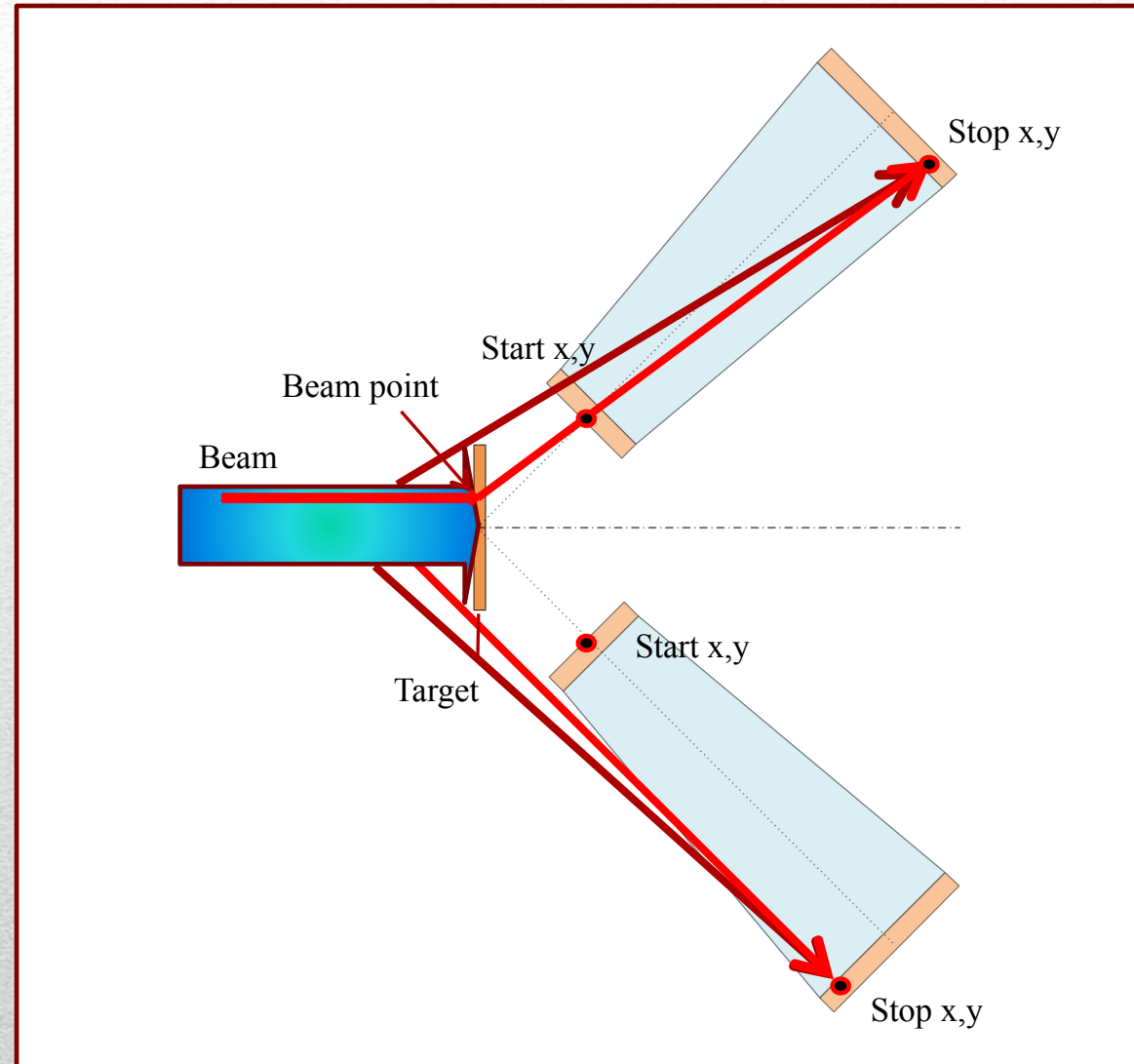


TOSCA at JYFL



February - March - September 2023

TOF Spec. with Position Sensitive START



TOSCA unit: position resolution (1)

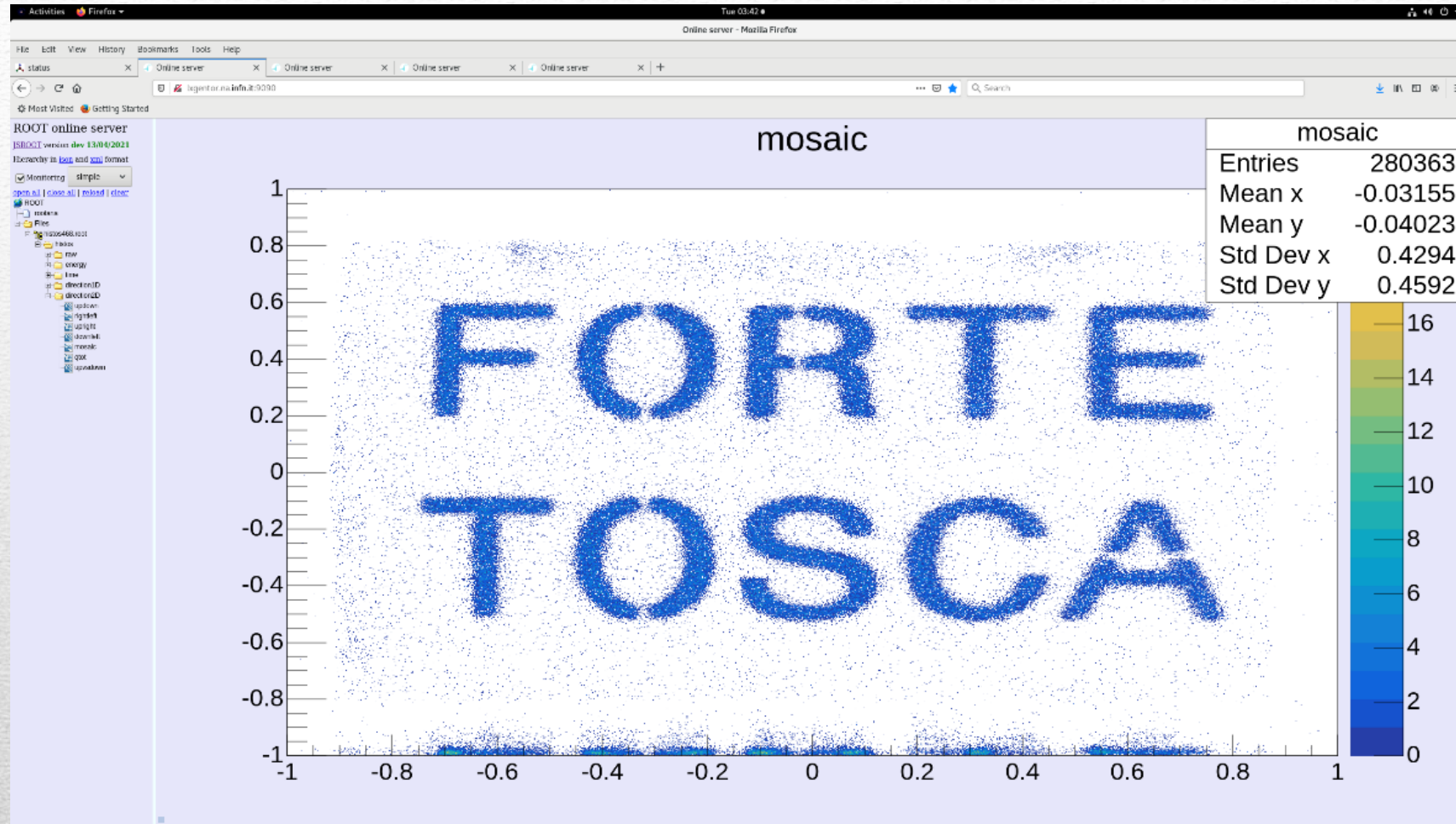
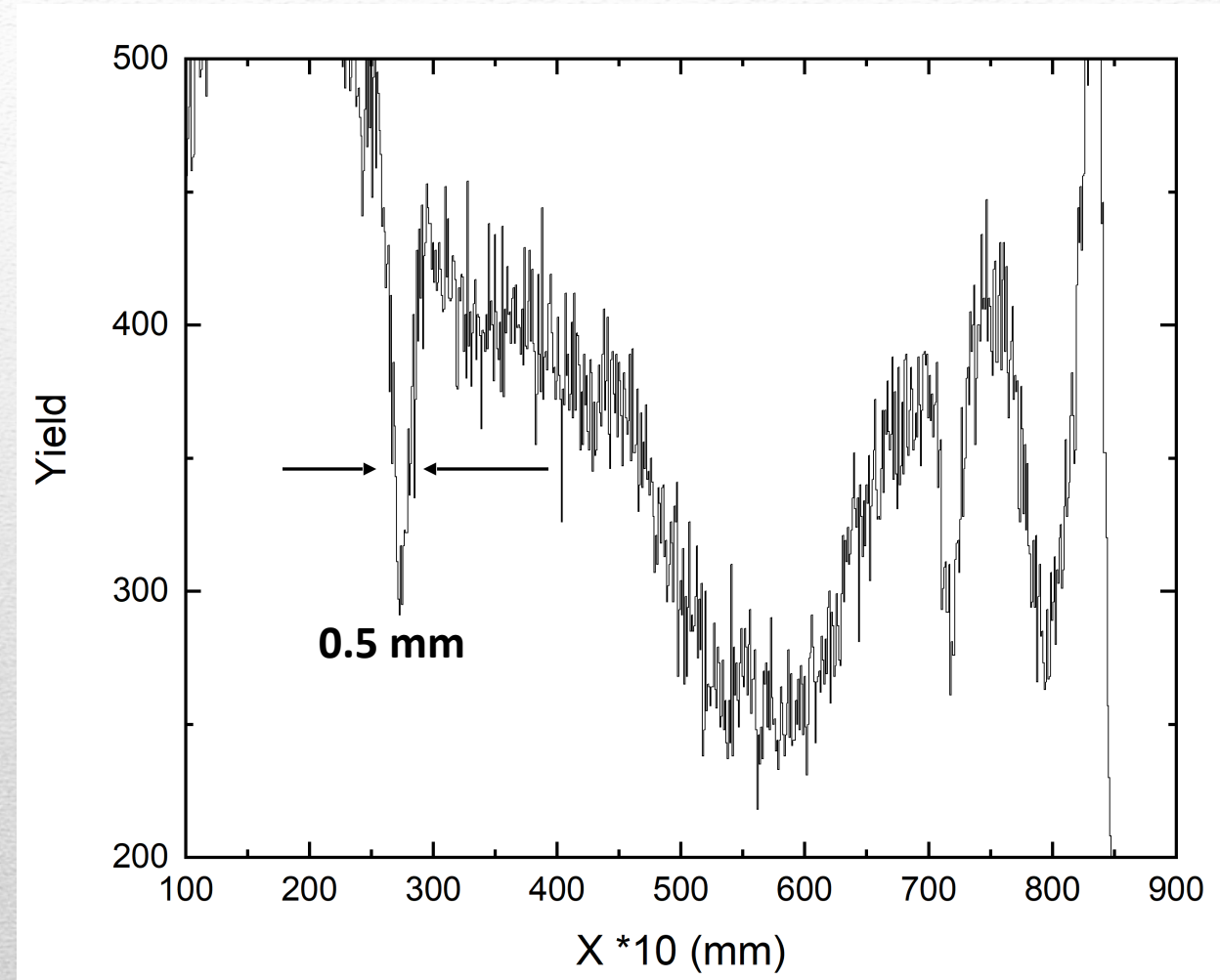
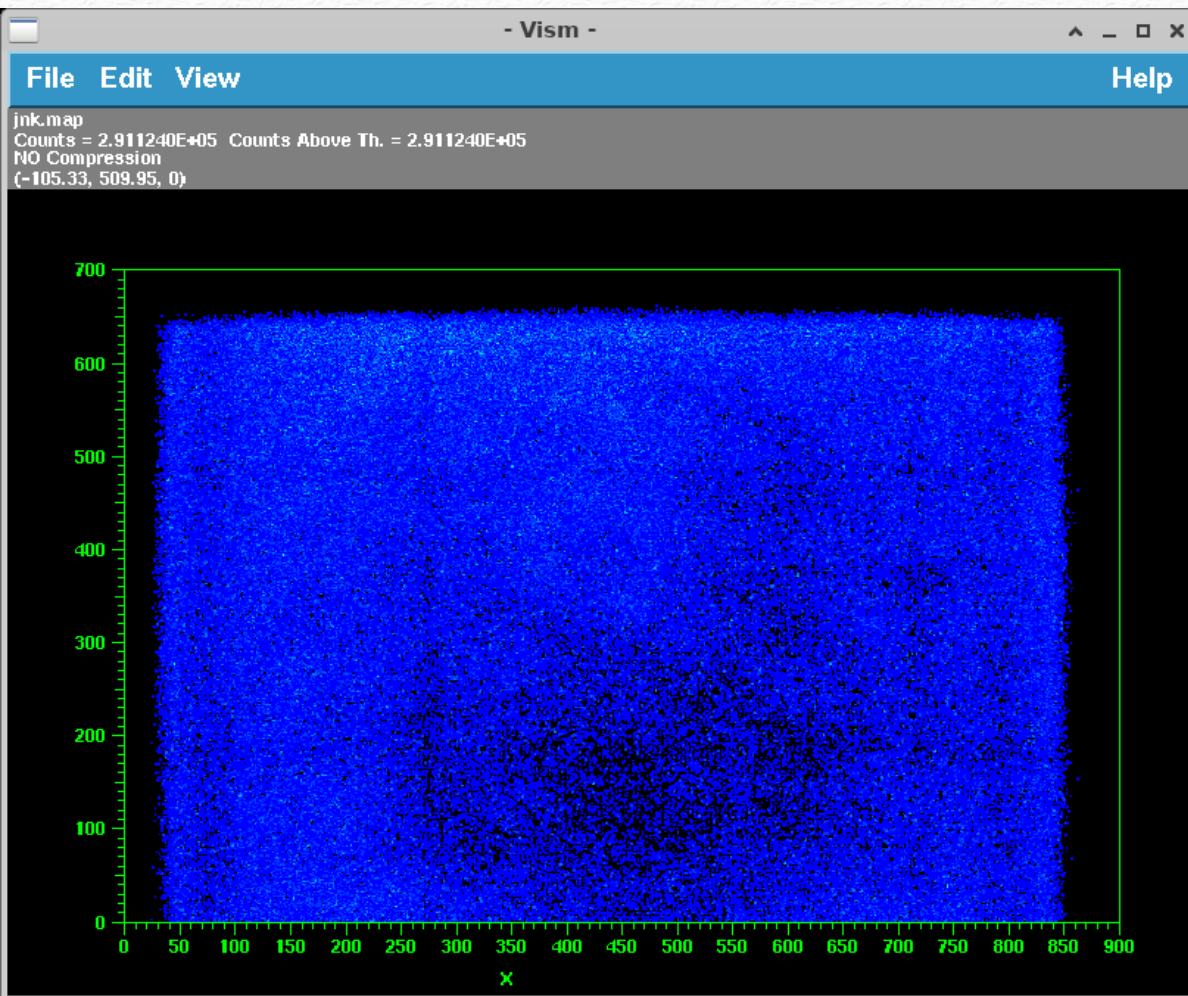
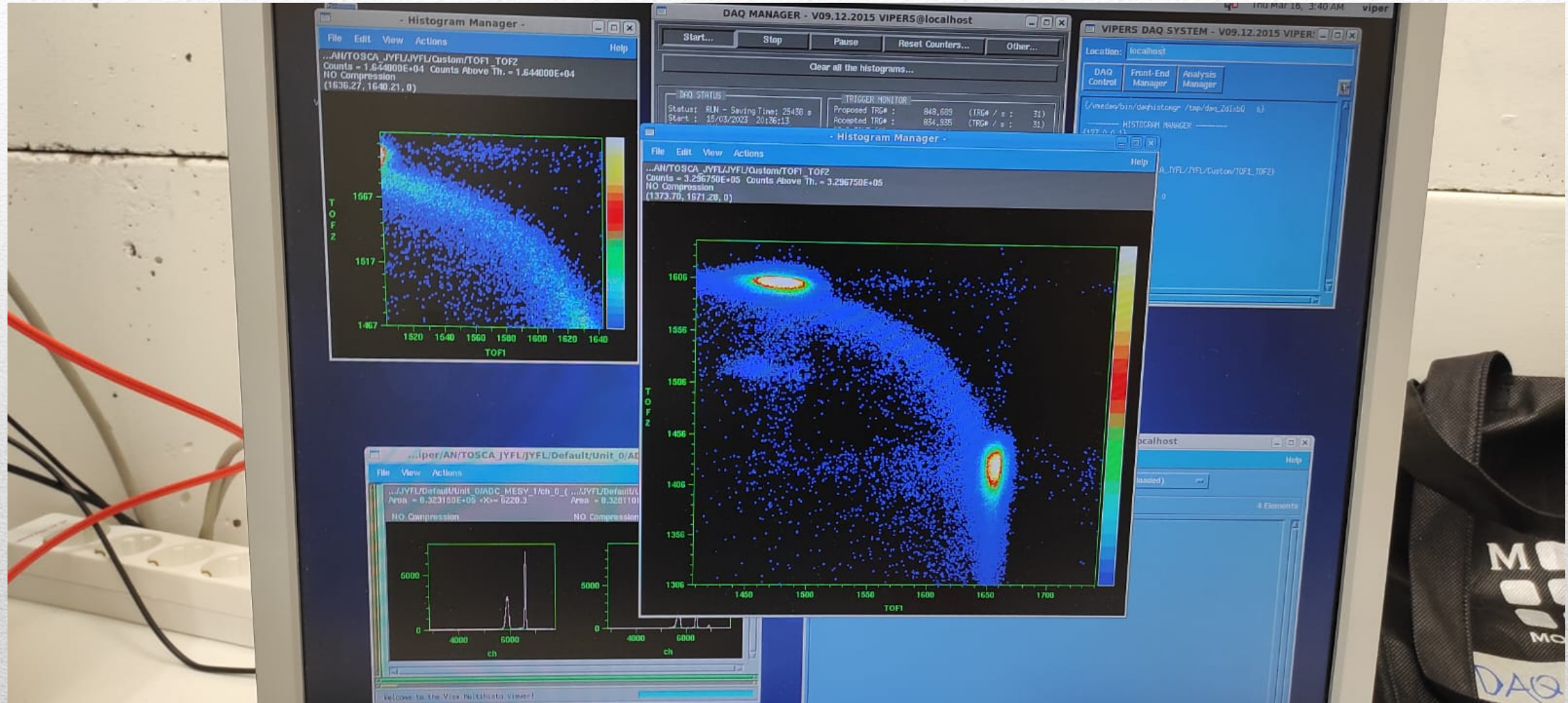


Figure 4. X-Y position matrix obtained with a mask in front of the detector and alpha particles from an Am source. These are raw data, without any “cleaning” methods (thresholds, gate on the total charge, position calibration...). The letters have a width of 3mm. The lines that appear on the letters O, R and A have a width of 1mm.

TOSCA unit: position resolution with mirror

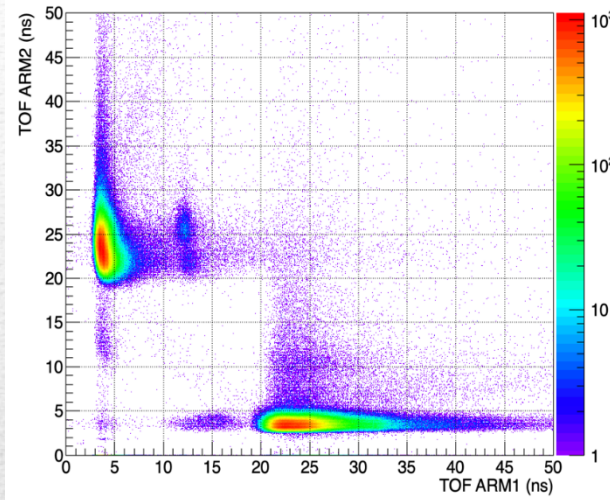




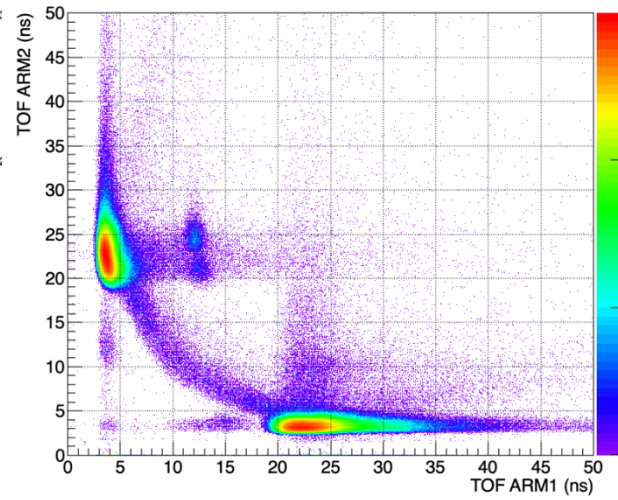
TOSCA – JYFL - March 2023

$^{54}\text{Cr} + ^{209}\text{Bi}$

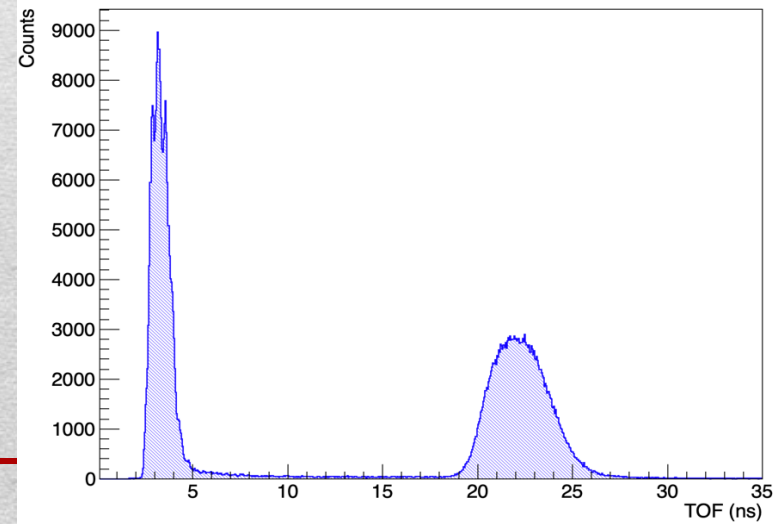
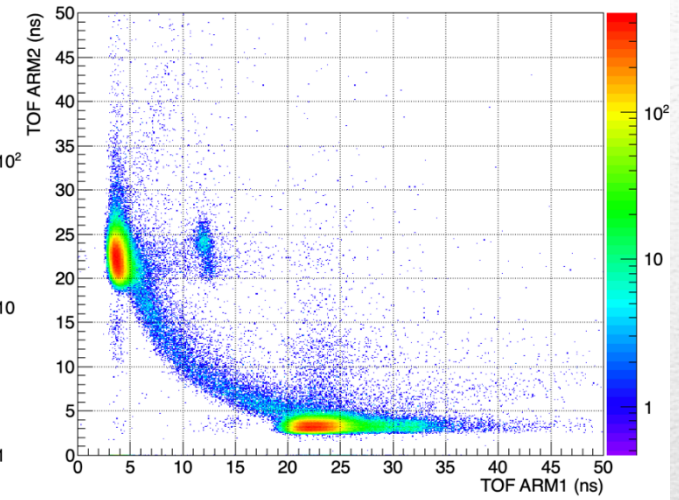
E = 261 MeV



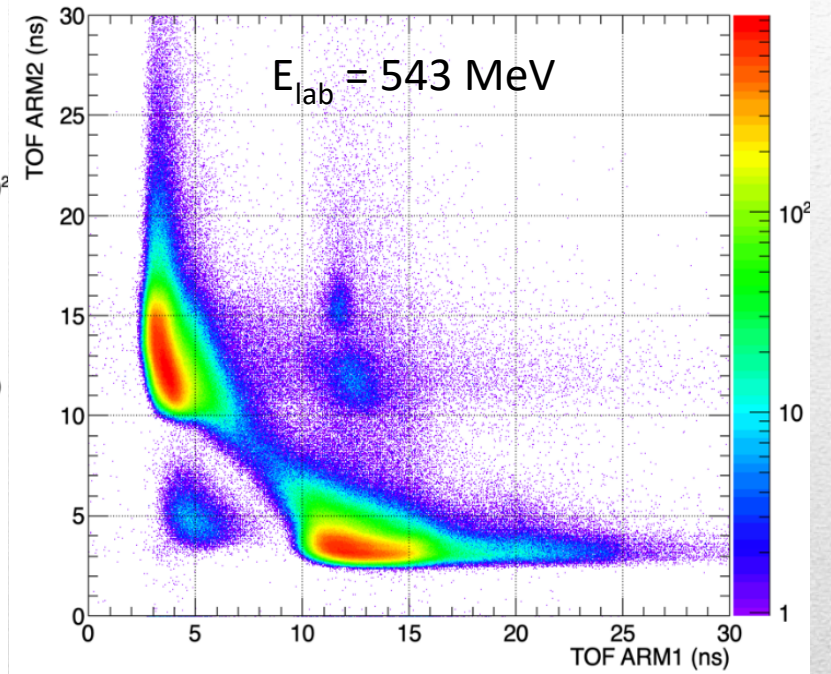
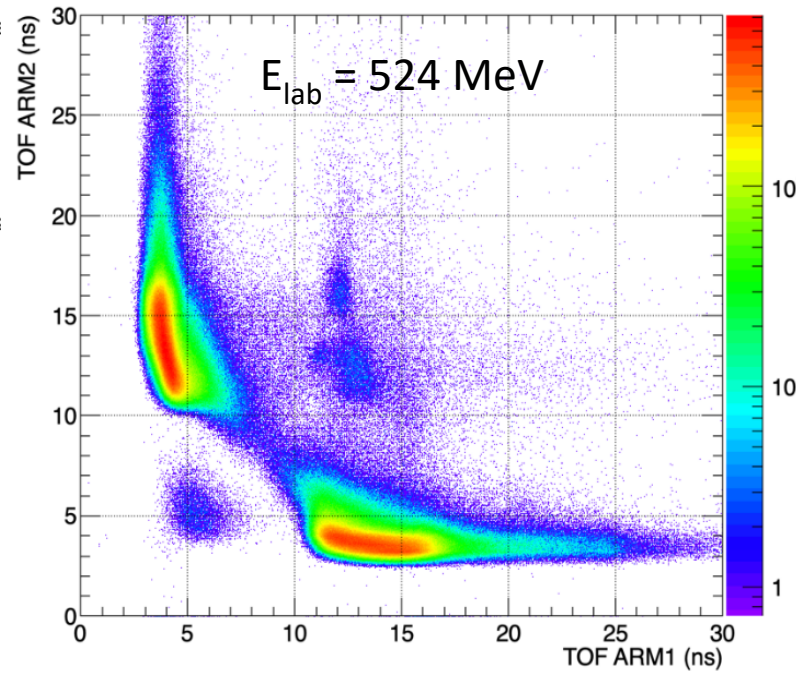
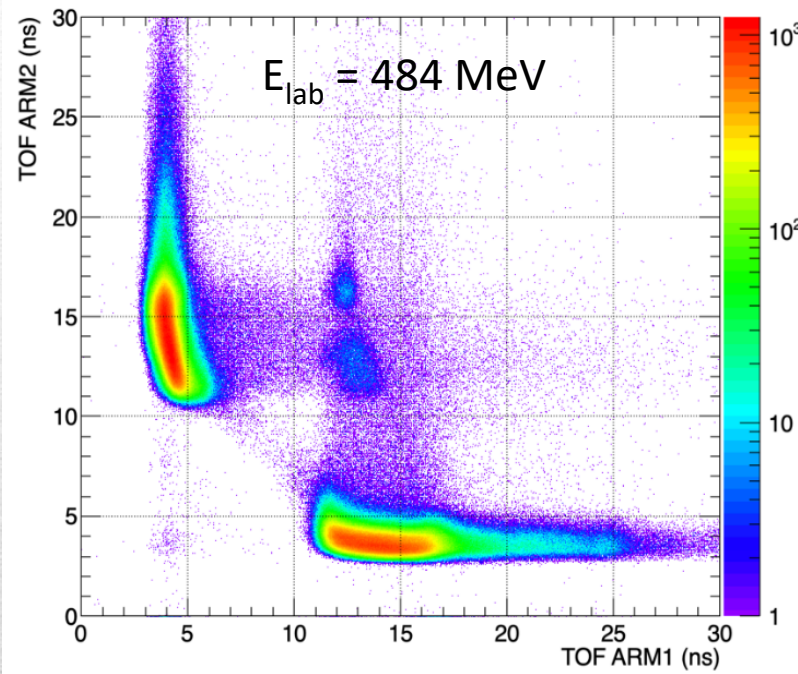
E = 271 MeV



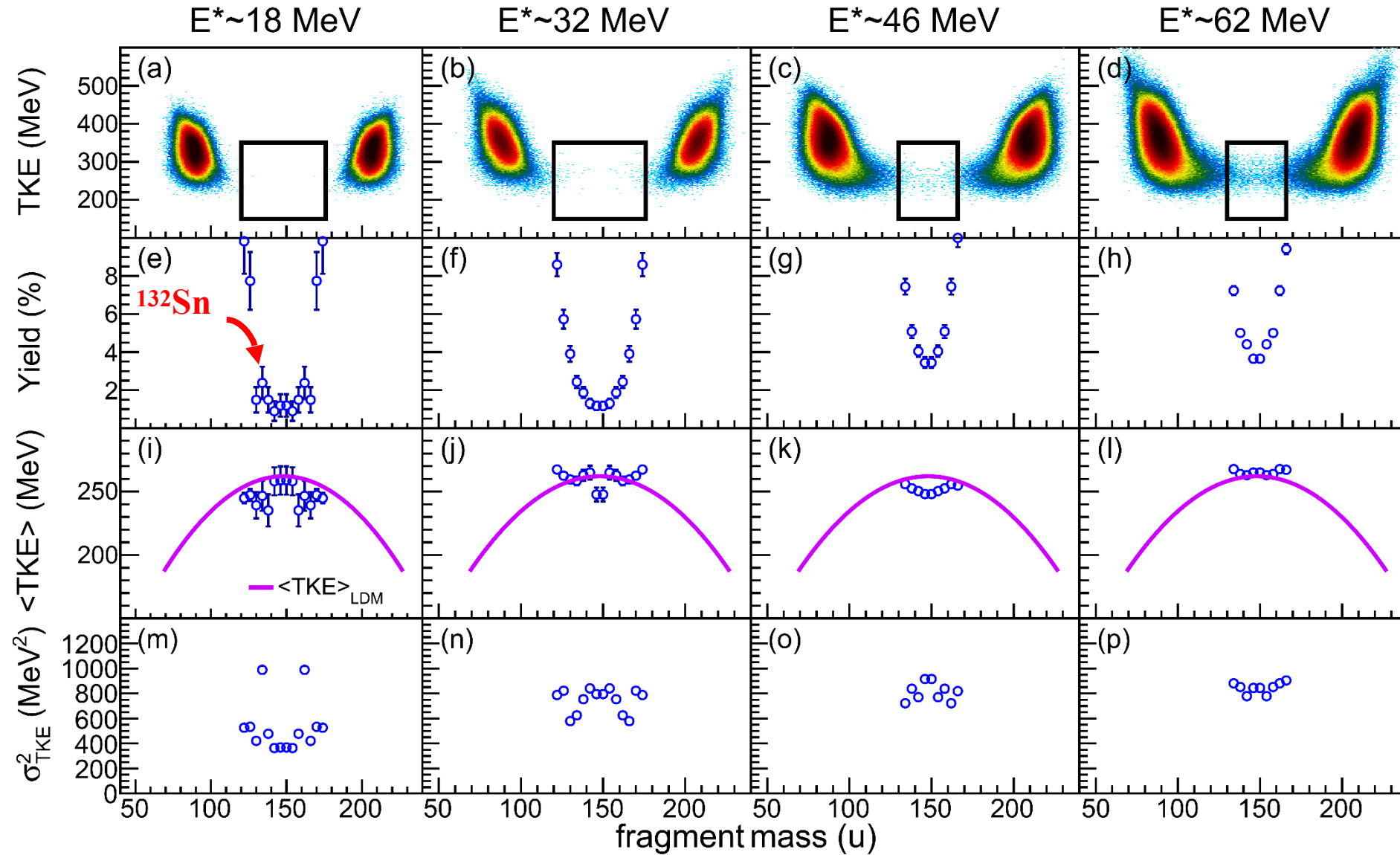
E = 278 MeV



$^{88}\text{Sr} + ^{208}\text{Pb} \rightarrow ^{296}120$



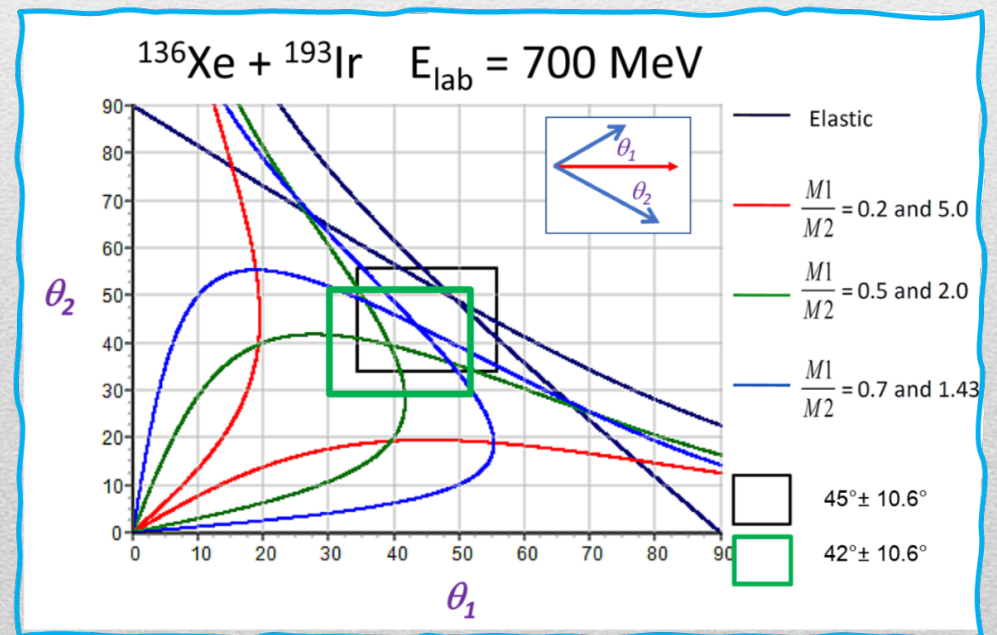
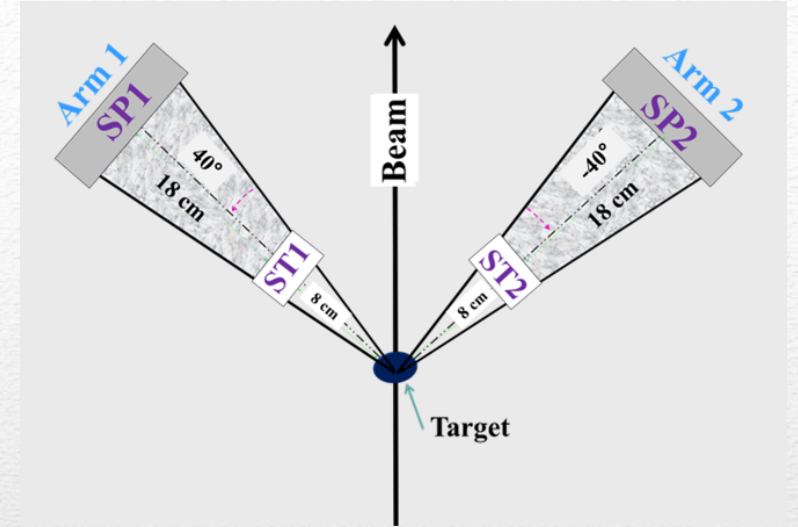
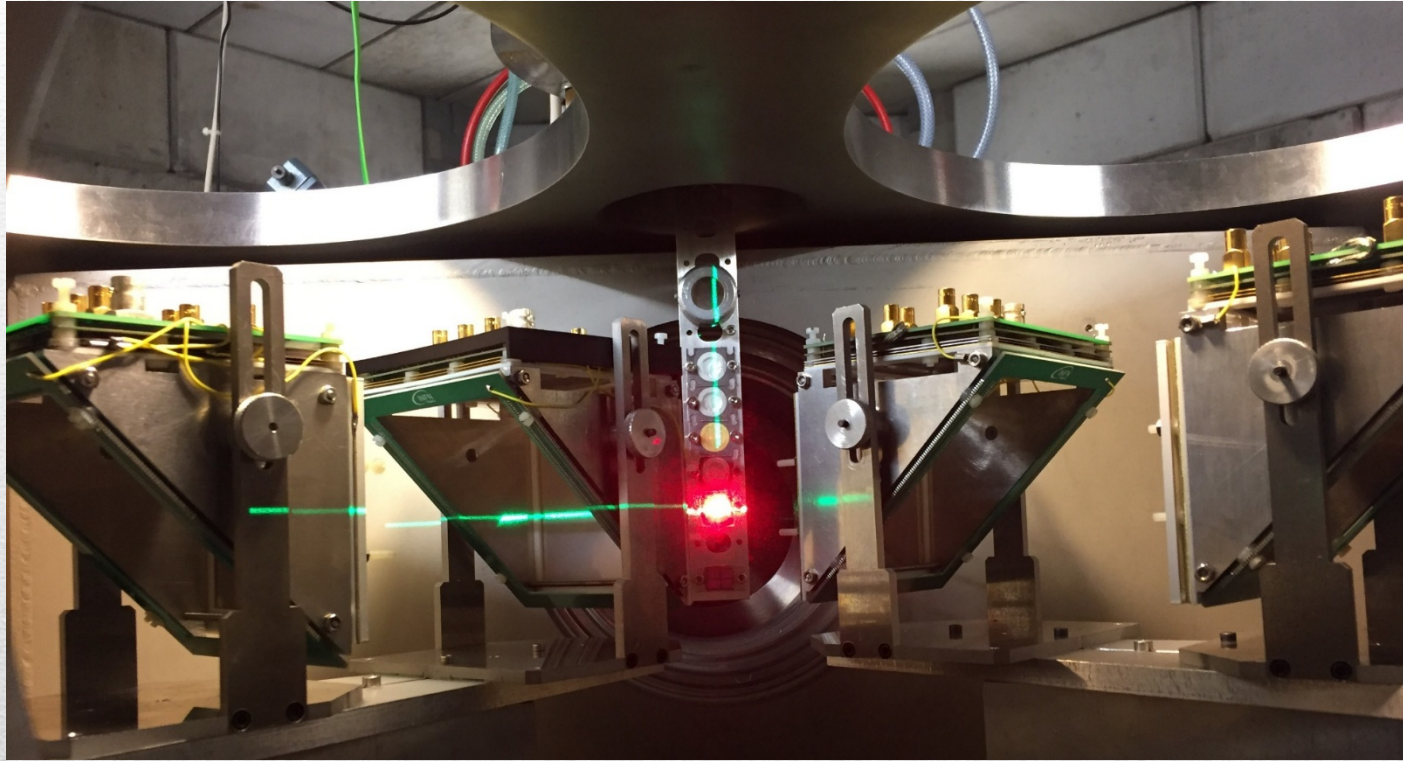
$^{88}\text{Sr} + ^{208}\text{Pb} \rightarrow ^{296}120$

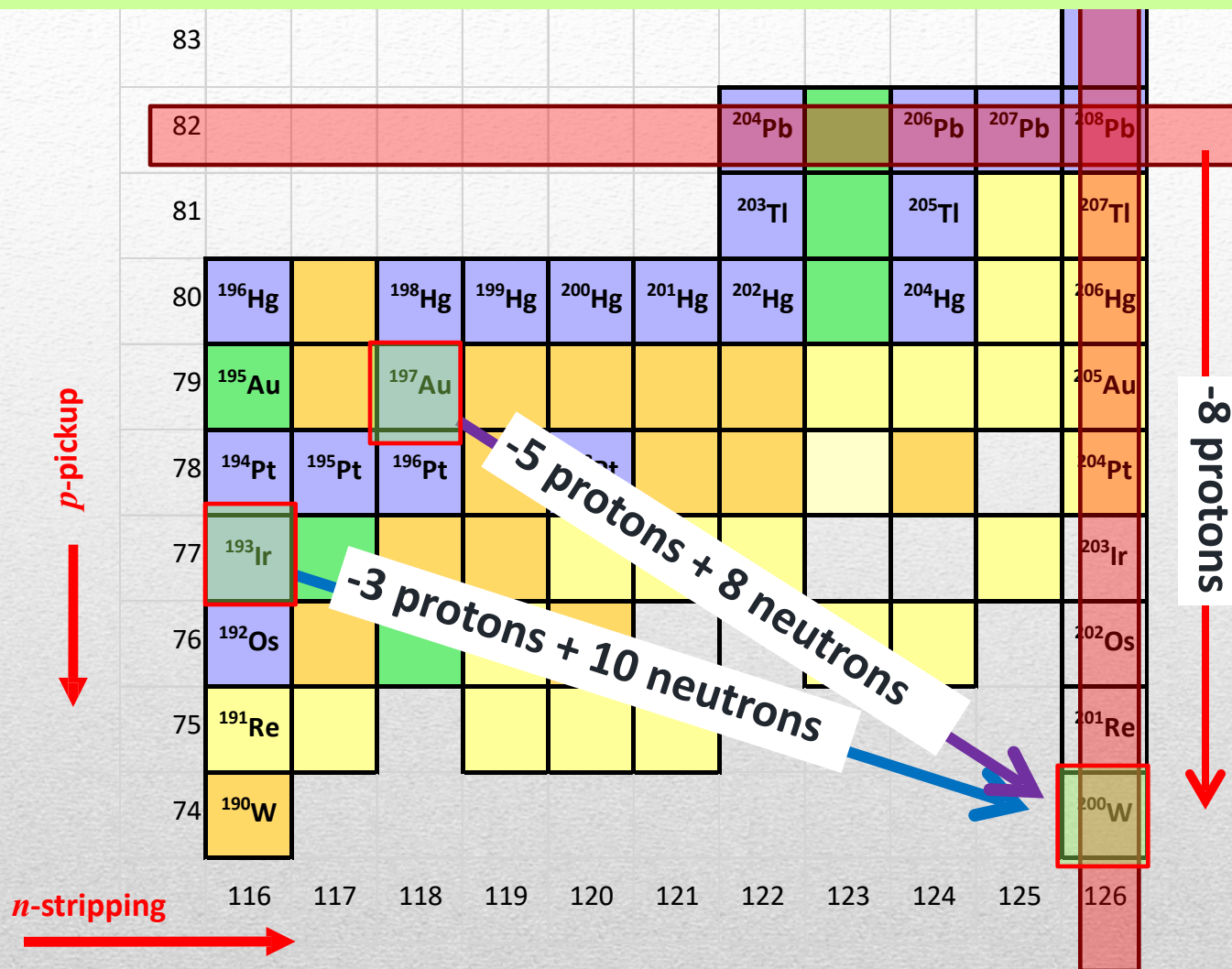


...Preliminary...

TOSCA - JYFL - 2023

TOSCA @ GSI (X6) for Binary channel Xe + Au/Ir



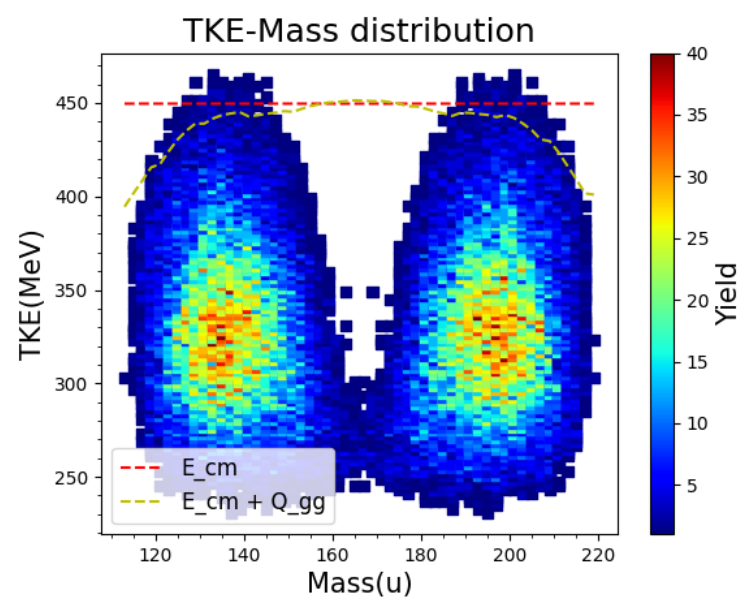


Target	$Q_{gg}^{200\text{W}}$
Pb	-18.9
Pt	-24.2
Ir	-32.7
Au	-32.2

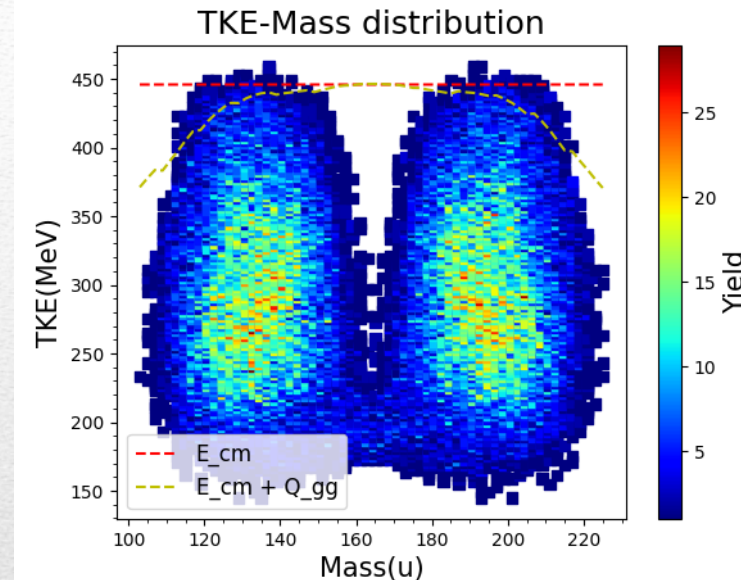
$$E_x = E_{\text{cm}} - \text{TKE} + Q_{gg}$$

- More likely (with respect to models) transfer of many nucleons
- More negative Q values (less excited fragments)

$^{136}\text{Xe} + ^{197}\text{Au}$

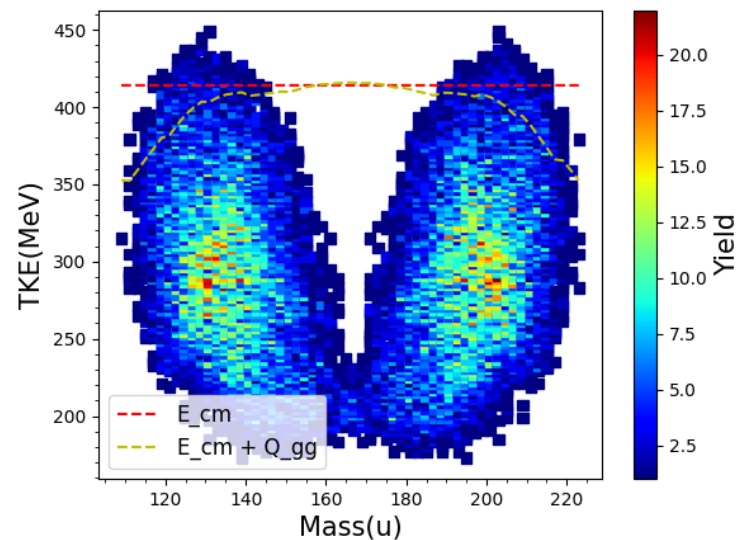


$^{136}\text{Xe} + ^{193}\text{Ir}$



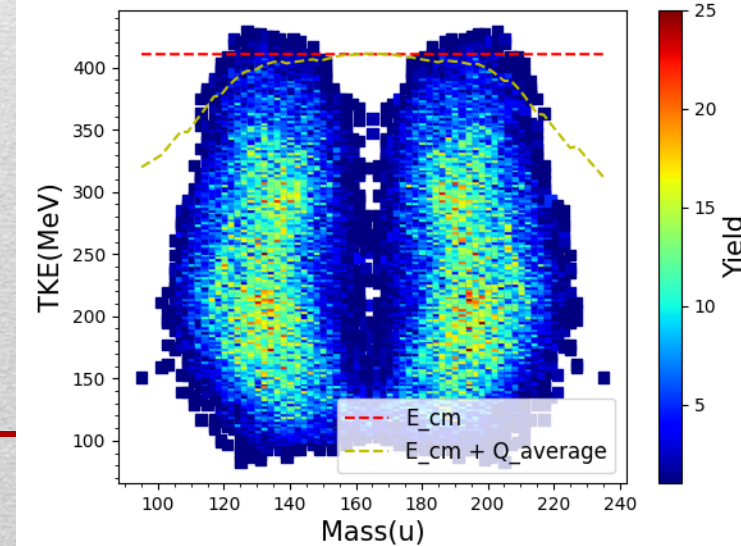
760 MeV

TKE-Mass distribution

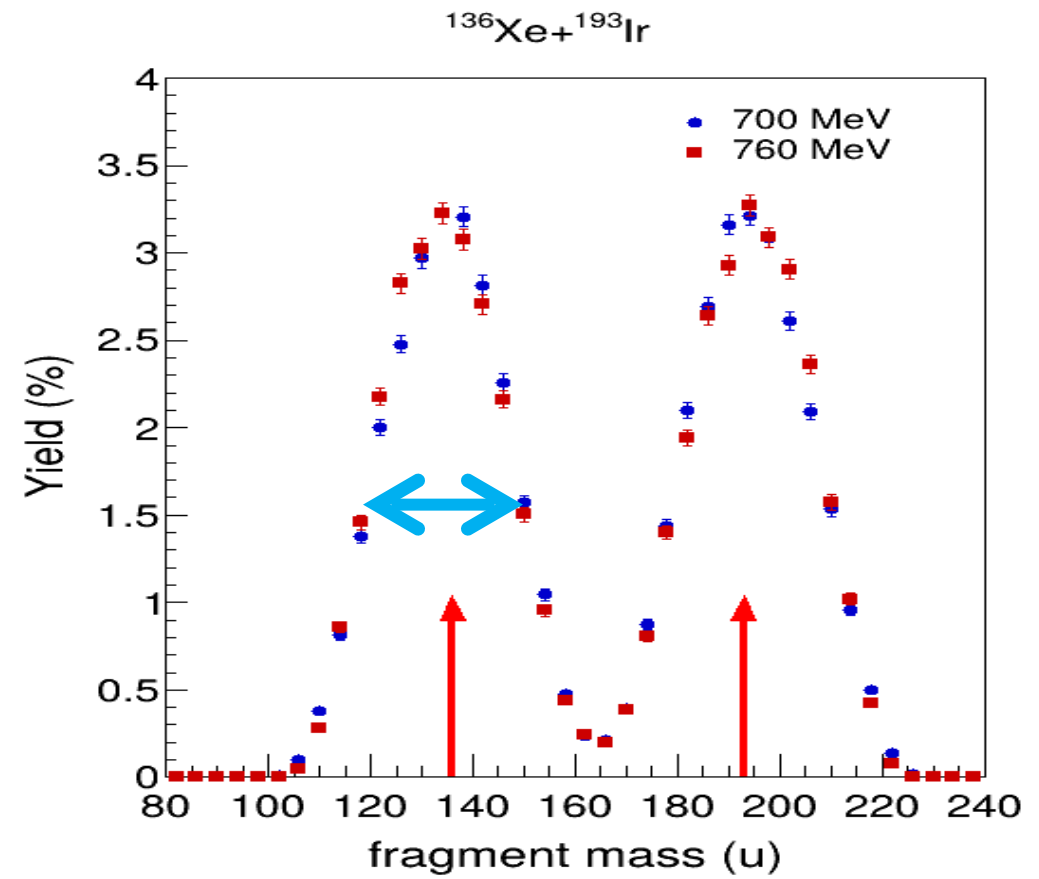
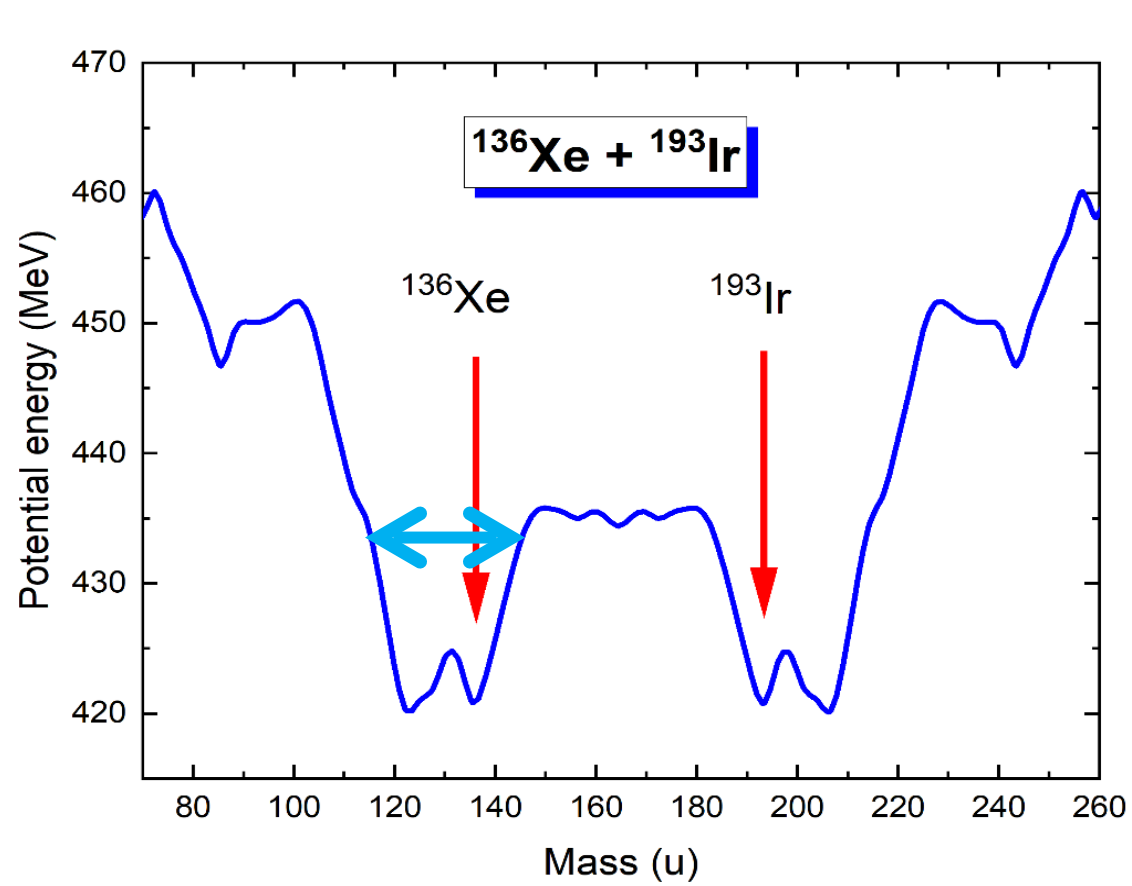


700 MeV

TKE-Mass distribution

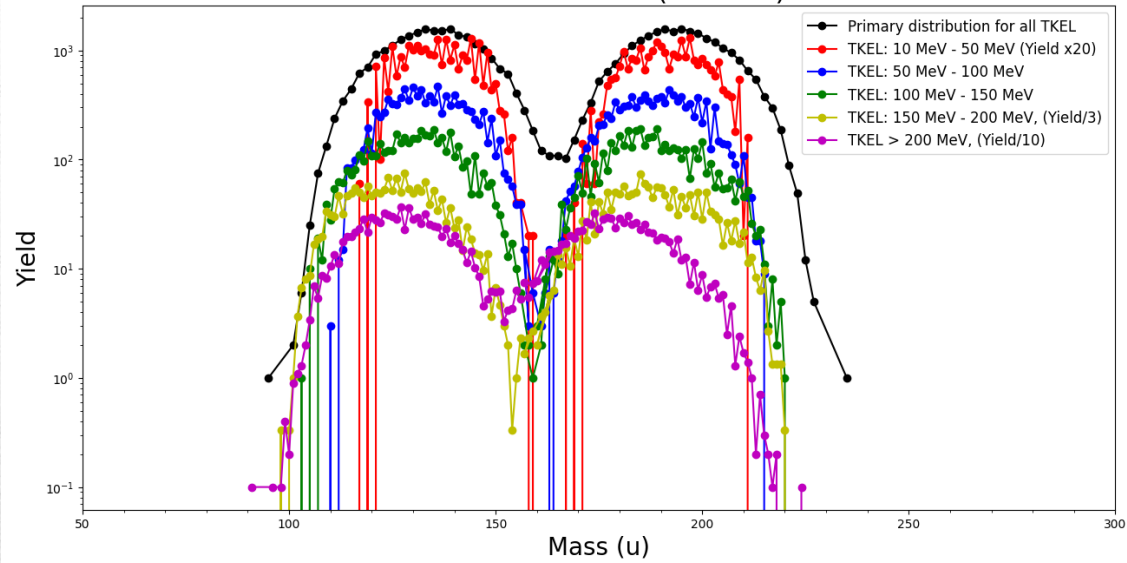


Mass Width



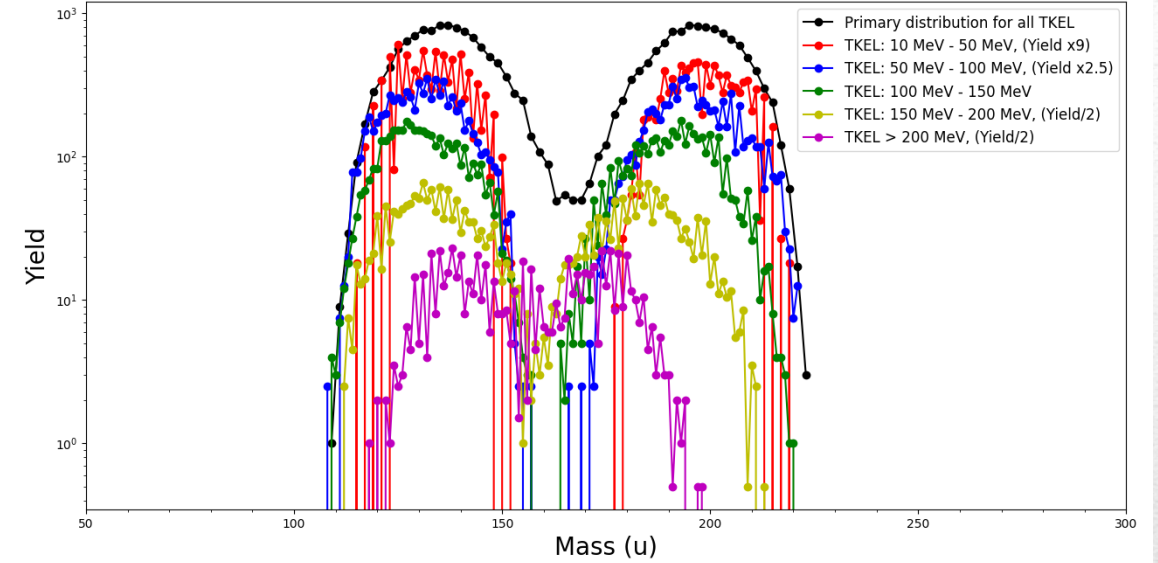
$^{136}\text{Xe} + ^{193}\text{Ir}$

Mass distribution (XeIr700)

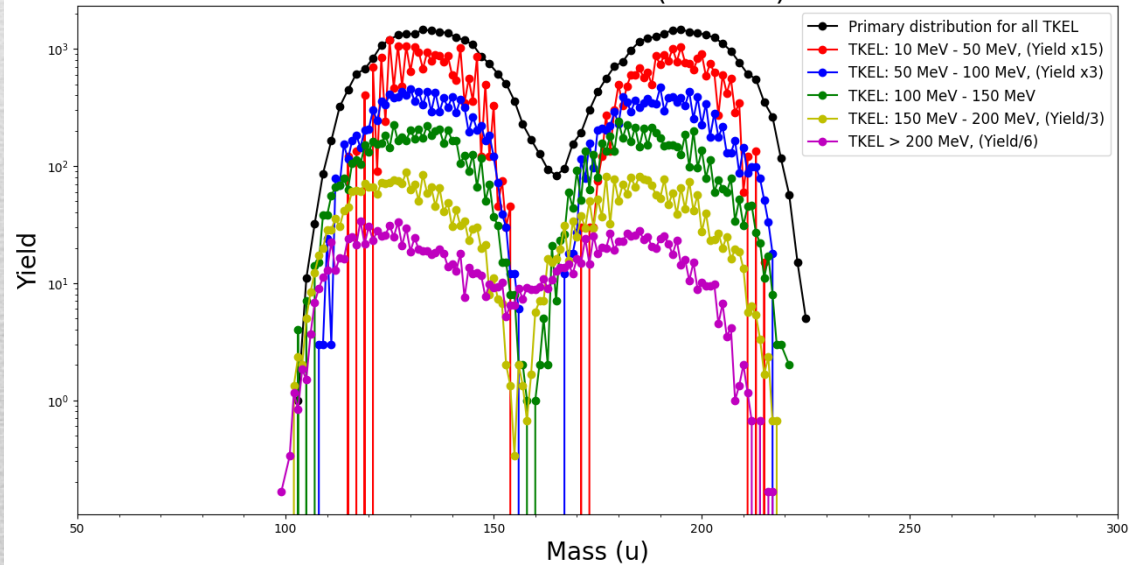


$^{136}\text{Xe} + ^{197}\text{Au}$

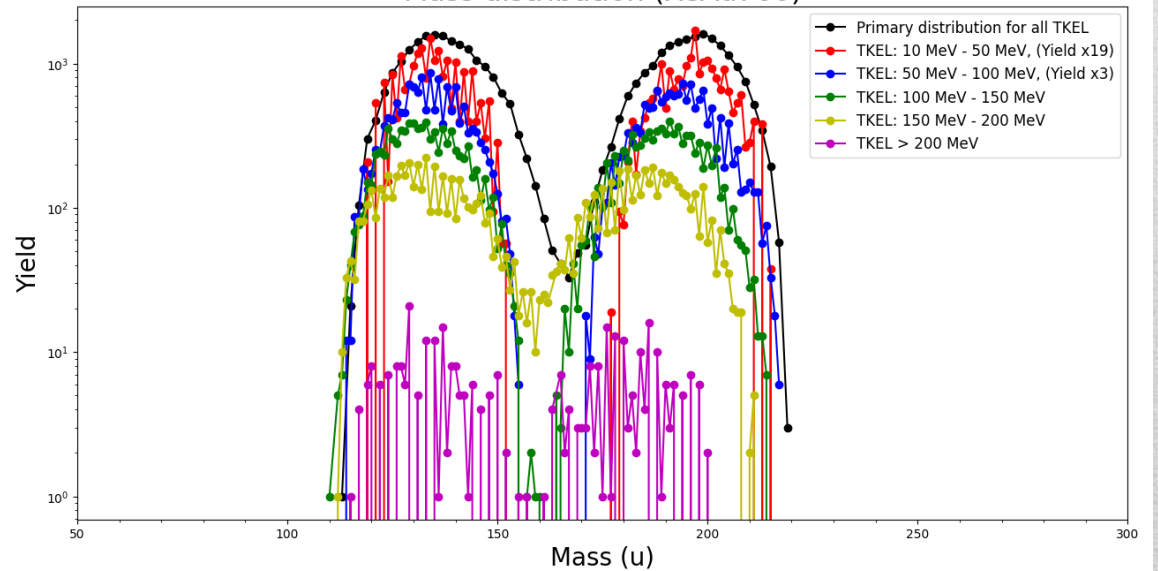
Mass distribution (XeAu700)



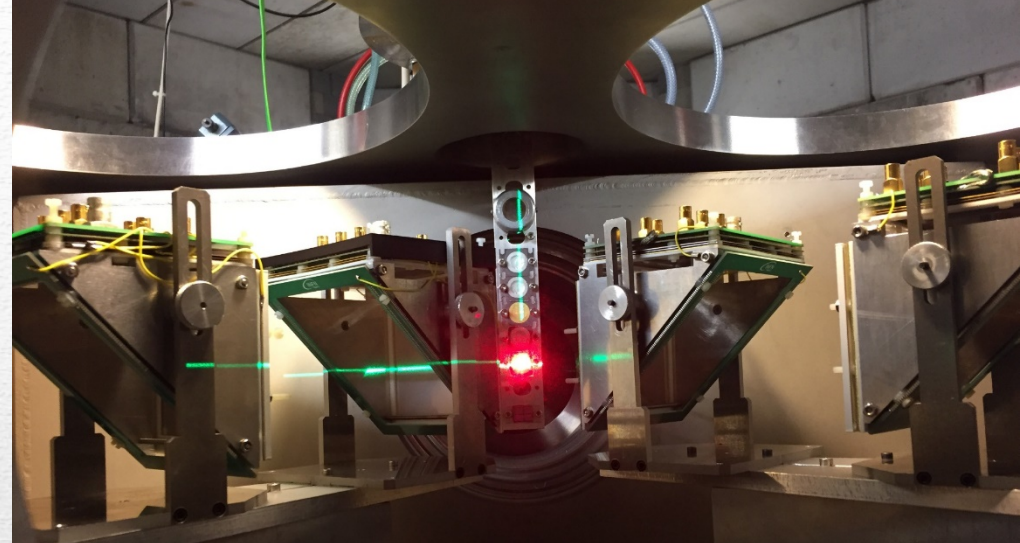
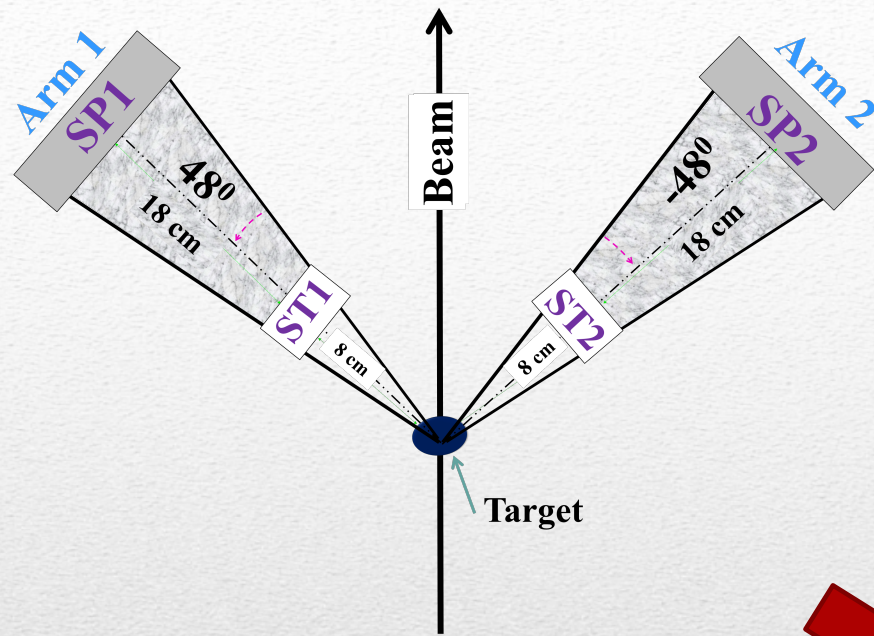
Mass distribution (XeIr760)



Mass distribution (XeAu760)



2V - Kinematics method



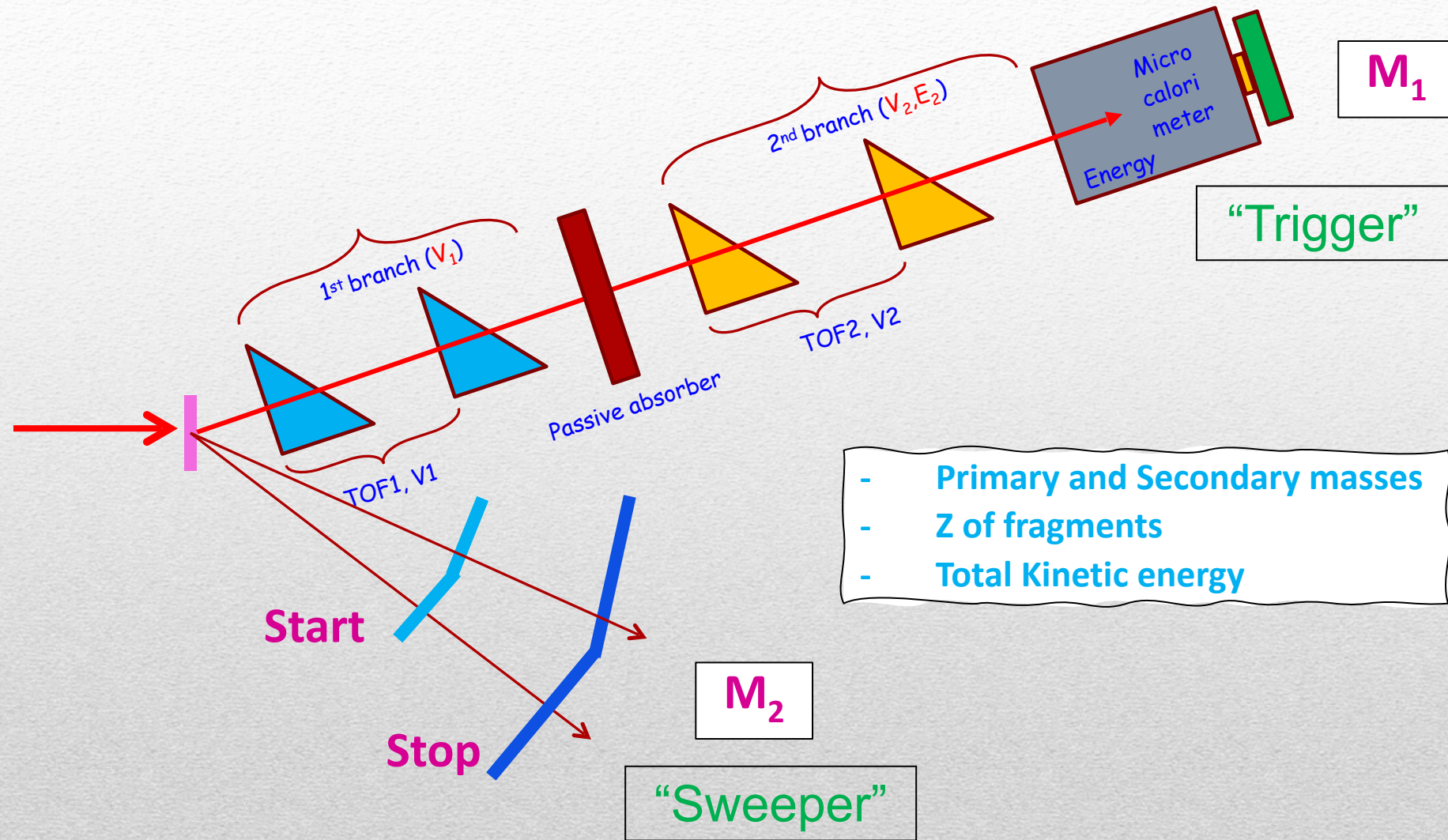
Primary M1, M2, TKE, folding angles, V_{par} , V_{per}

- No Z identification

Key Point:

measure Z of the products event-by-event

Two-Arm TOF-TOF- ΔE - E method



In-beam test of a TOF-DE-E method for complete identification via mass-(A) and charge-(Z) number of fragments produced in Multi Nucleon Transfer reactions

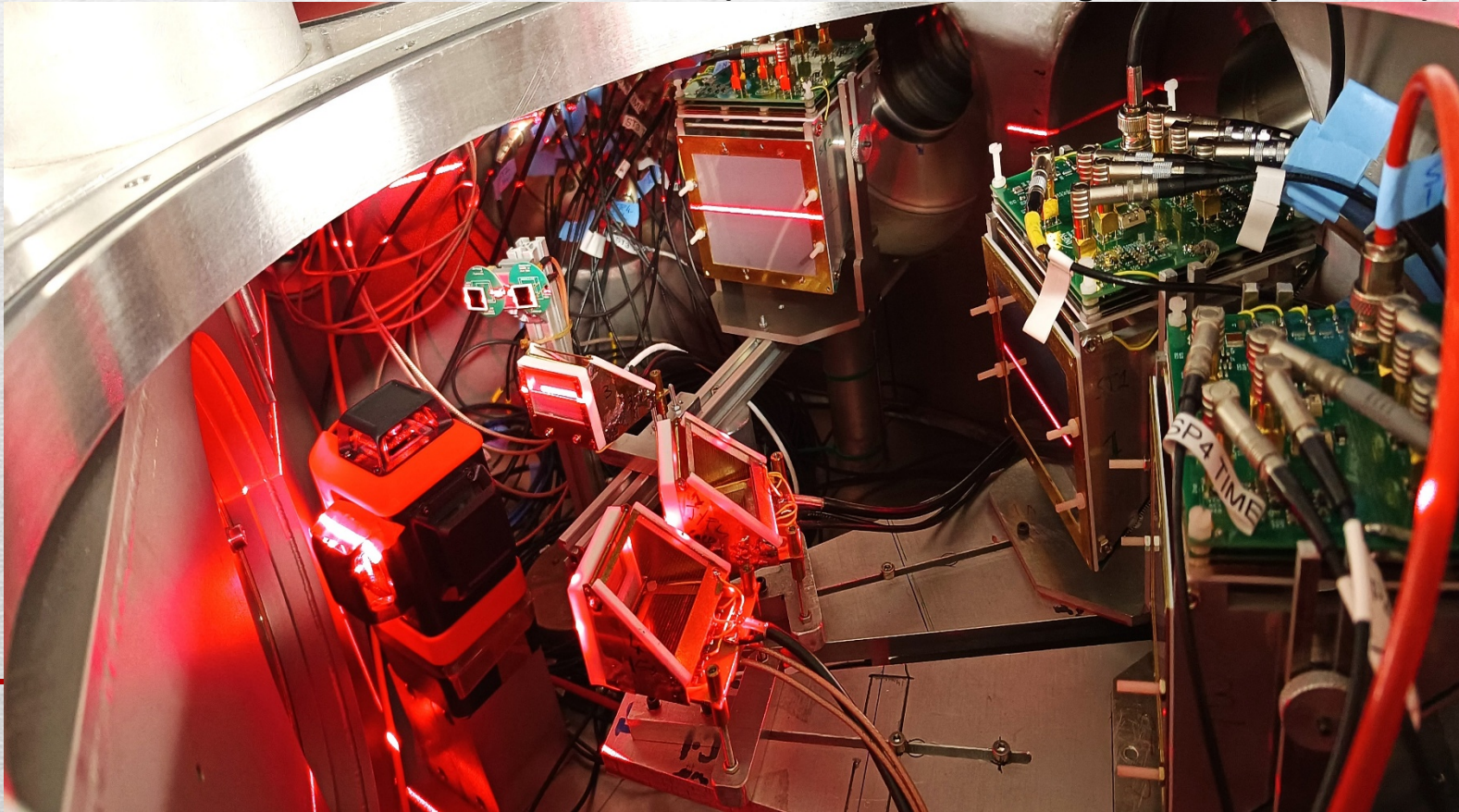
Reactions: $^{209}\text{Bi} + ^{124}\text{Sn}$, ^{115}In Beam time, 9-13 May 2025

Spokespersons:

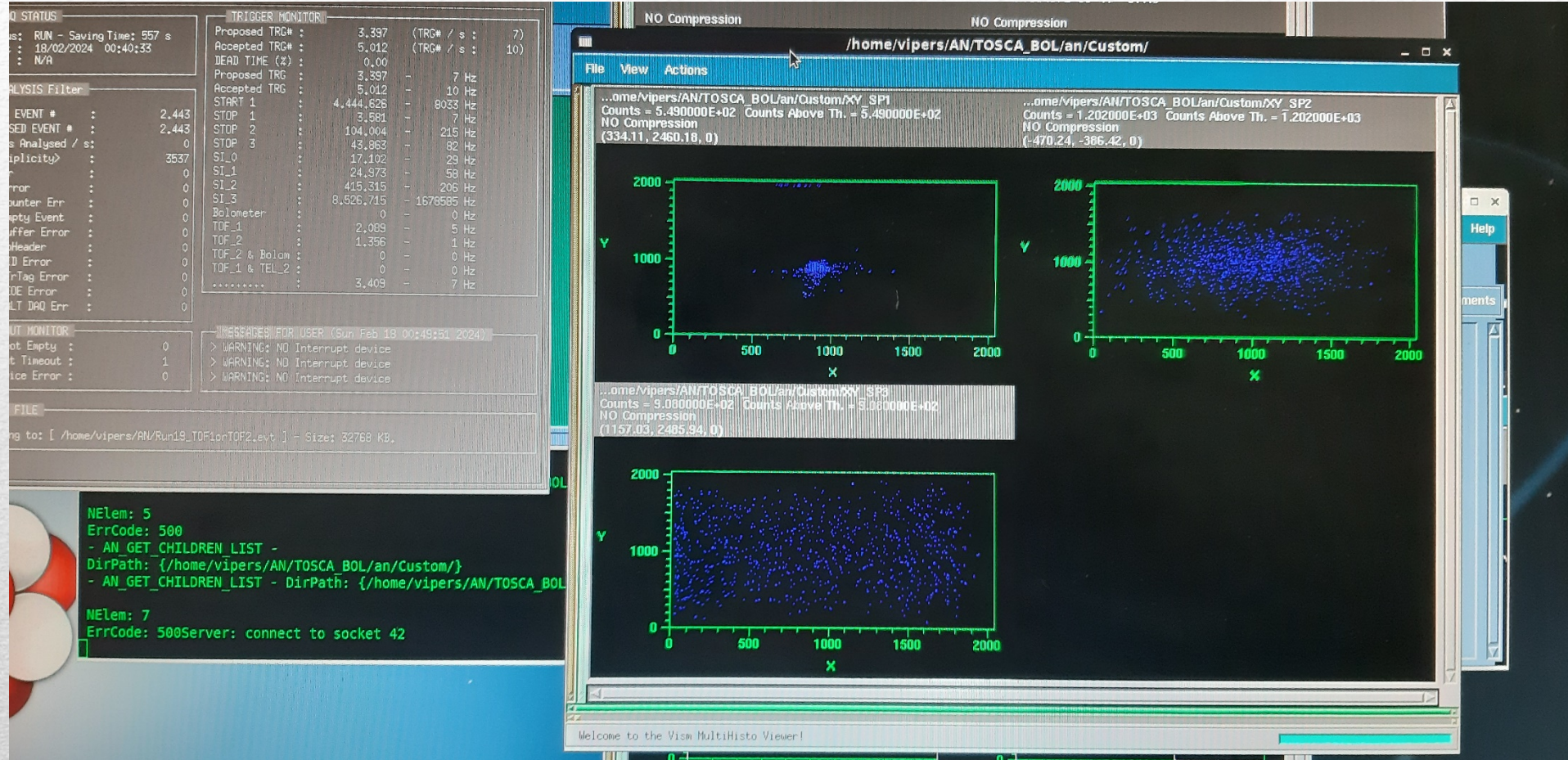
E. Vardaci (UNINA and INFN, Naples, Italy);

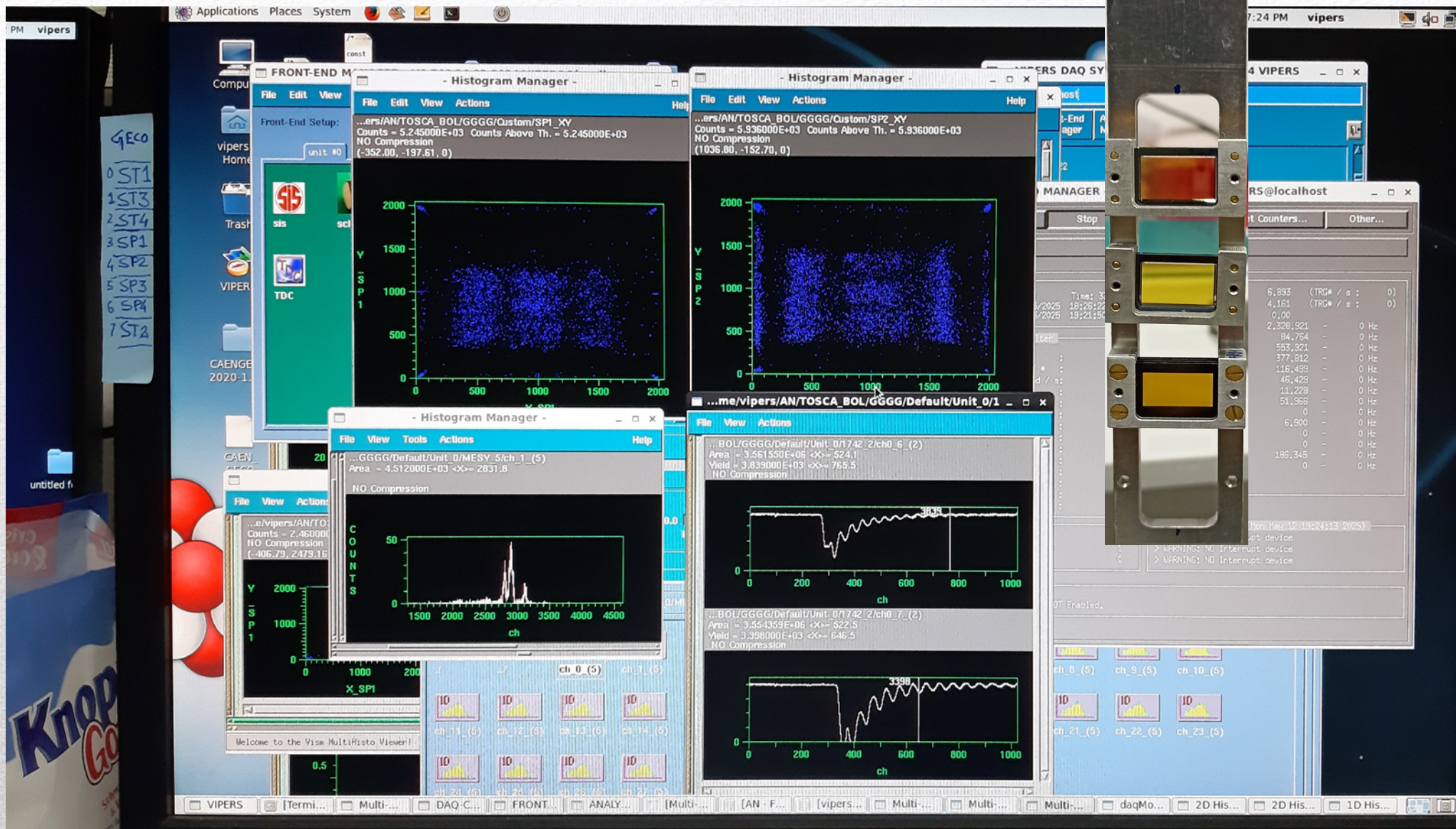
S. Kraft-Bermuth (IMPRP, THMUAS, Gießen, Germany)

GSI Contact Person: Timo Dickel (GSI and Justus-Liebig-University Gießen)



VIPERS DAQ 4.0





Conclusions and Perspectives

1. Kinematic method allows to extract a wealth of information about Two-Body Reactions
 2. Extension of the TOF spectrometer necessary to fully identify the ions
 3. Detector development (replacement of MCP)
mandatory
-



@JYFL



Thank you for your
attention
