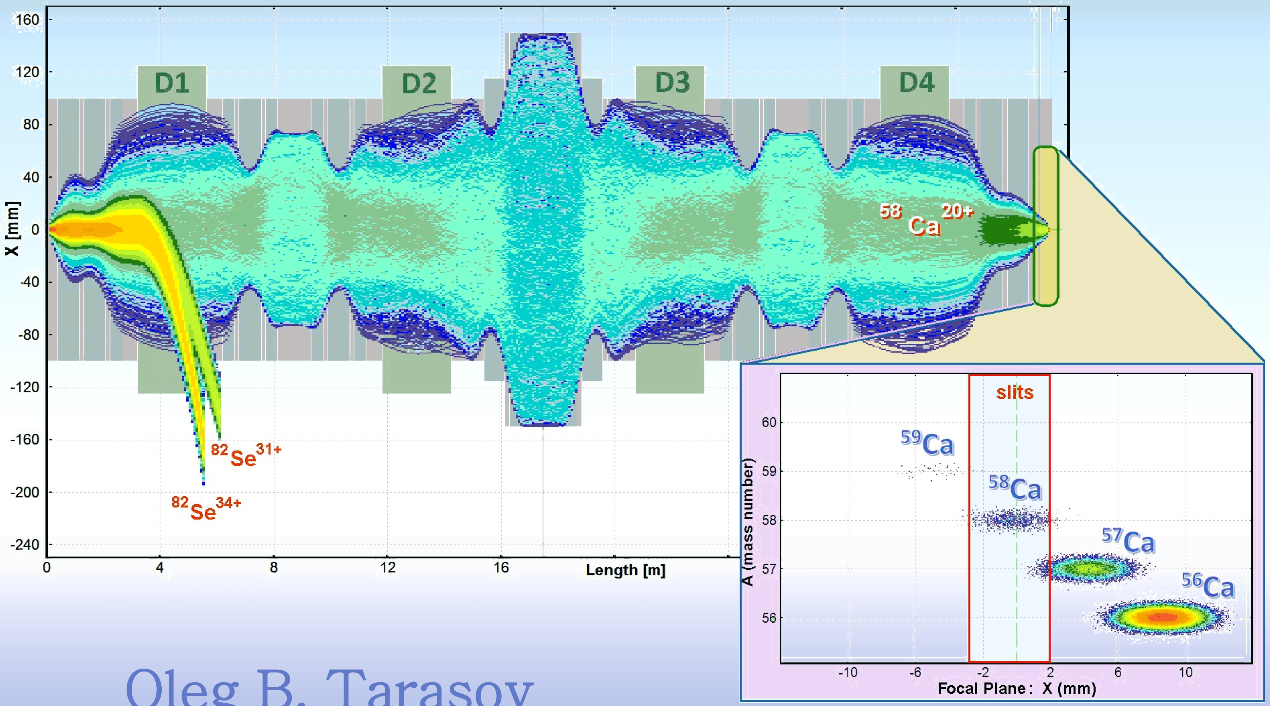
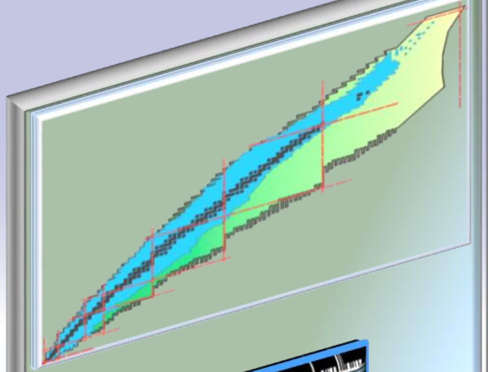
LISE++ pictures studio presents

How to Make Rare Isotope Beams at Home





Oleg B. Tarasov

FRIB/NSCL Staff Information Talk

04/04/2018

with all my deep respect for my scientific supervisor,
who has a great sense of humor,
who knows the story and some details of this presentation,
who helped me with the preparation,
but has not seen yet it.

I hope he'll have fun.

How to Make Rare Isotope Beams at Home

Keyword: “Home”

HARPER'S MAGAZINE

ARCHIVE / 1998 / NOVEMBER ‹ Previous Article | Next Article ›

ARTICLE — From the November 1998 issue

The Radioactive Boy Scout

When a teenager attempts to build a breeder reactor *.. in Michigan…*

By Ken Silverstein

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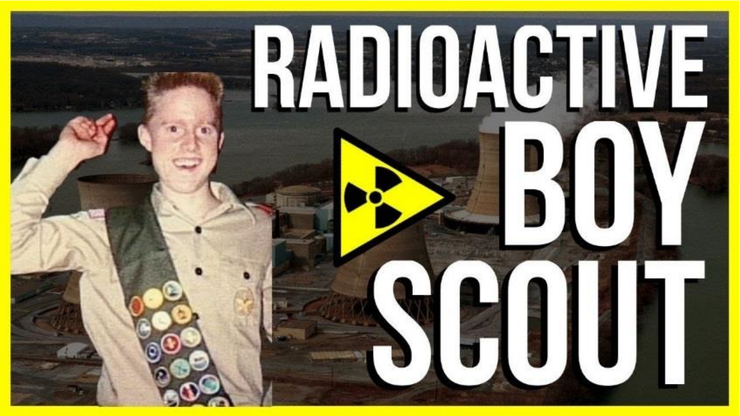
There is hardly a boy or a girl alive who is not keenly interested in finding out about things. And that's exactly what chemistry is: Finding out about things—finding out what things are made of and what changes they undergo. What things? Any thing! Every thing!
—The Golden Book of Chemistry Experiments



ISO 14001
Environmental
management

How to Make Rare Isotope Beams at Home

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ARCHIVE / 1998 / NOVEMBER

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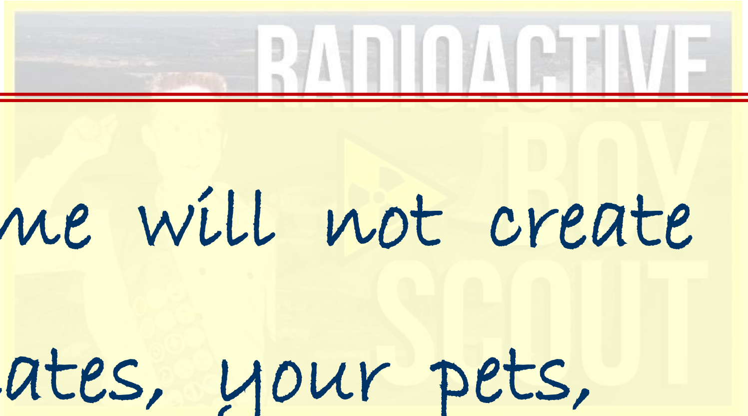
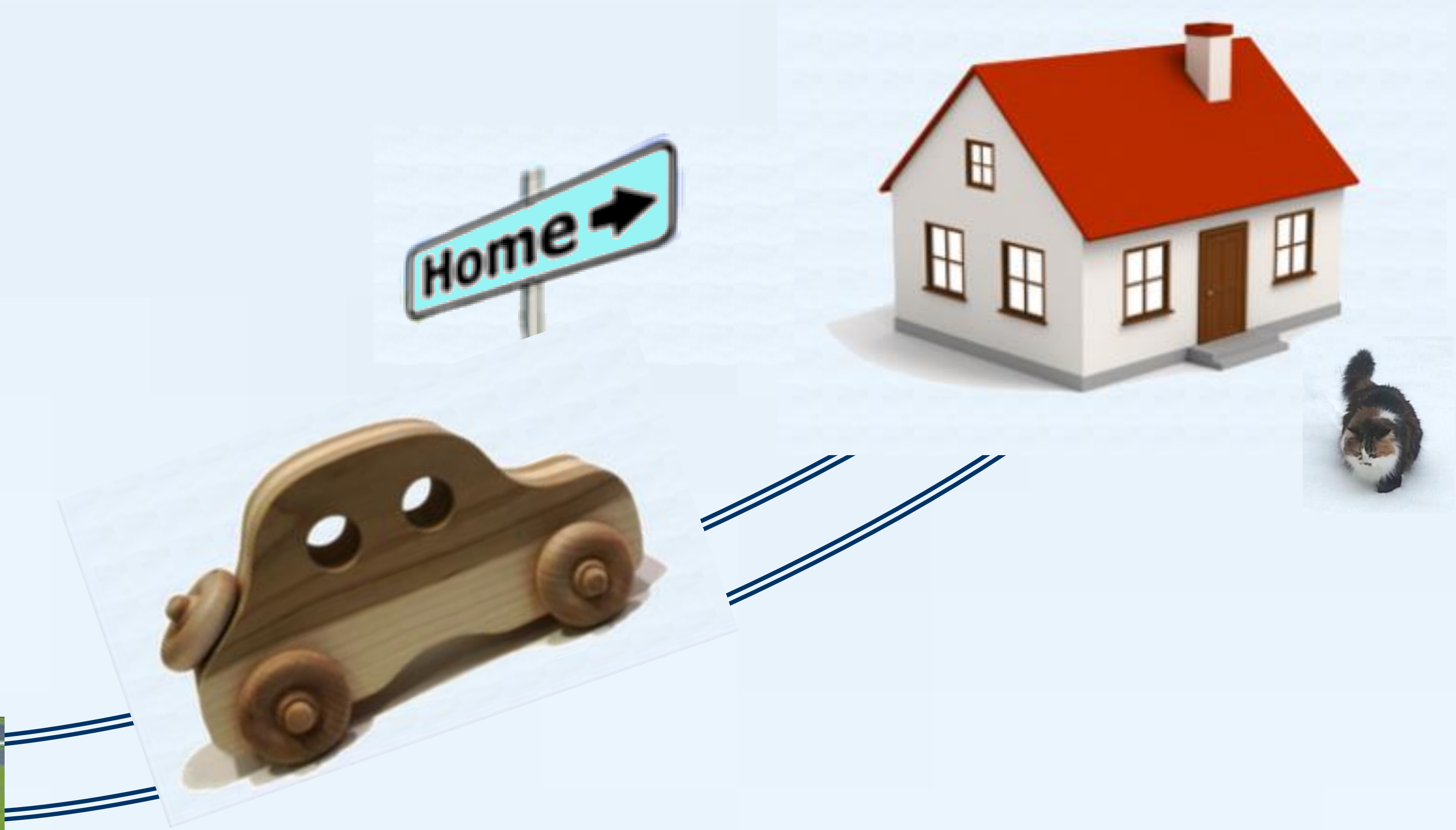


Our case with rare beams at home will not create a danger to you, your housemates, your pets, your property, even your neighbors !!!



after a hard day's work…

Today is our day?

WE ARE SPARTANS

GO GREEN GO WHITE

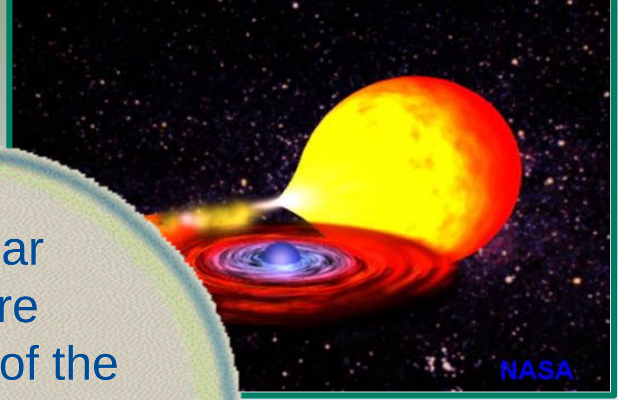
May be the next time….

athlonsports.com

Well-known Spartans fan

not in a good mood, we begin to quickly switch between channels

…. and suddenly!



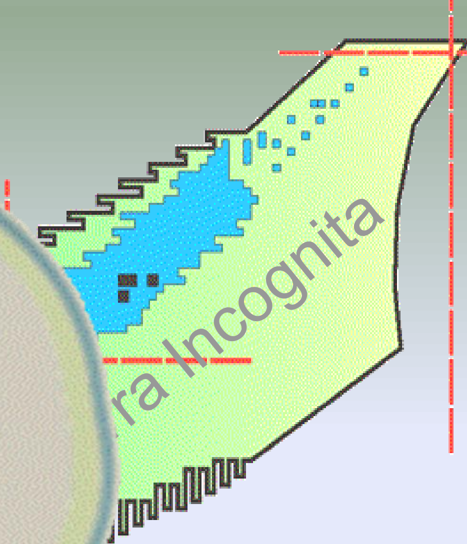
Nuclear reactions in stars and stellar explosions generate energy and are responsible for the ongoing synthesis of the elements. They are, therefore, at the heart of many astrophysical phenomena, such as stars, novae, supernovae, and X-ray bursts.

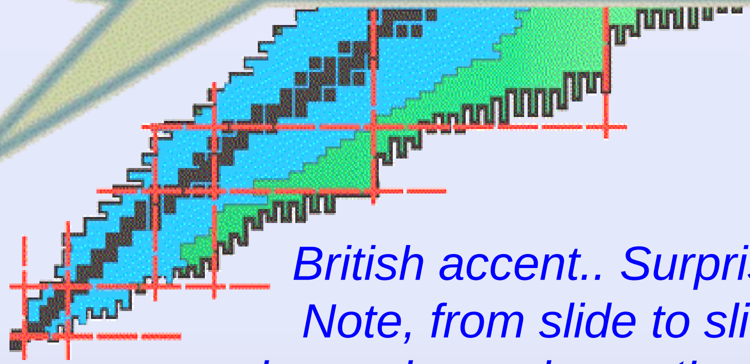
MSUCL-1345

Sorry, I could not find the "original" voice, but at least this voice sounds without my Kirghiz accent

Terra incognita

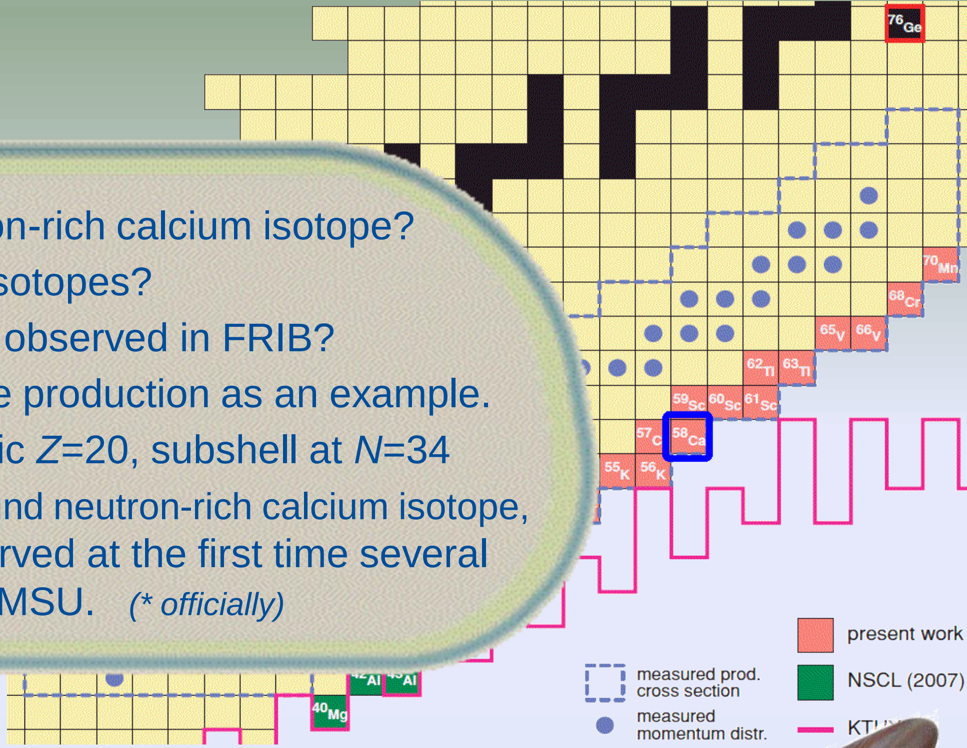
- Around 260 stable isotopes found in nature (>1Gy)
- Less than 1000 known isotopes in 1966, currently about 3000 (blue) know isotopes
- New territory (Terra incognita) to be explored with next-generation rare isotope facilities as FRIB
- They will produce more than 1000 NEW isotopes at useful rates (4500 available for study)





British accent.. Surprise!
Note, from slide to slide
the cat is moving to the TV…

- What is last particle neutron-rich calcium isotope?
- How do we produce rare isotopes?
- What isotopes can be first observed in FRIB?
- Let's consider ^{58}Ca isotope production as an example.
- Why is ^{58}Ca isotope? Magic Z=20, subshell at N=34
- ^{58}Ca is the last* particle-bound neutron-rich calcium isotope, and furthermore was observed at the first time several years ago at MSU. *(* officially)*



May be it will useful to change the voice to a more pleasant one on the next page?

You've Got Mail

Learn how to make rare isotope beams.

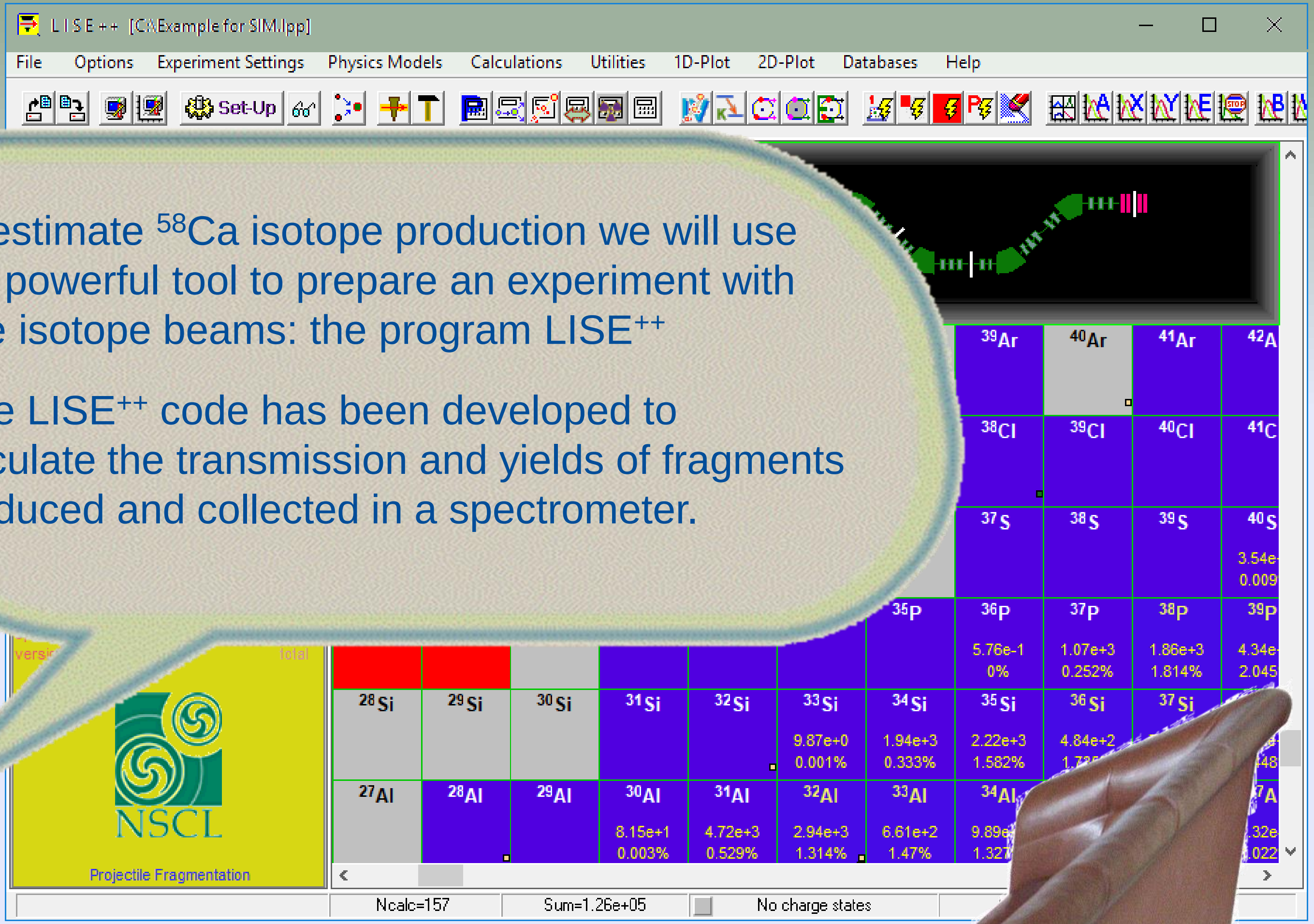
Do you know how to use email?
Then you can learn how to make a rare isotope.
It is that simple.

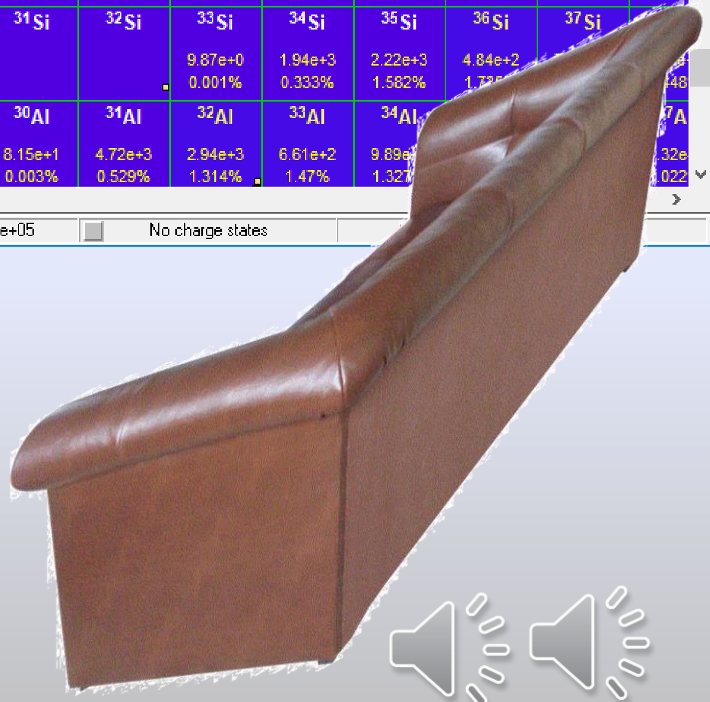
Learn how.

By the way, Brad came up with these phrases.

L I S E ++

- To estimate ^{58}Ca isotope production we will use our powerful tool to prepare an experiment with rare isotope beams: the program LISE^{++}
- The LISE^{++} code has been developed to calculate the transmission and yields of fragments produced and collected in a spectrometer.

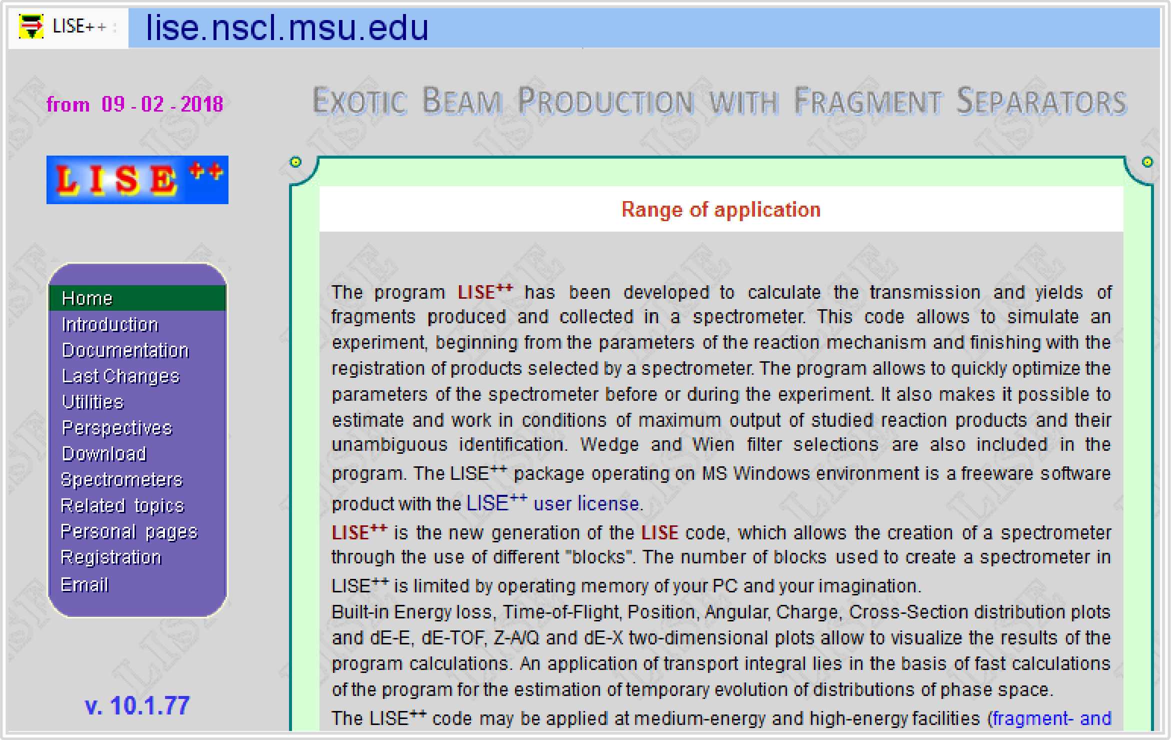




This is the last animated slide.
Sorry for the following inconvenience ....

LISE^{++} : Introduction

- LISE^{++} is maintained by **LISE^{++} group @ Michigan State University** and is freely available and distributable through the LISE^{++} website: <http://lise.nscl.msu.edu>.
- The LISE^{++} package (including codes PACE4, Global, Charge, MOTER, ETACHA4, Spectroscopic Calculator) operating on **MS Windows** environment
- Currently the LISE^{++} software suite is undergoing a major transportation to a new graphics framework in order to support modern compilers and computing methods.



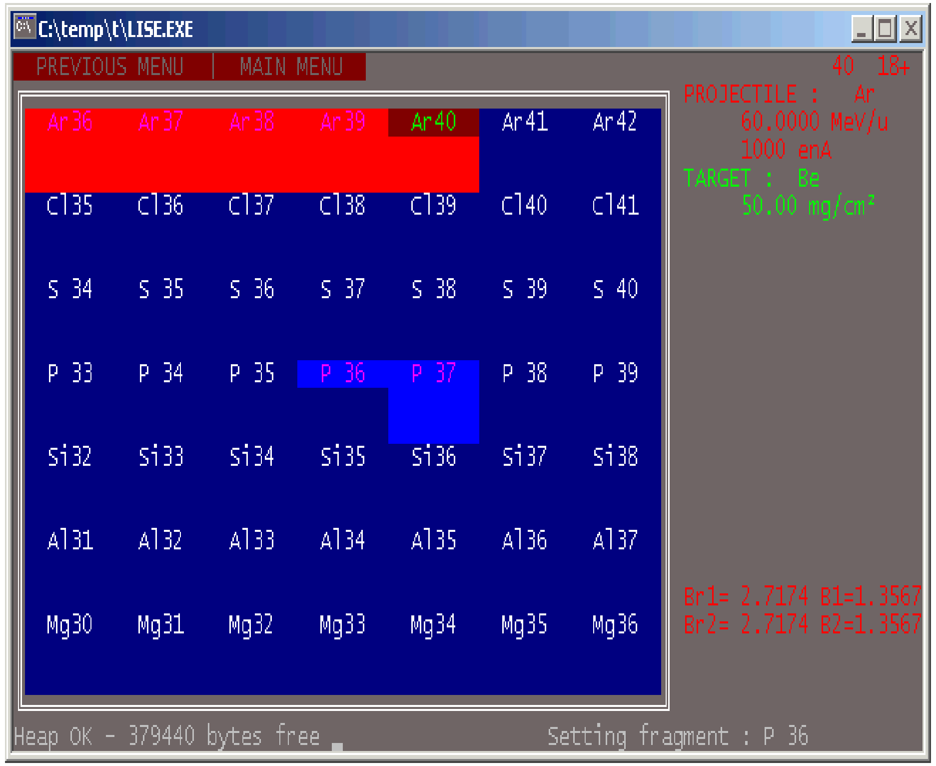
No hidden bitcoin mining procedures. Travis checked it recently.

LISE++ history : DOS-version

Named after the LISE separator @ GANIL

GRAND ACCELERATEUR NATIONAL D'IONS LOURDS

LISE → Ligne d'Ions Super Epluches (fr) (Line of full-stripped ions)



1986-1990
D.Bazin, GANIL
v.1.0-1.*

1990-1992
D.Bazin, MSU
O.Sorlin, Orsay
v.2.1-2.3

1994-1997
O.T.,
GANIL/Dubna
v.2.3 – 2.9

LISE REFERENCE MANUAL

Version 2.2 - June 8, 1992 ….

LISE is a DOS-based software running on any IBM compatible PC. It runs under DOS 3.1 and following versions, and only needs 640 kbytes of memory. The speed of the program depends greatly on the CPU type, speed and configuration. The use of a co-processor is greatly recommended: the program uses FFT (Fast Fourier Transform) algorithms which contain extensive floating-point operations.The last version has been developed on a 386-SX at 16 MHz with a ***co-processor*** which provides a *reasonable speed* (about 1 second per transmission calculation).

In 1998 the MS-DOS version with 14 C++ files and
less than *10 000* lines of code,

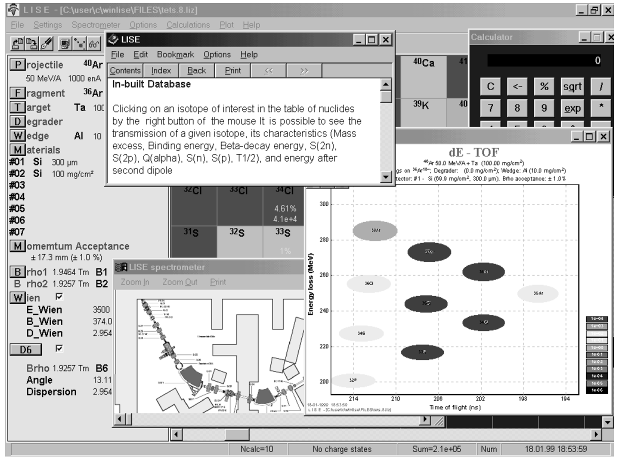
and grew on MS Windows (2016) to
615 files, about *400 000* lines,
and size of ~69 MB after Installation.

LISE^{++} history : MS Windows

MICHIGAN STATE UNIVERSITY

1998
O.T., GANIL/Dubna
v.3.1

LISE operates under MS Windows



1999-2000
O.T., GANIL
v.3.2-4.9

Active development of the LISE code stimulated by M.Lewitowicz

Feel the difference...

LISE

0.84”

LISE^{++}

0.93”

2001
NSCL / MSU
v.4.10 –5.12

Active development of the LISE code stimulated by B.Sherrill.
Abrasion-Ablation model construction

2003
NSCL / MSU
v.6

LISE^{++} is the new generation of the LISE code, which allows the creation of a spectrometer through the use of different “blocks”.

20...
NSCL / MSU
v.7-10

RF separation system.
Abrasion – Fission.

Fusion – Fission

Monte Carlo calculation of fragment transmission

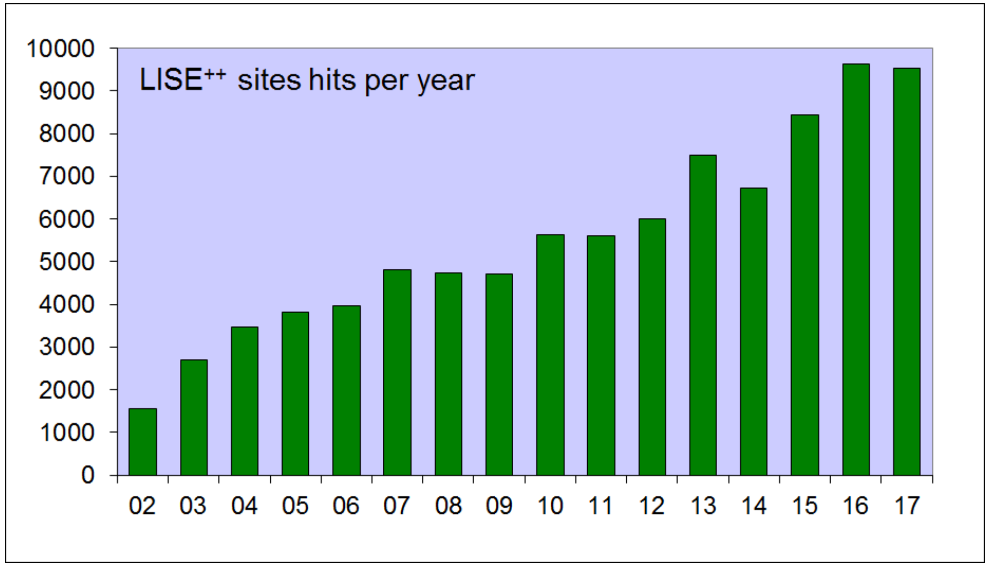
Optics calculation up to 2nd order
Beam Optics Optimization (incl. 2^{nd} order)

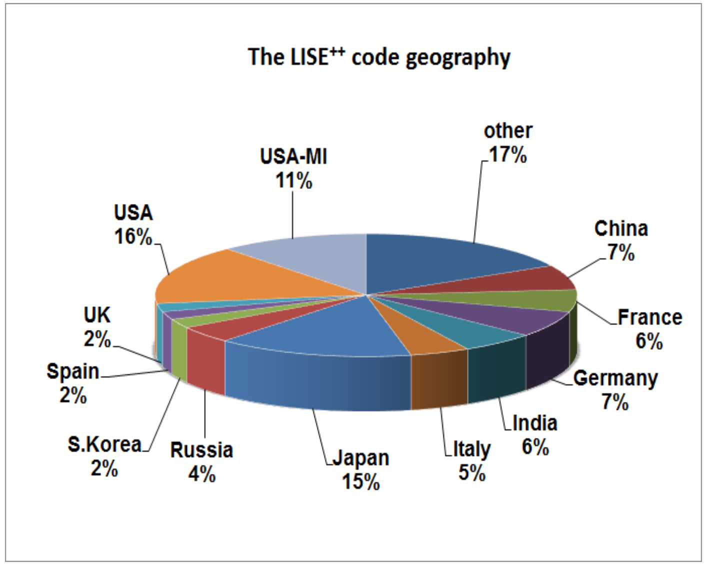
2018
NSCL / MSU
v.10.1

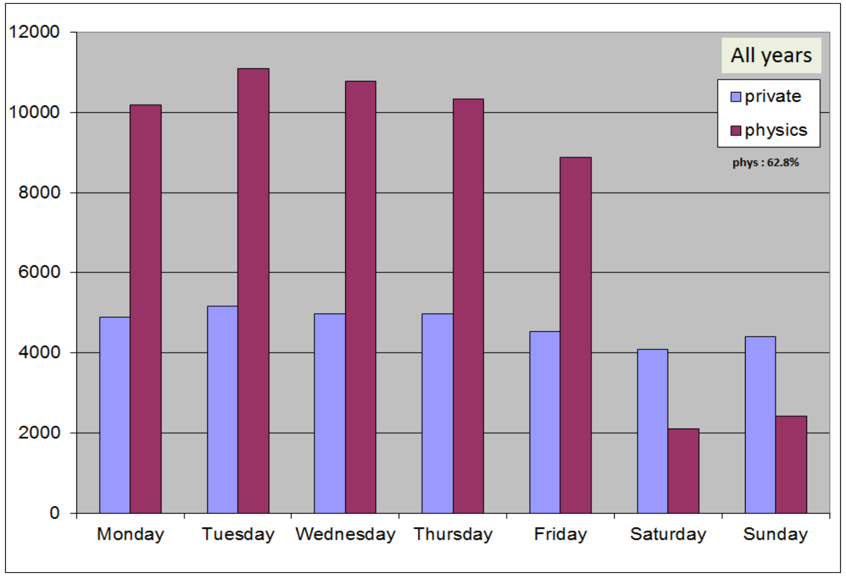
Wider opportunities

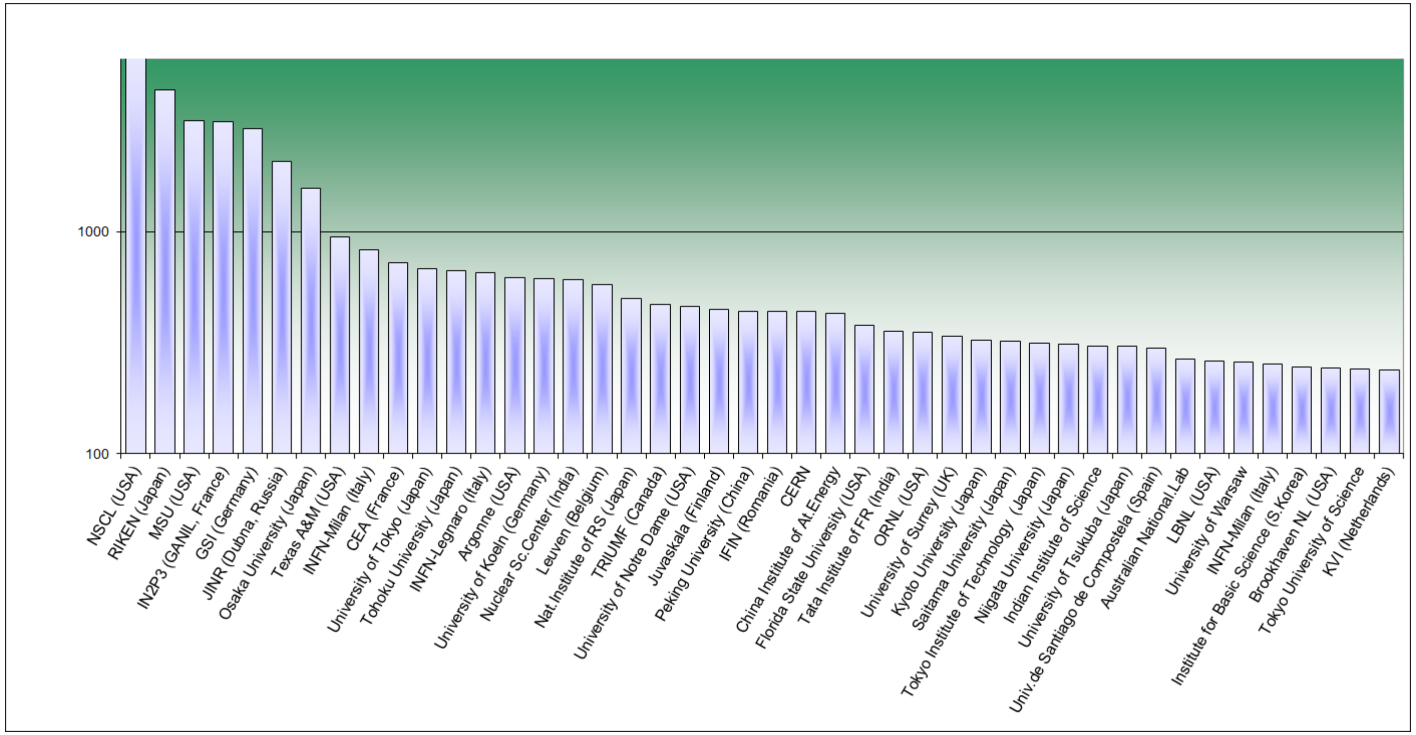
LISE^{++} : Statistics, Geography

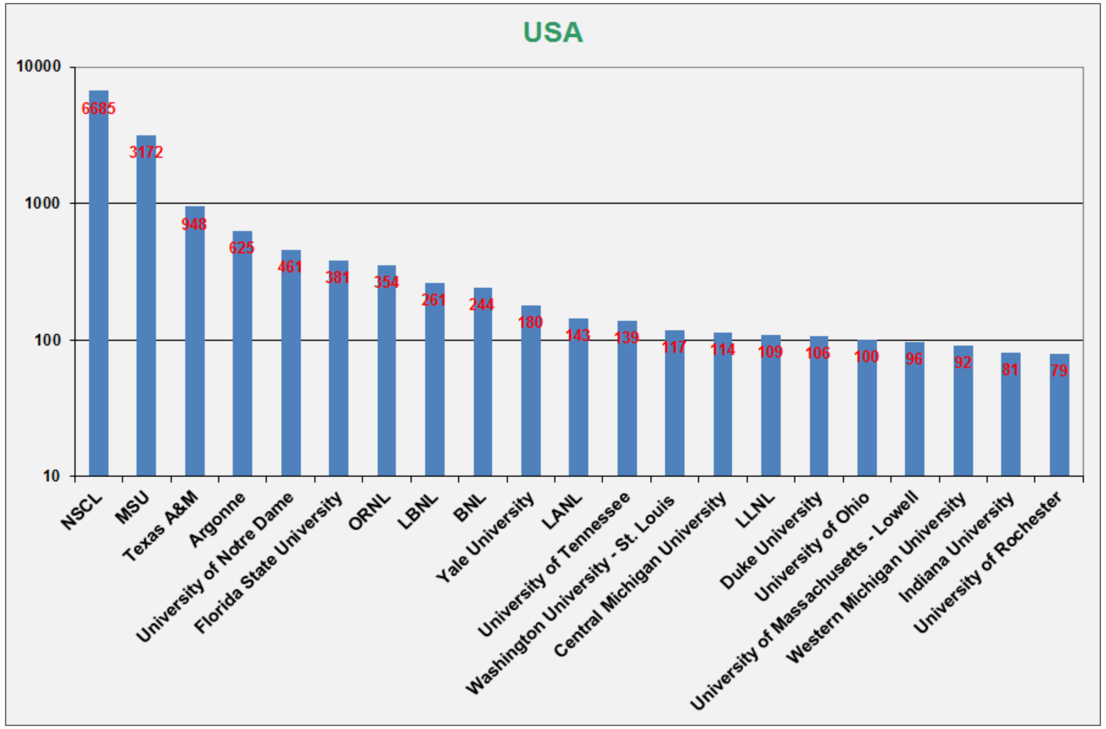
MICHIGAN STATE UNIVERSITY



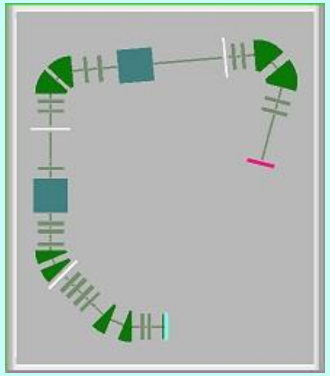




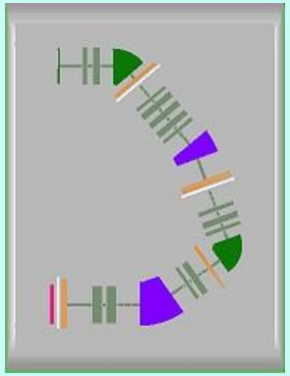




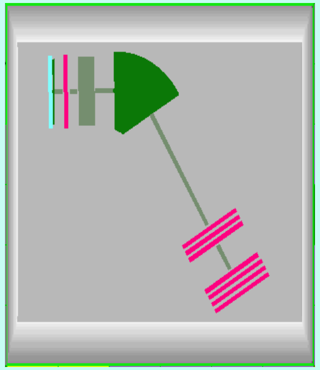
Application : Energy region and Facilities



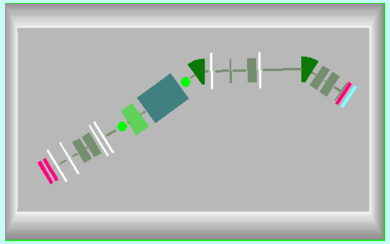
SECAR, *MSU*



DRAGON,
Canada

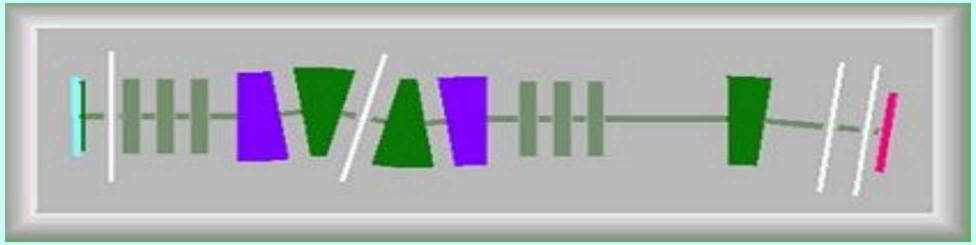


PRISMA,
Italy

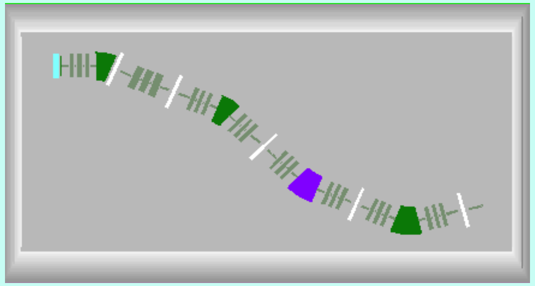


MARS,
TAMU, USA

The LISE^{++} code may be applied at low, medium, and high-energy facilities (fragment- and recoil-separators with electrostatic and/or magnetic selections).

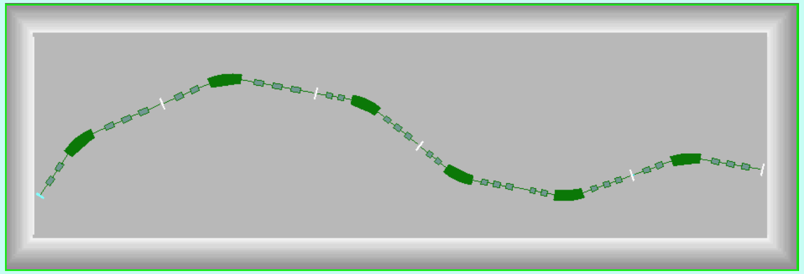


SHELS,
Russia



S^3,
France

BigRIPS+ZeroDegree,
Japan



SuperFRS_HEB,
Germany

Fragment Separator Construction

- with different sections called "blocks" (magnetic and electric multipoles, solenoid, velocity filter, RF deflector and buncher, material in beam, drift, rotation element, and others).

- a user-friendly interface that helps to seamlessly construct a fragment separator from the different blocks.

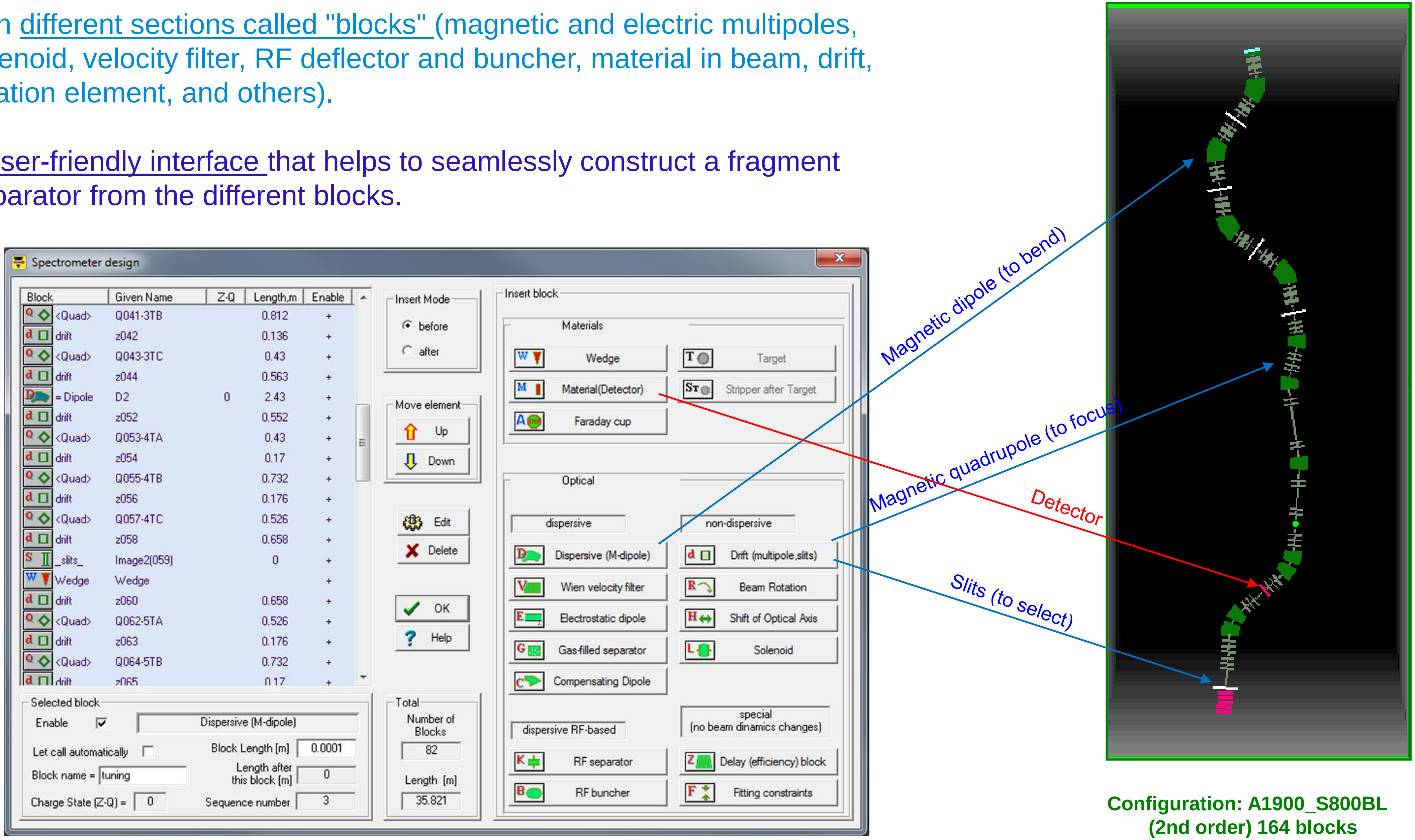


Fig. 1. Updated view of the "Spectrometer Design" dialog window.

Configuration: A1900_S800BL (2nd order) 164 blocks

LISE^{++} package

Besides analytical calculation of the transmission and yields of fragments

Built-in powerful tools:

- **Monte Carlo simulation of fragment transmission,**
- **Monte Carlo simulation of fission fragment kinematics,**
- **Ion Optics calculation and Optimization** *(new)*,
- **LISE for Excel (MS Windows, Mac OS - download)**

LISE^{++} calculators:

- **«Physical Calculator»,**
- **«Relativistic Kinematics Calculator»,**
- **«Evaporation Calculator»,**
- **«Radiation Residue Calculator»** *(new)*,
- **«Ion Mass calculator"** *(new)*,
- **«Matrix calculator"**

Implemented codes:

- **«PACE4» (fusion-evaporation code),**
- **«MOTER» (raytracing-type program for magnetic optic syste**
- **«ETACHA4» (charge-state distribution code)** *(new)*,
- **«Global» (charge-state distribution code),**
- **«Charge» (charge-state distribution code),**
- **«Spectroscopic Calculator" (of J.Kantele»)**

LISE^{++} Utilities:

- **Stripper Foil Lifetime Utility,**
- **Brho Analyzer,**
- **Twinsol (solenoid) utility,**
- **Units Converter,**
- **ISOL Catcher,**
- **Decay Analysis** (includes Proton, Alpha, Cluster, Sp.Fission half-lives calculation),
- **Reaction Utilities** (Characteristics, Converters, Plots),
- **«BI»-** the automatized search of two-dimensional peaks in spectra

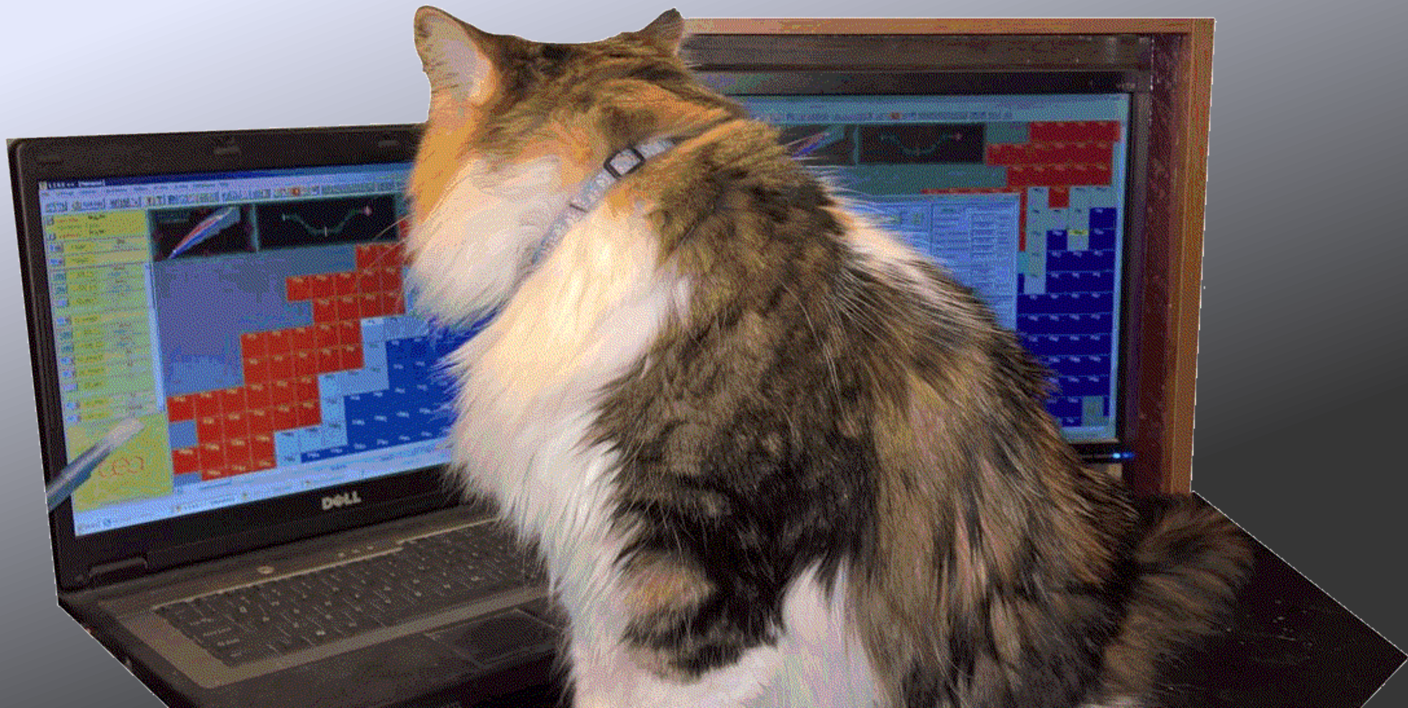
Databases:

- **Nuclide and Isomeric State databases with utilities,**
- **Large Set of Calculated Mass Tables (includes FRIB mass tables),**
- **Ionization Energy database (used with the Ion Mass calculator),**
- **Decay Branching Ratio database (used with the Radiation Residue calculator),**

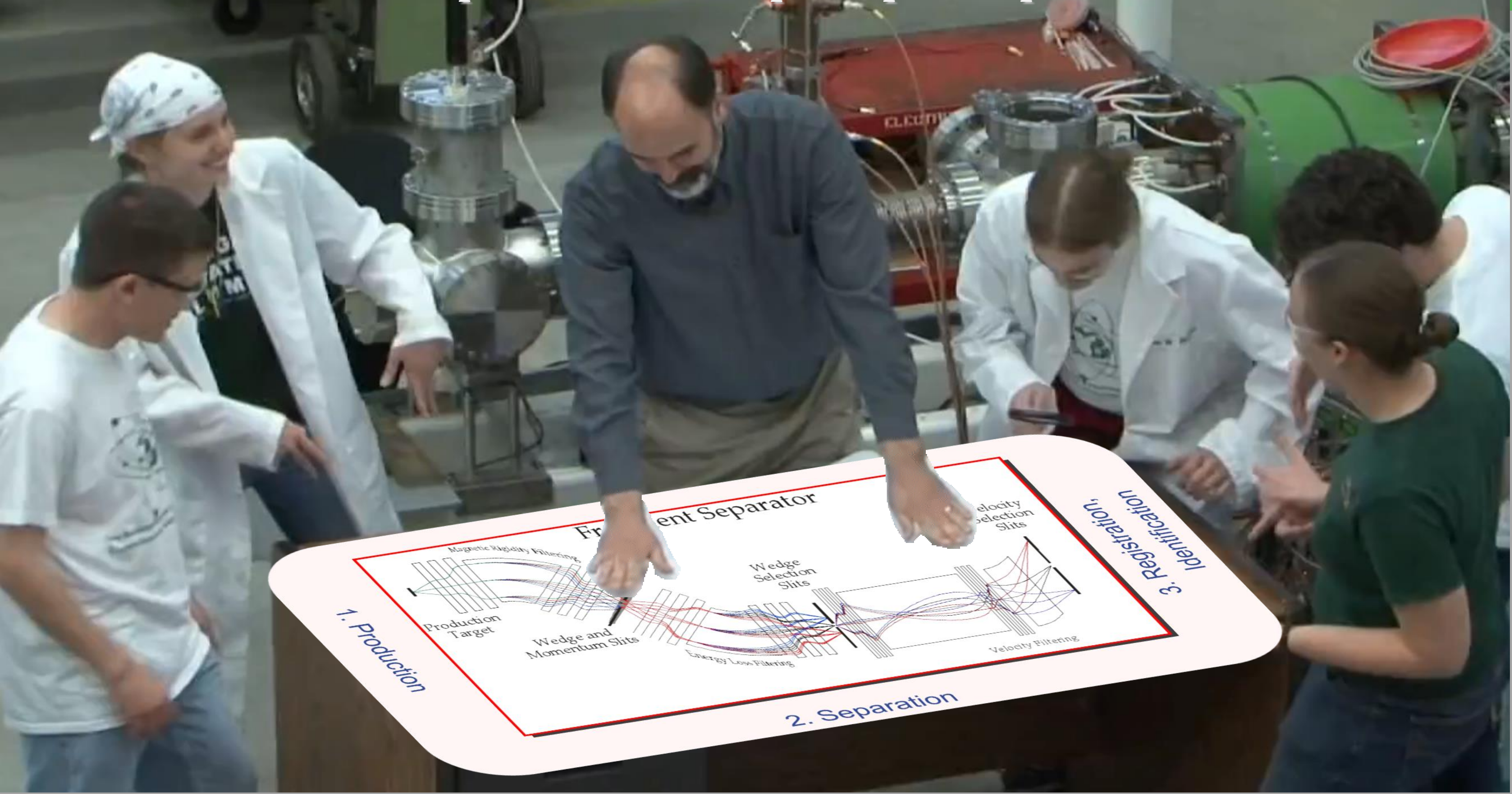
permit to work well below this energy limit, and this makes the program very attractive for all users dealing with physics of heavy ions from 10 keV up to some GeV per nucleon.

Are you ready?

LET'S GET STARTED



Rare isotope beams: Basic principle of operation

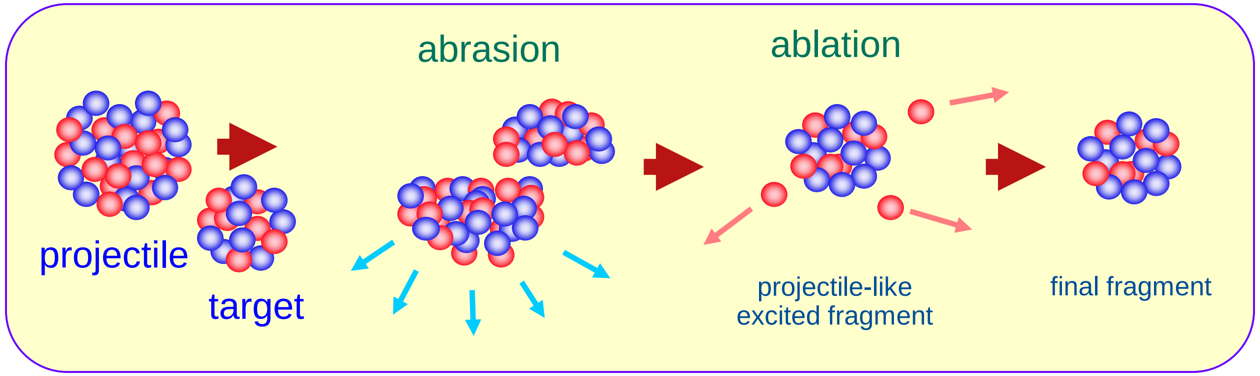


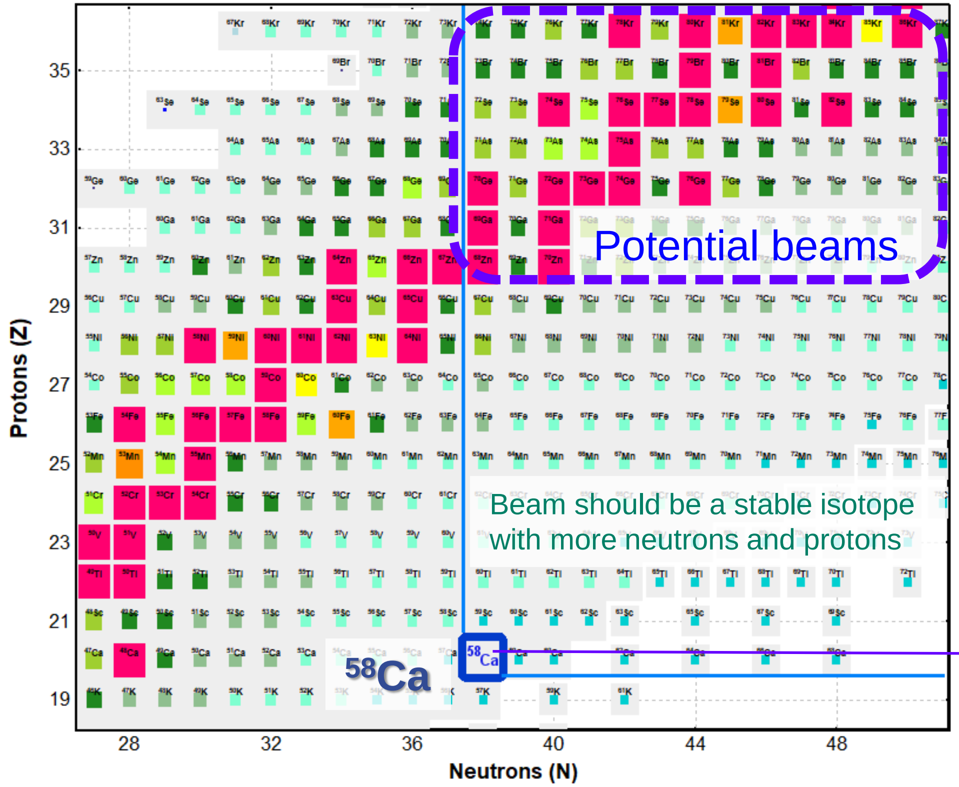
Production

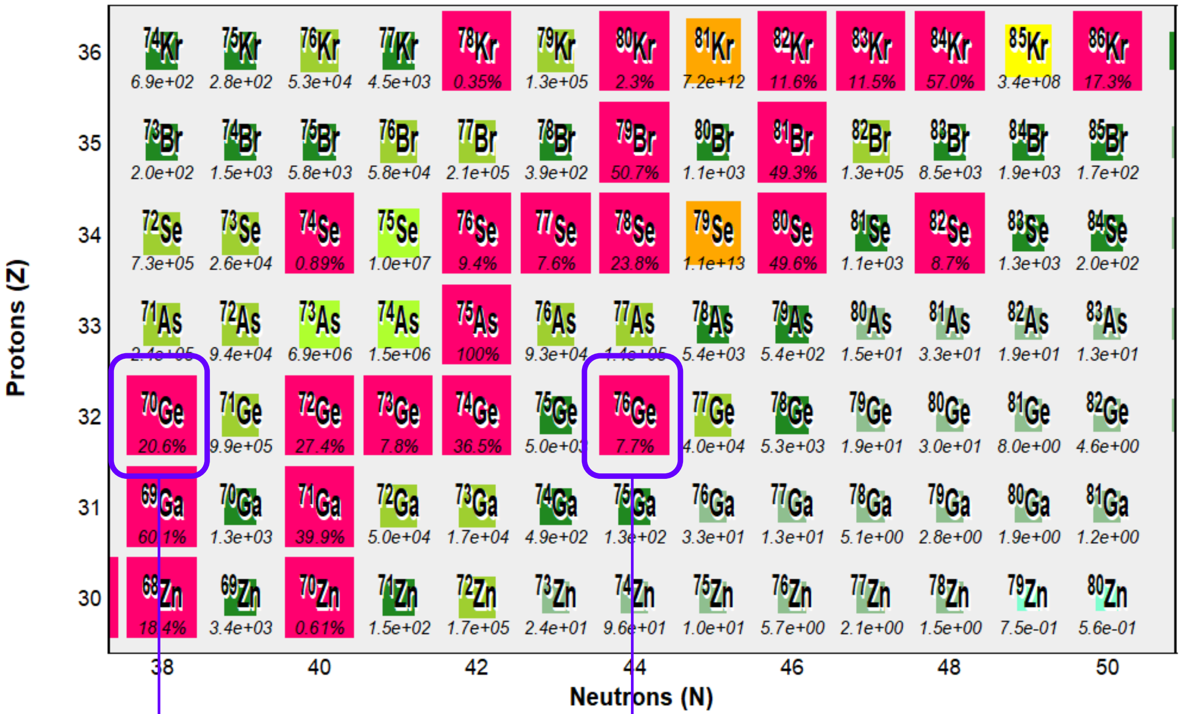
Production

1. Fragment of interest	^{58}Ca	
2. Choice of place for the experiment	A1900 @ NSCL	*default configuration*
3. Settings		
✓ Reaction mechanism	Projectile fragmentation	*> 95% experiments @ MSU*
✓ Beam		
✓ Target		
✓ Charge state model	no charge states	assumed at these energies in this Z-region
✓ Energy loss model	default	ATIMA
✓ Secondary reactions in target	no	assumed at these energies

Projectile Fragmentation







^{70}Ge (38n+32p) $\quad$ ^{76}Ge (44n+32p)

-10p $\quad$ -10p -6n

^{58}Ca (38n+20p)

What is more probable:

To strip 10p and 6n or only 10p?

What factor?

Duke or Kansas? What score?

Primary beam choice

MICHIGAN STATE UNIVERSITY

What is more probable:
To strip 10p and 6n or only 10p?
What factor?

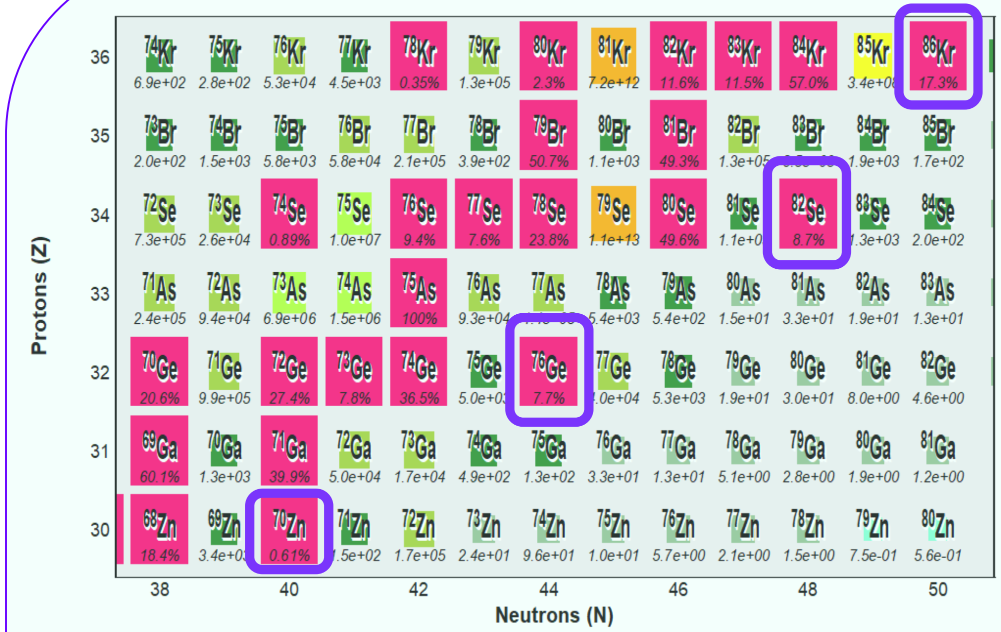
$$P(z,n)=\frac{\binom{Z_p}{z}\binom{N_p}{n}}{\binom{A_p}{a}}$$

^{70}Ge (38n+32p) → -10p → P = 2.1e-5

^{76}Ge (44n+32p) → -10p,-6n → P = 1.3e-2

P(^{76}Ge) / P(^{70}Ge) = 600 !!!!

Conclusion: a primary beam should be more neutron-rich



http://www.nscl.msu.edu/users/beams.html

NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY

CCF PRIMARY BEAM LIST

A	Element	Energy (MeV/nucleon)	Intensity (pnA)
76	Ge	130	25
82	Se	140	45
86	Kr	100	15
86	Kr	140	25

What beam from the NSCL list of available beams is more favorable to obtain a ^{58}Ca beam?

Primary beam settings

What beam from the NSCL list of available beams is more favorable to obtain a ^{58}Ca beam?

Answer: ^{82}Se & ^{76}Ge are even

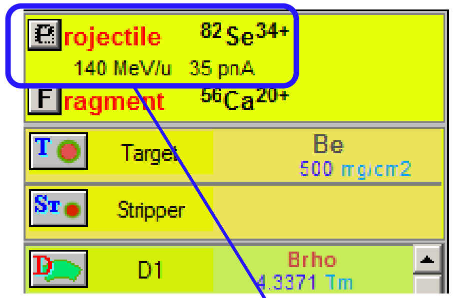
We observed 2 events in the NSCL experiments with a ^{82}Se beam, and with a ^{76}Ge beam.

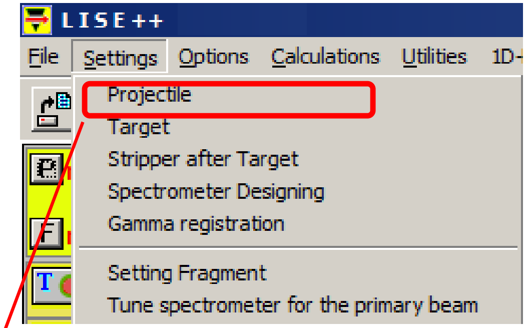
^{82}Se beam is more preferable to explore nuclei above calcium, below calcium a ^{76}Ge beam.

But, recently the MSU & RIKEN collaboration has observed two ^{60}Ca events even with a ^{70}Zn beam. No ^{82}Se and ^{76}Ge beams available currently in RIKEN.

So, let's select a ^{82}Se beam for our purpose

for all icons in the toolbar and in the production panel there are corresponding commands in the menu

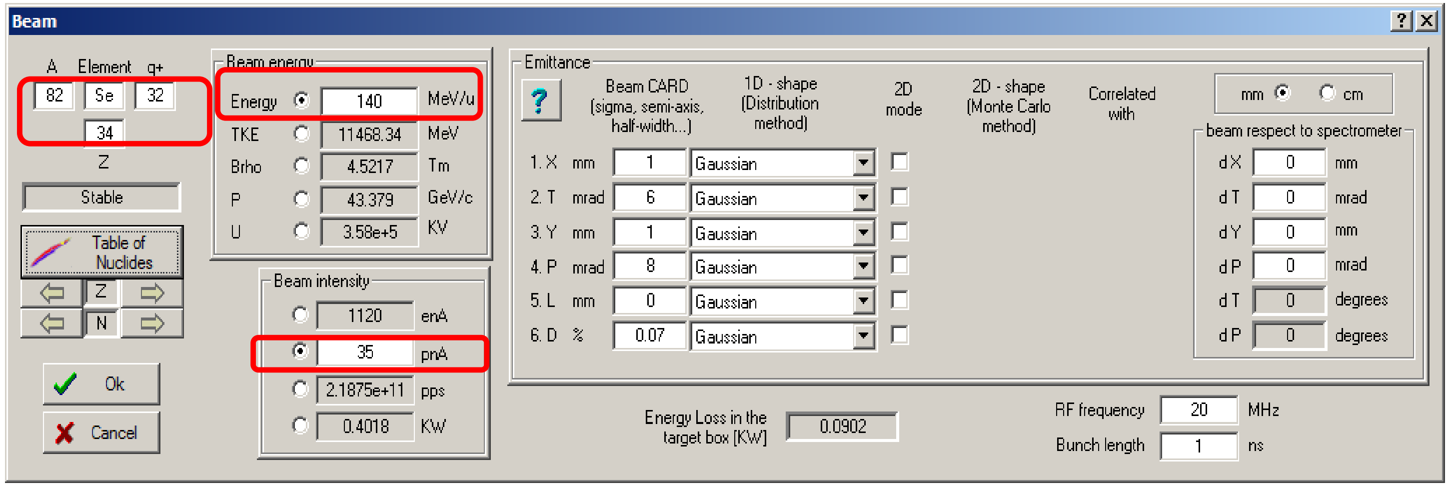




Home › NSCL Primary Beam List

Developed Primary Beams

Particle	Energy (MeV/nucleon)	Intensity (pnA)
^{16}O	150	175
^{18}O	120	150
^{20}Ne	170	80
^{22}Ne	120	80
^{22}Ne	150	100
^{24}Mg	170	60
^{36}Ar	150	75
^{40}Ar	140	75
^{40}Ca	140	50
^{48}Ca	90	15
^{48}Ca	140	80
^{58}Ni	160	20
^{64}Ni	140	7
^{76}Ge	130	25
^{82}Se	140	35
^{78}Kr	150	25
^{86}Kr	100	15
^{86}Kr	140	25
^{96}Zr	120	1.5
^{112}Sn	120	4
^{118}Sn	120	1.5
^{124}Sn	120	1.5
^{124}Xe	140	10
^{136}Xe	120	2
^{208}Pb	85	1.5
^{209}Bi	80	1
^{238}U	45	0.1
^{238}U	80	0.2

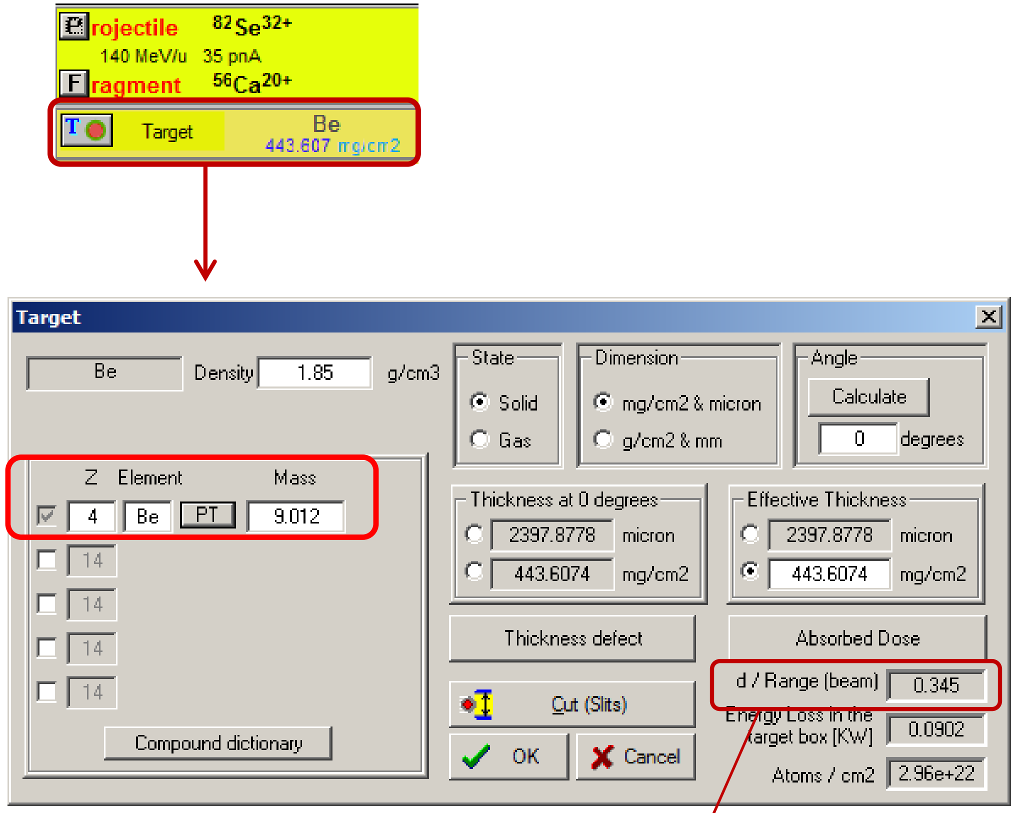


Target settings

Projectile fragmentation case:

- Heavy target : larger cross sections
- Light targets have more nuclei per electron, hence larger nuclear interaction probability at fixed electronic slowing down than heavy target
- **Overall case for projectile fragmentation:**
  $(\sigma N_t)_{light} > (\sigma N_t)_{heavy}$
- **Chemical and physical properties of material**
  as melting point, thermal conductivity etc,
  so lifetime of Be target >> lifetime of equivalent Ta target
- Charge state distribution after target:
  light targets provide higher average *q* of ions
  ** using strippers after heavy targets*
- Dissipation process larger with heavy targets
  so ^{40}Mg and ^{44}Si been have observed in ^{48}Ca+W

This favors light targets (NSCL uses Be)

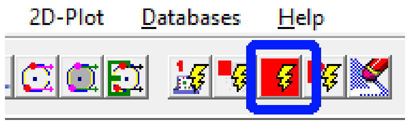


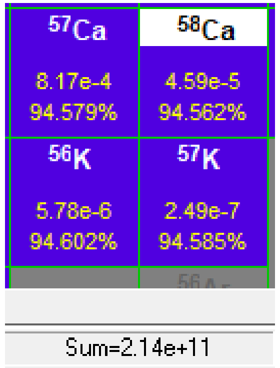
Ratio between target thickness and projectile range (in target)
(range = thickness required to stop a particle)

- d/R ~ 0.3-0.35 for maximum fragment yield
- Special utility “Optimum target”

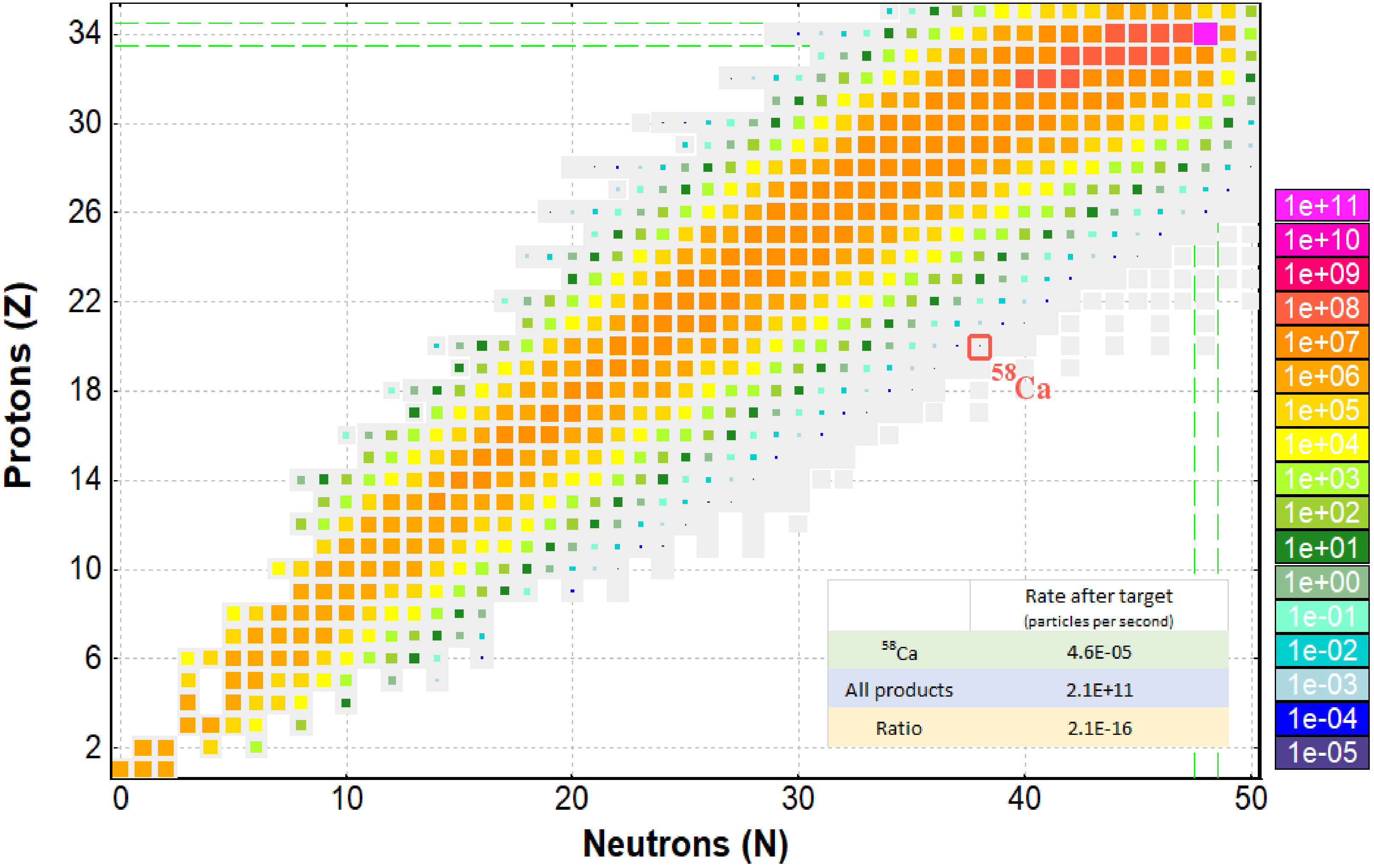
Selection

Yield after target



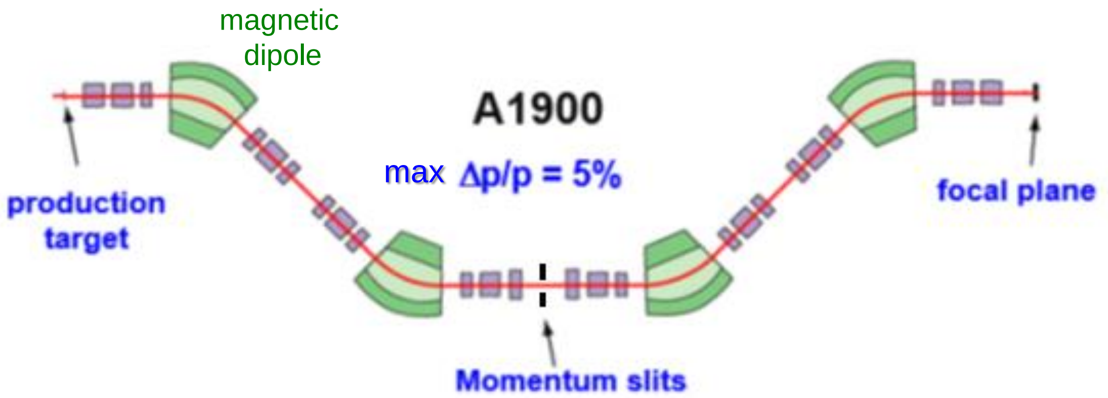


Menu “1D-plot” → “Transmission Characteristics”



How do we select ^{58}Ca?

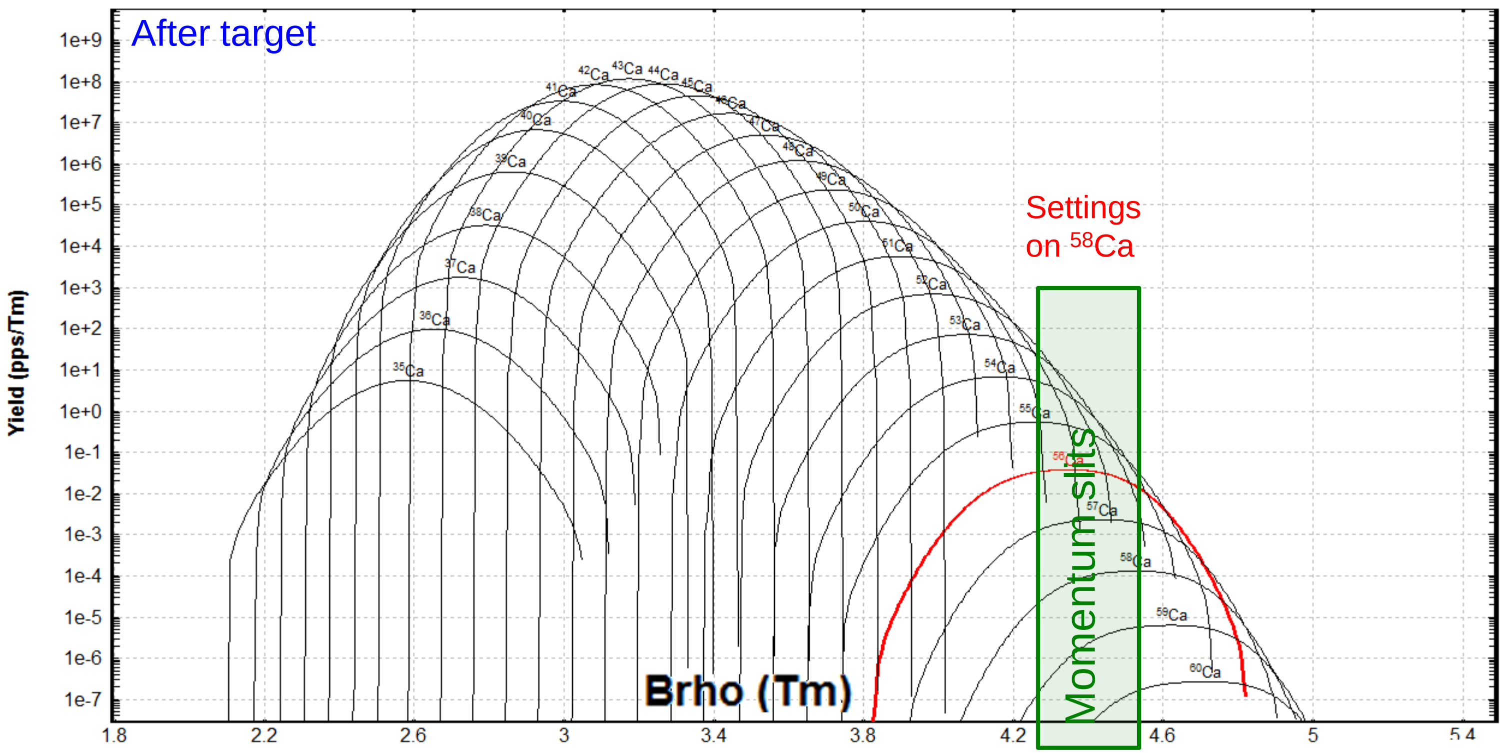
Fragment-separator A1900



Changing the I2 slits size,
we change the momentum acceptance

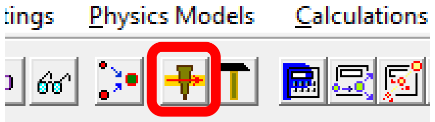
Separation device	Changeable field	Strength	Selection by
Magnetic dipole	Magnetic (B[T])	$\vec{F}_B = q\vec{v} \times \vec{B}$	Magnetic rigidity $B\rho = \frac{mv}{q}$ [T·m]

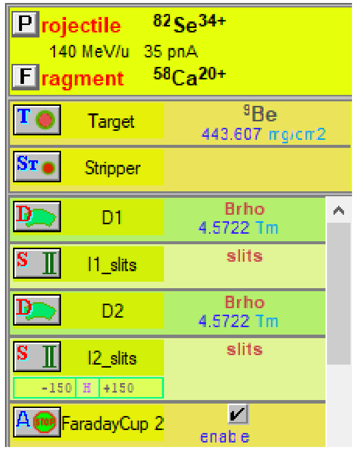
^{82}Se (140 MeV/u) + Be (443mg/cm^2) $\Rightarrow$ **Ca

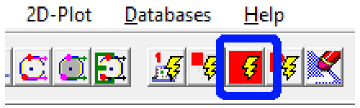


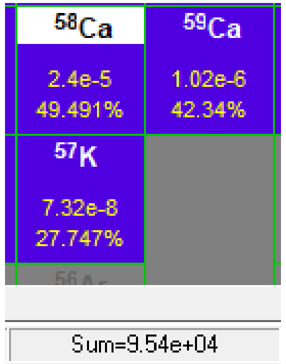
Bρ (magnetic rigidity) selection

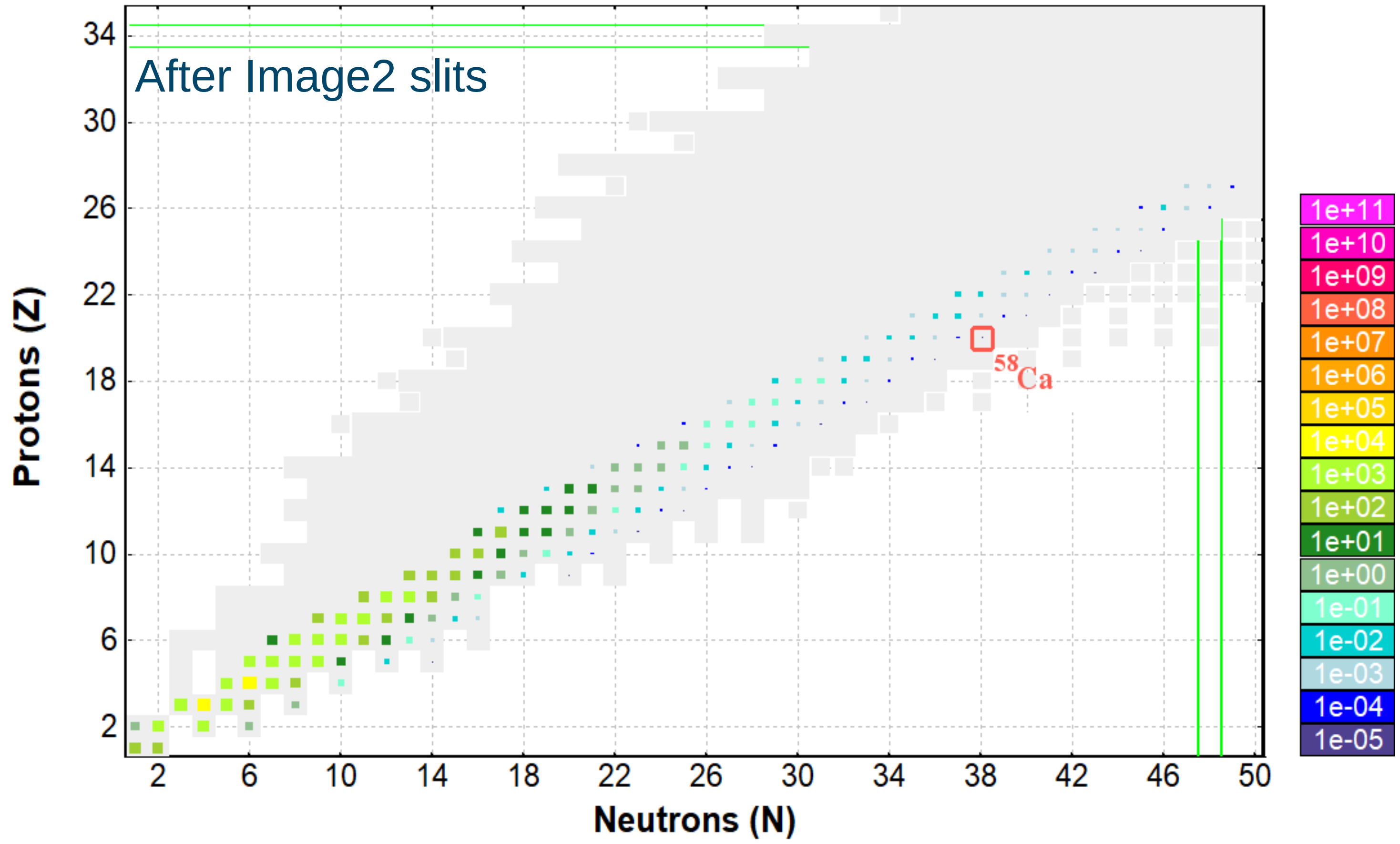
Tune separator for setting fragment











	Rate after I2-slits (particles per second)
^{58}Ca	2.4E-05
All products	9.5E+04
Ratio	2.5E-10

It corresponds to 2 events/day, but in reality it will be less (“calcium” anomaly)

Still very high. DAQ rate should less 1000 cps

"Wedge" selection (energy loss difference)

MICHIGAN STATE UNIVERSITY

27.2.2. ***Stopping power at intermediate energies*** :

The mean rate of energy loss by moderately relativistic charged heavy particles, $M_1/\delta x$, is well-described by the "Bethe-Bloch" equation,

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] . \qquad (27.3)$$

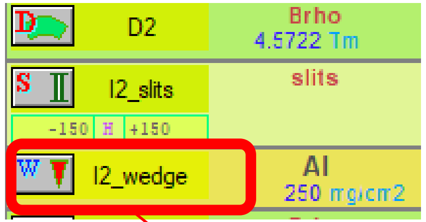
www-pdg.lbl.gov

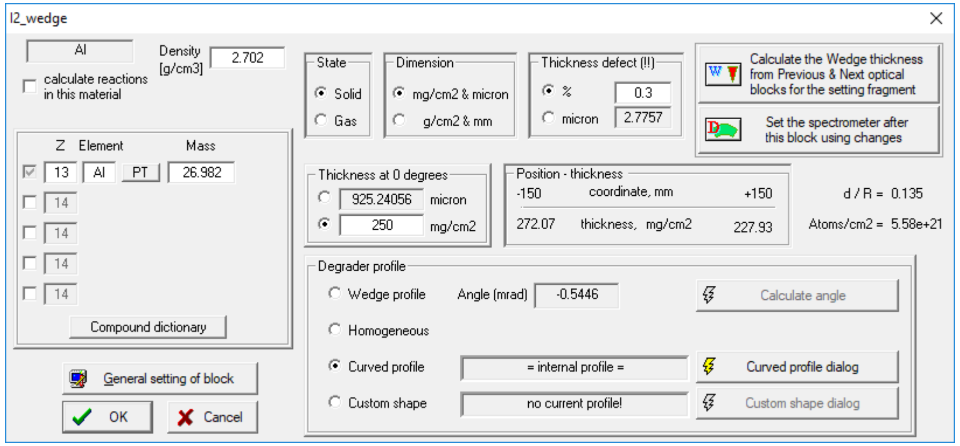
Atomic number of fragment

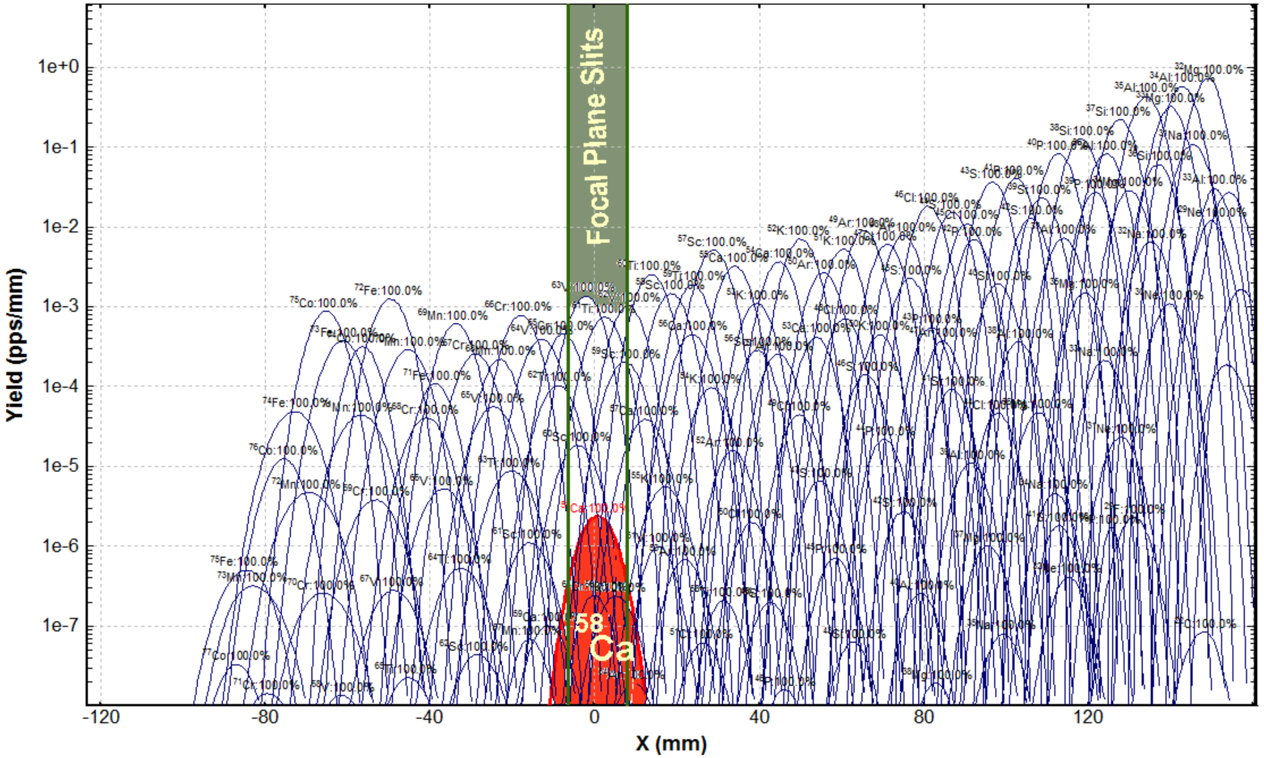
Fragment velocity

Then higher Z or smaller velocity, then larger dE/dx (in 10-100 MeV/u energy region)

"Wedge" = wedge-shaped degrader

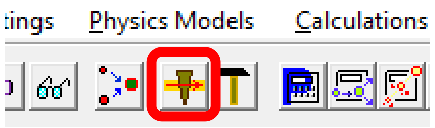


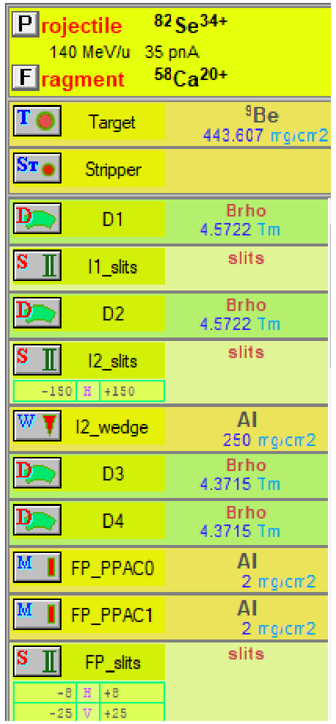


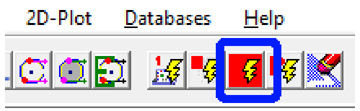


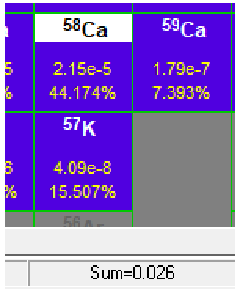
Wedge selection (energy loss difference)

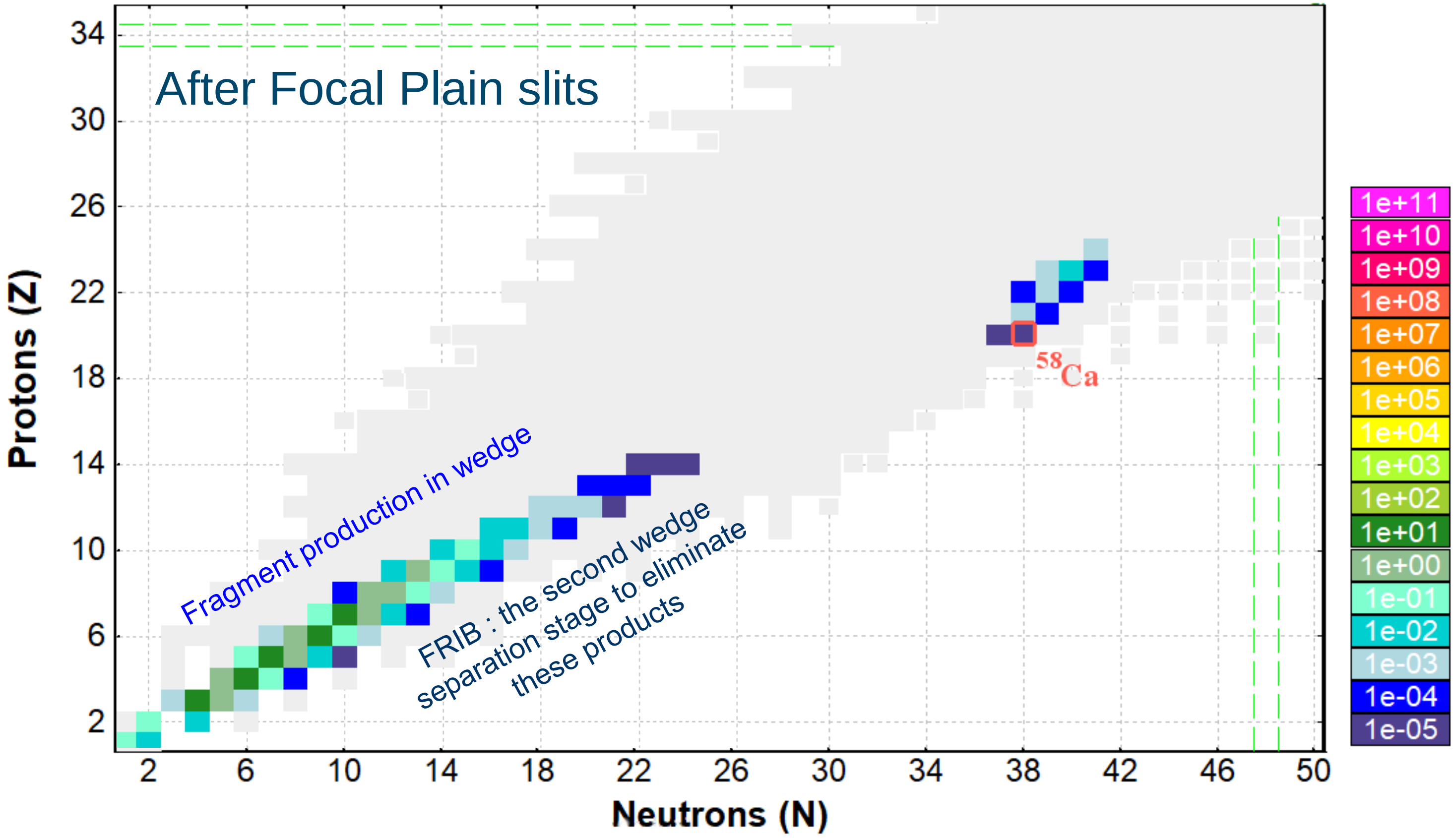
Tune separator for setting fragment











	Rate after FP-slits (particles per second)
^{58}Ca	2.2E-05
All products	2.6E-02
Ratio	8.3E-04

Selection summary

	Rate after target (particles per second)	Rate after I2-slits (particles per second)	Rate after FP-slits (particles per second)	Total ^{58}Ca selection gain
^{58}Ca	4.6E-05	2.4E-05	2.2E-05	
All products	2.1E+11	9.5E+04	2.6E-02	
Ratio	2.1E-16	2.5E-10	8.3E-04	3.9E+12

Identification

Particle IDentification

Courtesy by A.Stolz

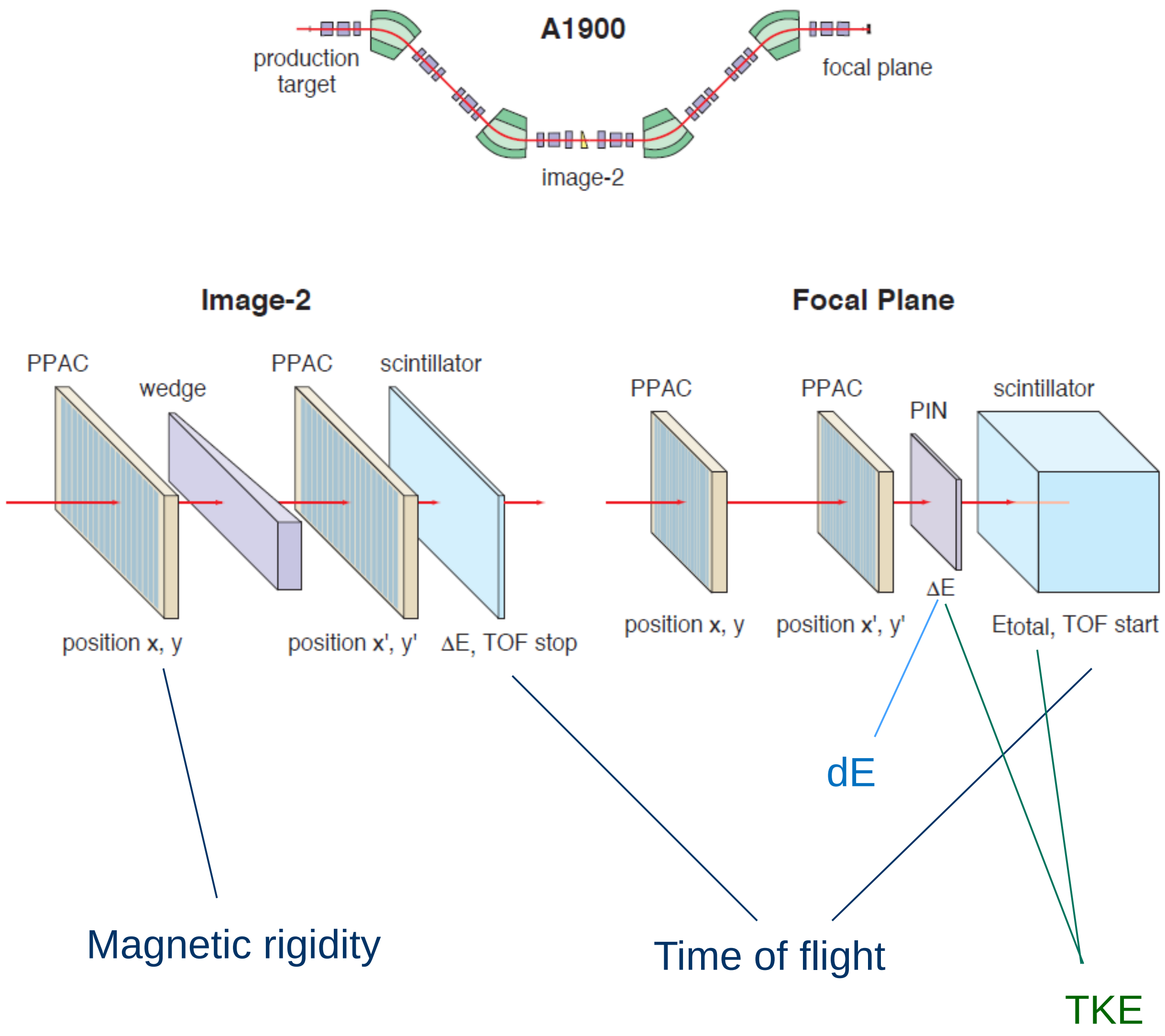
What do we want to know?

1. A
2. Z
3. Q
4. Energy (property of incoming ion in detectors)

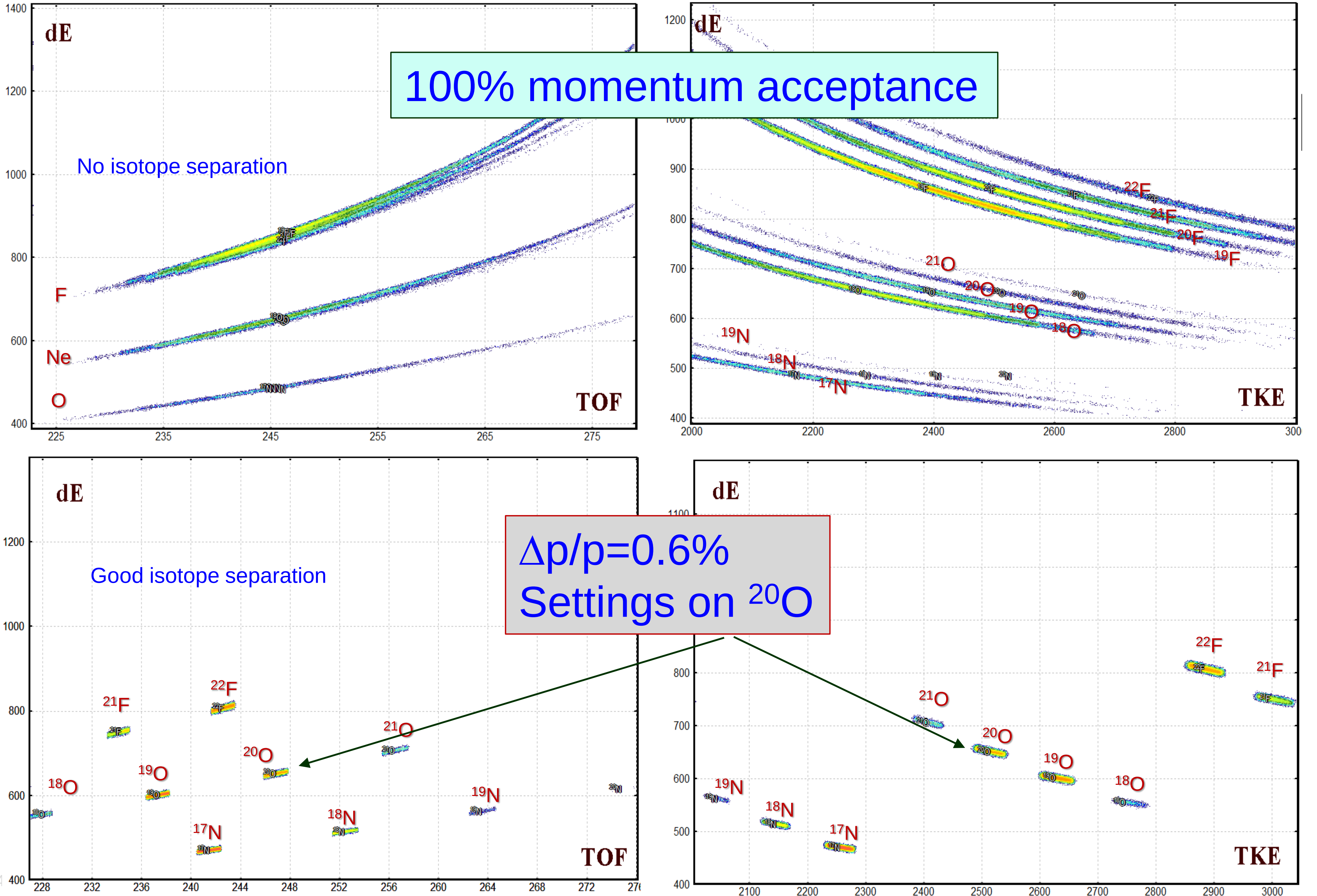
What do we measure?

1. Total kinetic energy
2. Magnetic (electric) rigidity
3. Energy loss in detector
4. Velocity (time of flight)

In our case (low Z, *E*=140 MeV/u) we assume Q=Z, so we do need only 3 values to measure



Correlation plots and Bρ-selection



Obtaining *A*, *Z*, *q*

The atomic number is determined from the combination of energy loss (ΔE) and time of flights (TOF) values according to the Bethe formula:

$$Z \approx \sqrt{\Delta E \Big/ \left(\frac{1}{\beta^2} \ln\left(\frac{5930}{1/\beta^2 - 1} \right) - 1 \right)}$$

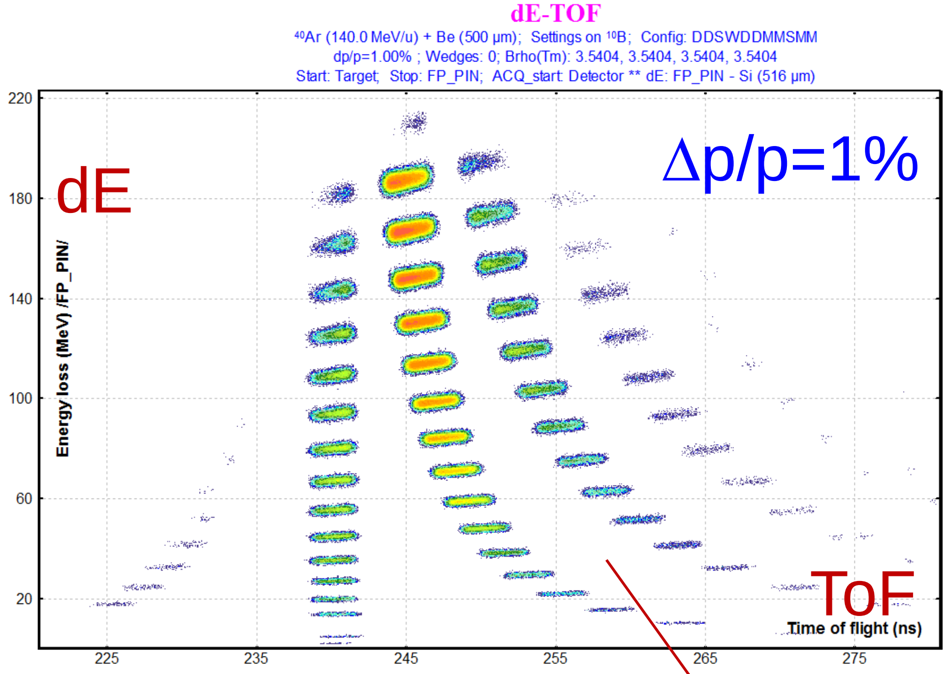
The fragment mass can be extracted in atomic units from the relativistic formula:

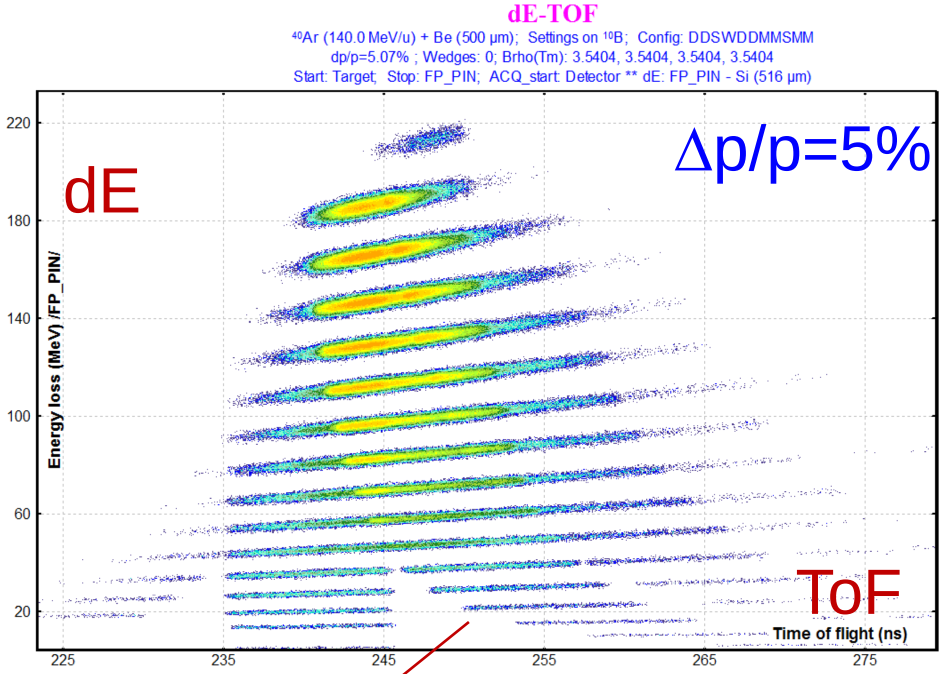
$$A = \frac{TKE}{931.5 \times (\gamma - 1)}$$

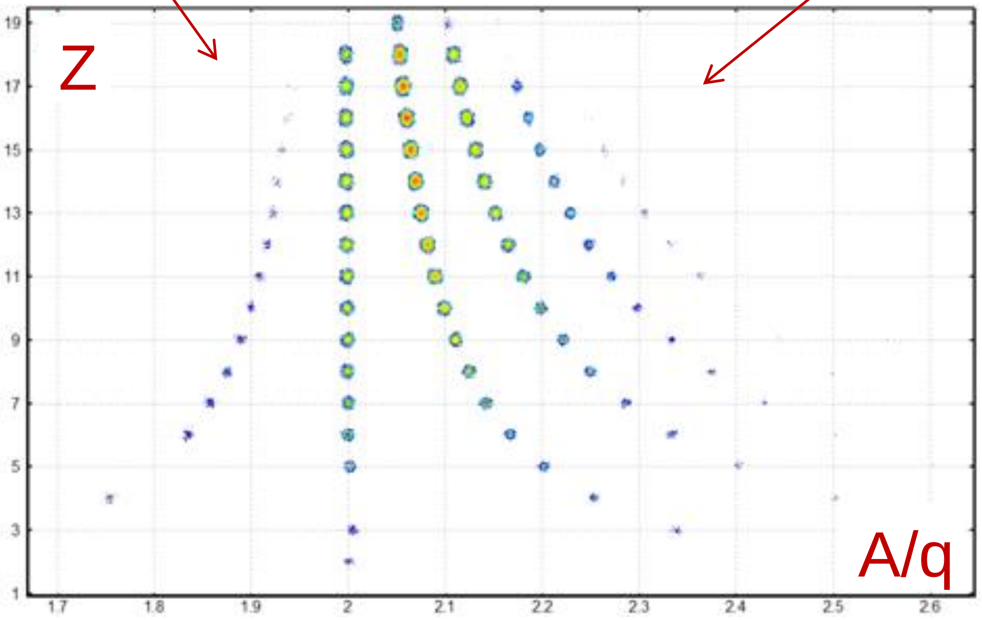
where TKE is calculated as a sum of the energy loss values in each of the detectors in a multilayer telescope stopping the products. The charge state (Q) of the ion evaluated from a relation based on the TKE, velocity and magnetic rigidity values:

$$Q = 3.33 \times 10^{-3} \frac{TKE \times \beta\gamma}{B\rho(\gamma - 1)}$$

Momentum acceptance

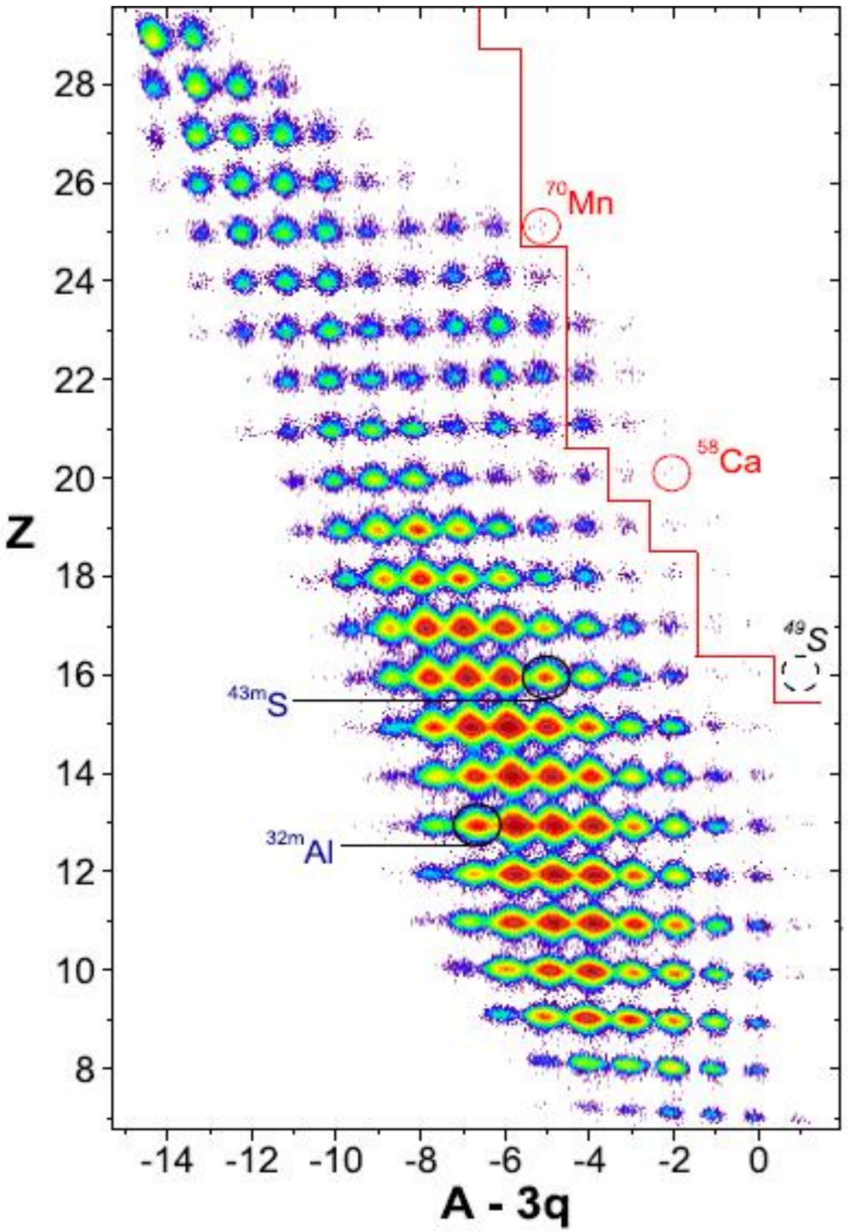


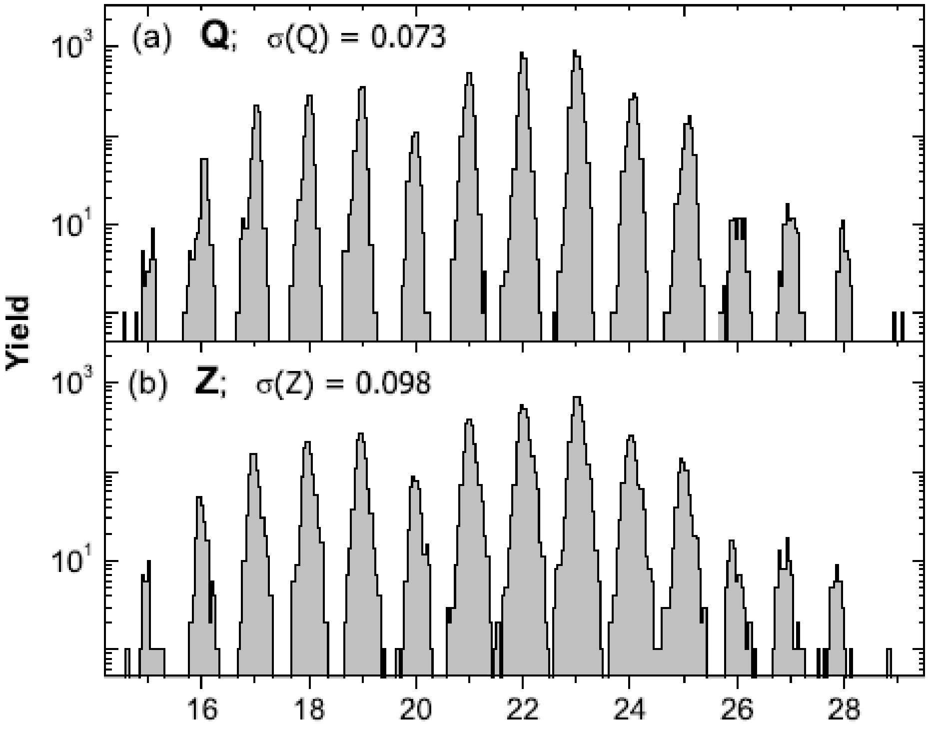




Z and A/q resolution will be the same in spite of momentum acceptance value

^{76}Ge(130MeV/u) + W,Be : PID, resolution





For all particles stopped in the Si-telescope in the production runs

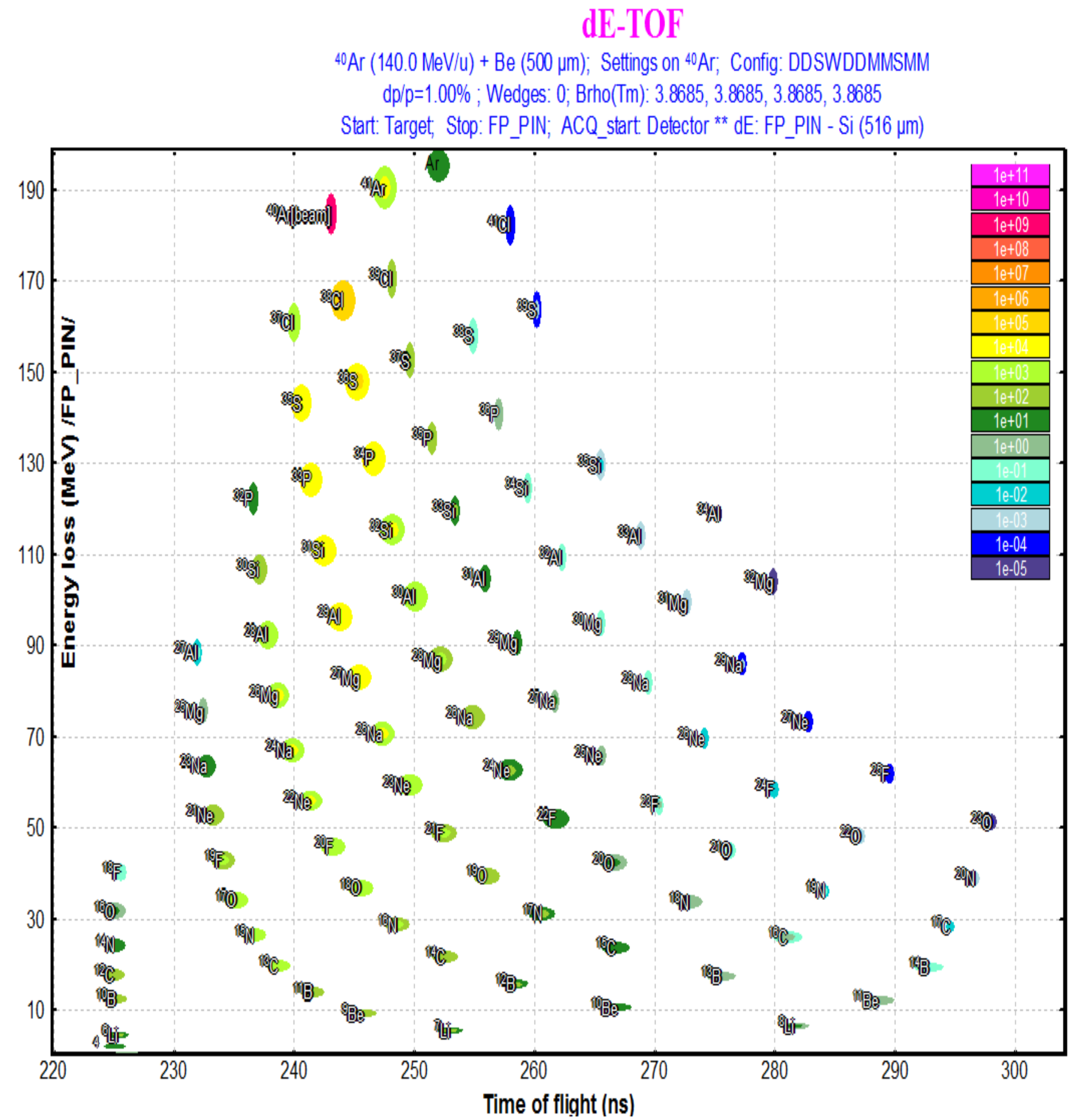
This means, the probabilities of one event misidentified as a neighboring charge state or element are equal to $\Phi_q(0.5) = 3.7\ 10^{-12}$ and $\Phi_Z(0.5) = 1.7\ 10^{-7}$, respectively.

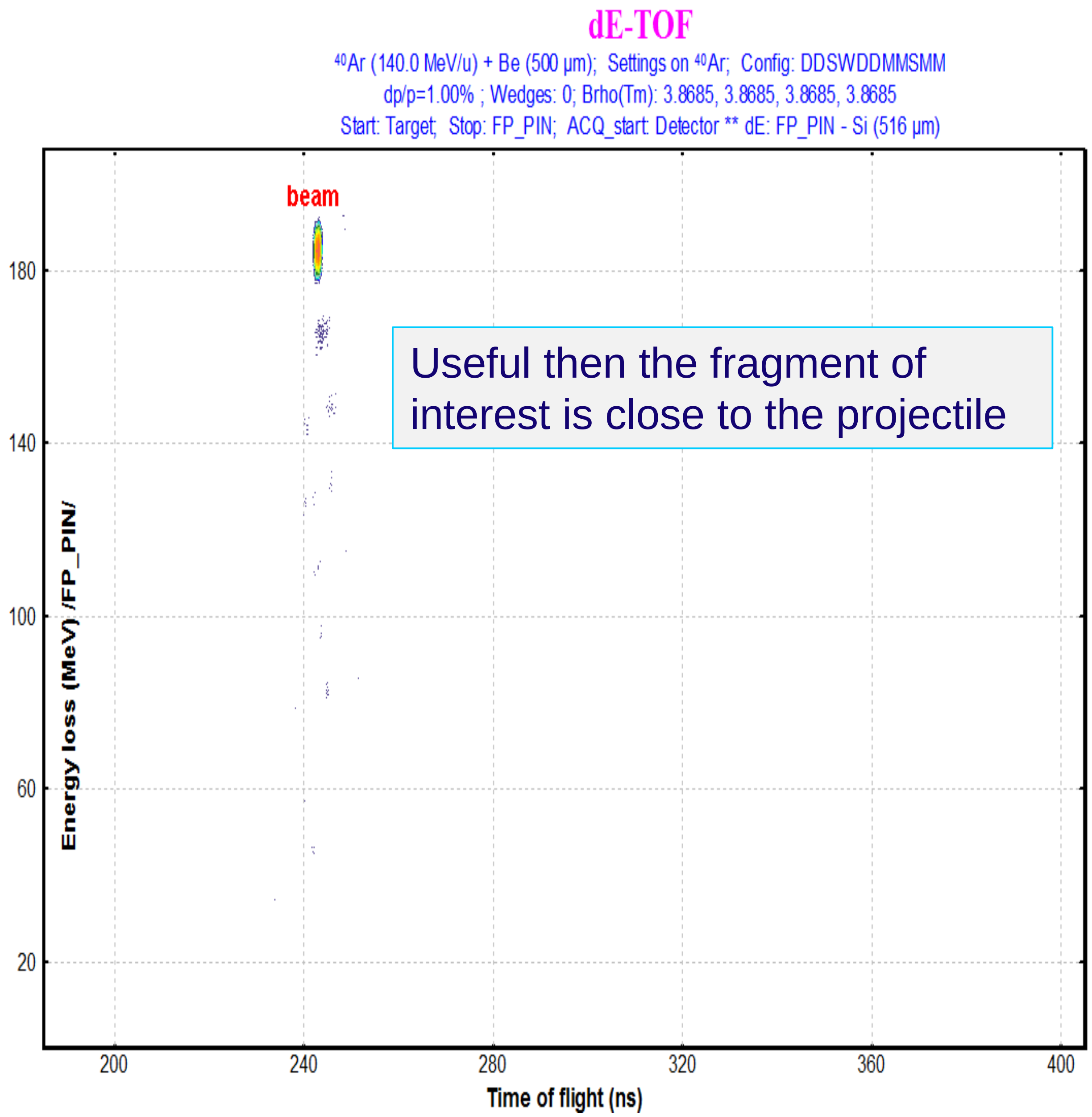
OT et al. Phys.Rev.Lett. 102, 142501 (2009)
OT et al. Phys.Rev.C. 80, 034609 (2009)

Particle identification assignments

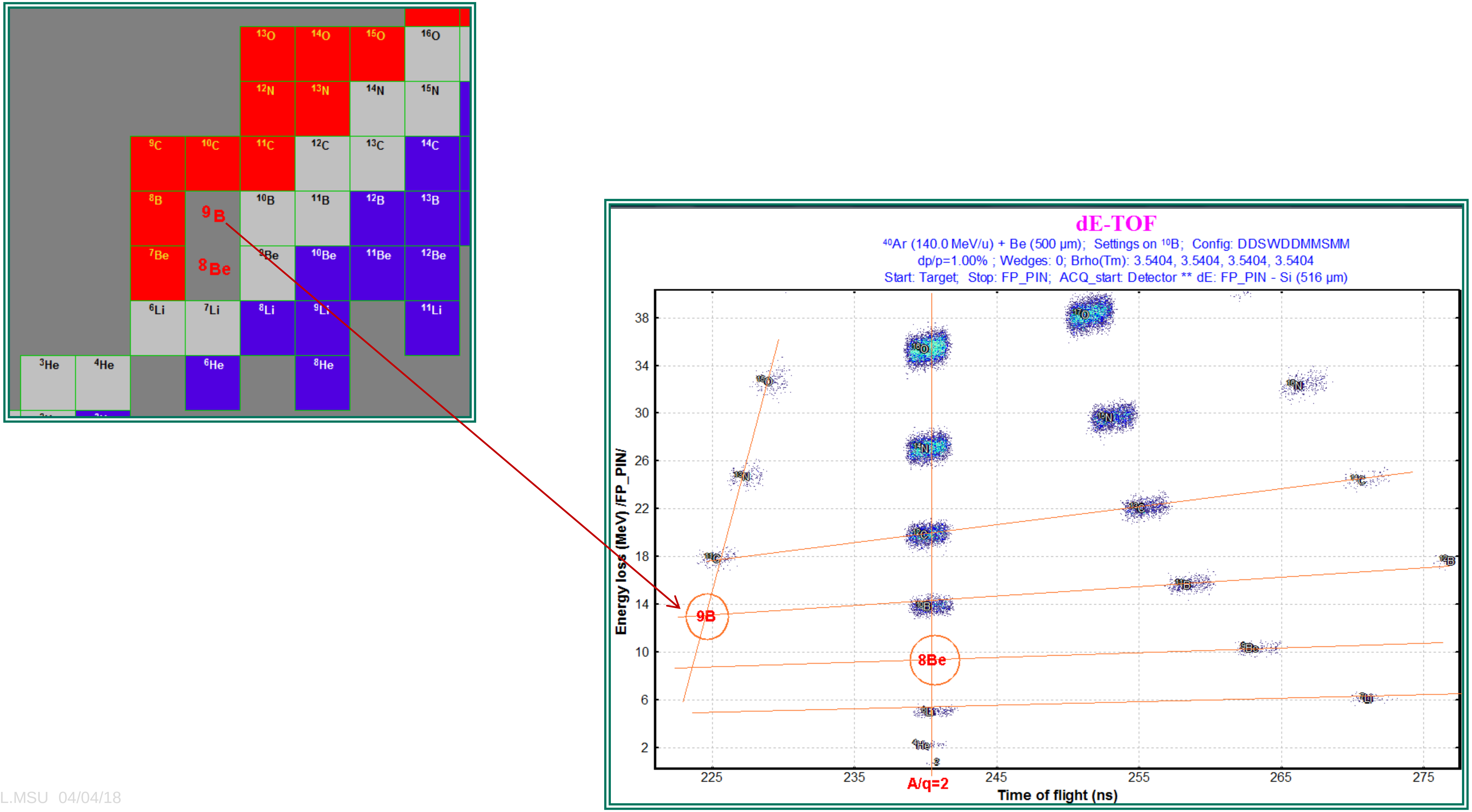
- Calibration with the primary beam (or other reference line as sources)
- Unbound nuclei in the table of nuclides
- Stopped fragment tagging with isomeric gamma-rays
- In-flight fragment tagging with prompt gamma
- X-ray from ions passing material
- Laser induced fluorescence
- Precise isobar selection with known masses

Calibration with the primary beam





Useful then the fragment of interest is close to the projectile



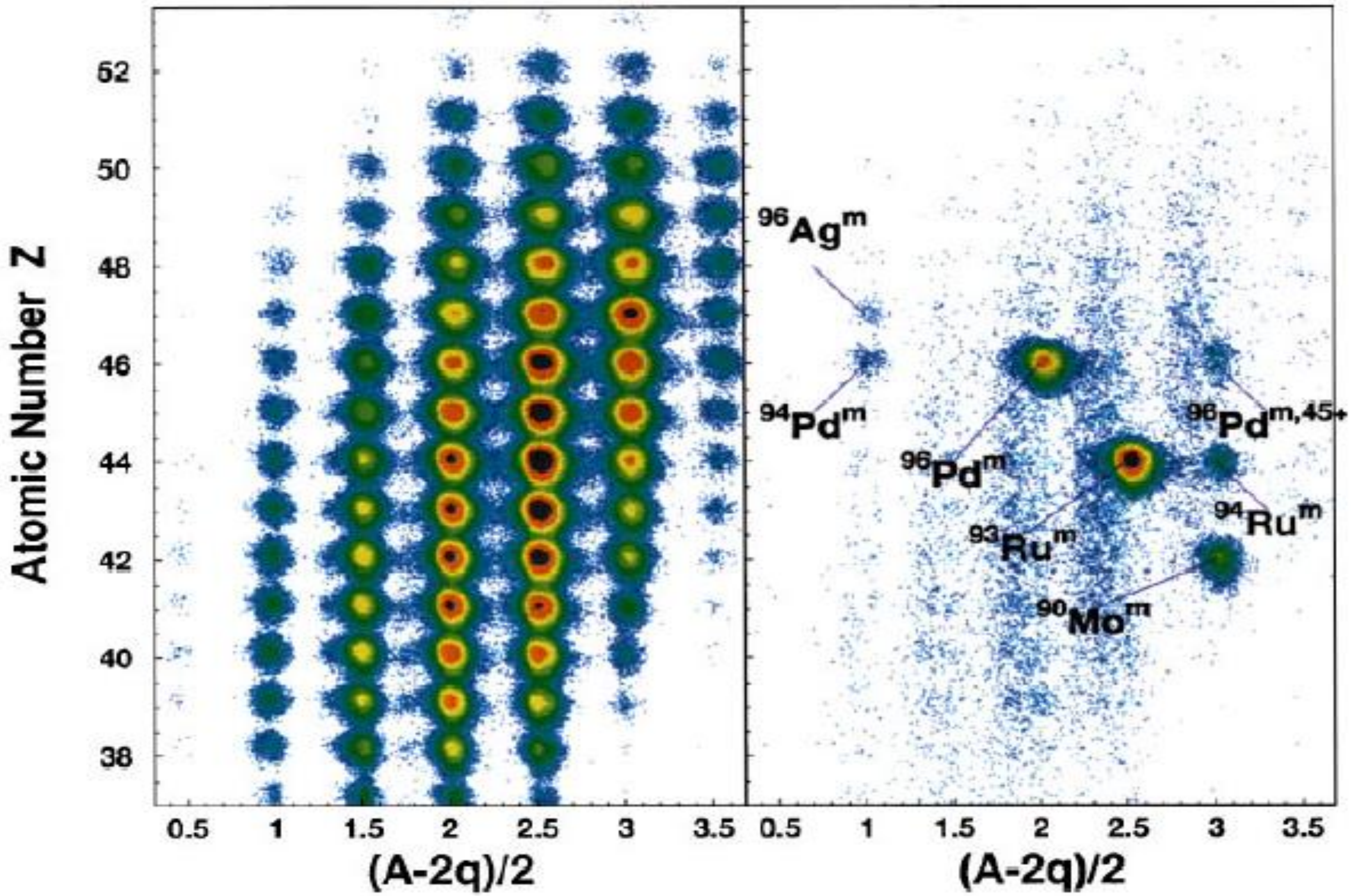
9B
8Be
dE-TOF
40Ar (140.0 MeV/u) + Be (500 µm); Settings on 10B; Config: DDSWDDMMSMM
dp/p=1.00% ; Wedges: 0; Brho(Tm): 3.5404, 3.5404, 3.5404, 3.5404
Start: Target; Stop: FP_PIN; ACQ_start: Detector ** dE: FP_PIN - Si (516 µm)
Energy loss (MeV) /FP_PIN/
Time of flight (ns)
A/q=2

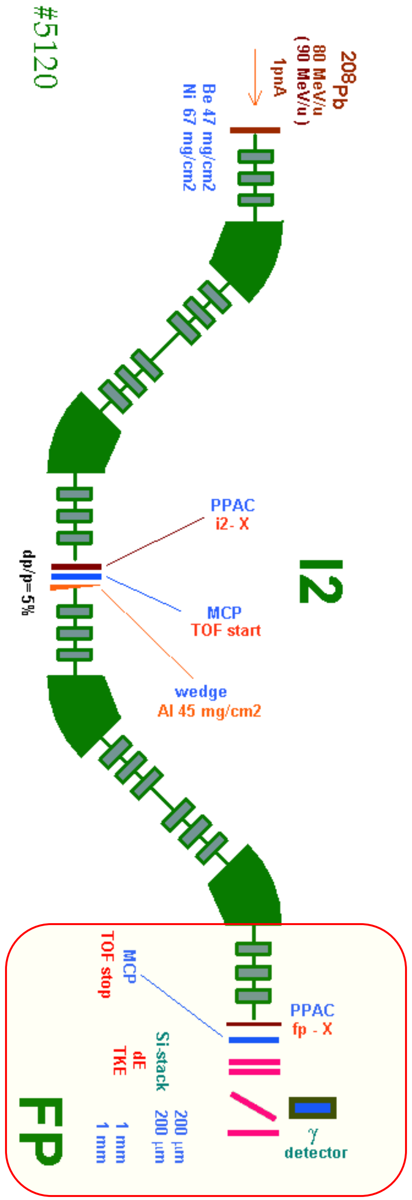
Stopped fragment tagging with isomeric gamma-rays

PHYSICAL REVIEW C VOLUME 55, NUMBER 3 MARCH 1997

New μs isomers in $T_z=1$ nuclei produced in the ^{112}Sn(63A MeV) + ^{nat}Ni reaction

R. Grzywacz,[1,2] R. Anne,[2] G. Auger,[2] C. Borcea,[3] J. M. Corre,[2] T. Dörfler,[4] A. Fomichov,[5] S. Grevy,[6] H. Grawe,[7] D. Guillemaud-Mueller,[6] M. Huyse,[8] Z. Janas,[7] H. Keller,[7] M. Lewitowicz,[2] S. Lukyanov,[5,2] A. C. Mueller,[6] N. Orr,[9] A. Ostrowski,[2] Yu. Penionzhkevich,[5] A. Piechaczek,[8] F. Pougheon,[6] K. Rykaczewski,[1,10] M.G. Saint-Laurent,[2] W. D. Schmidt-Ott,[4] O. Sorlin,[6] J. Szerypo,[1] O. Tarasov,[5,2] J. Wauters,[8] J. Żylicz[1]

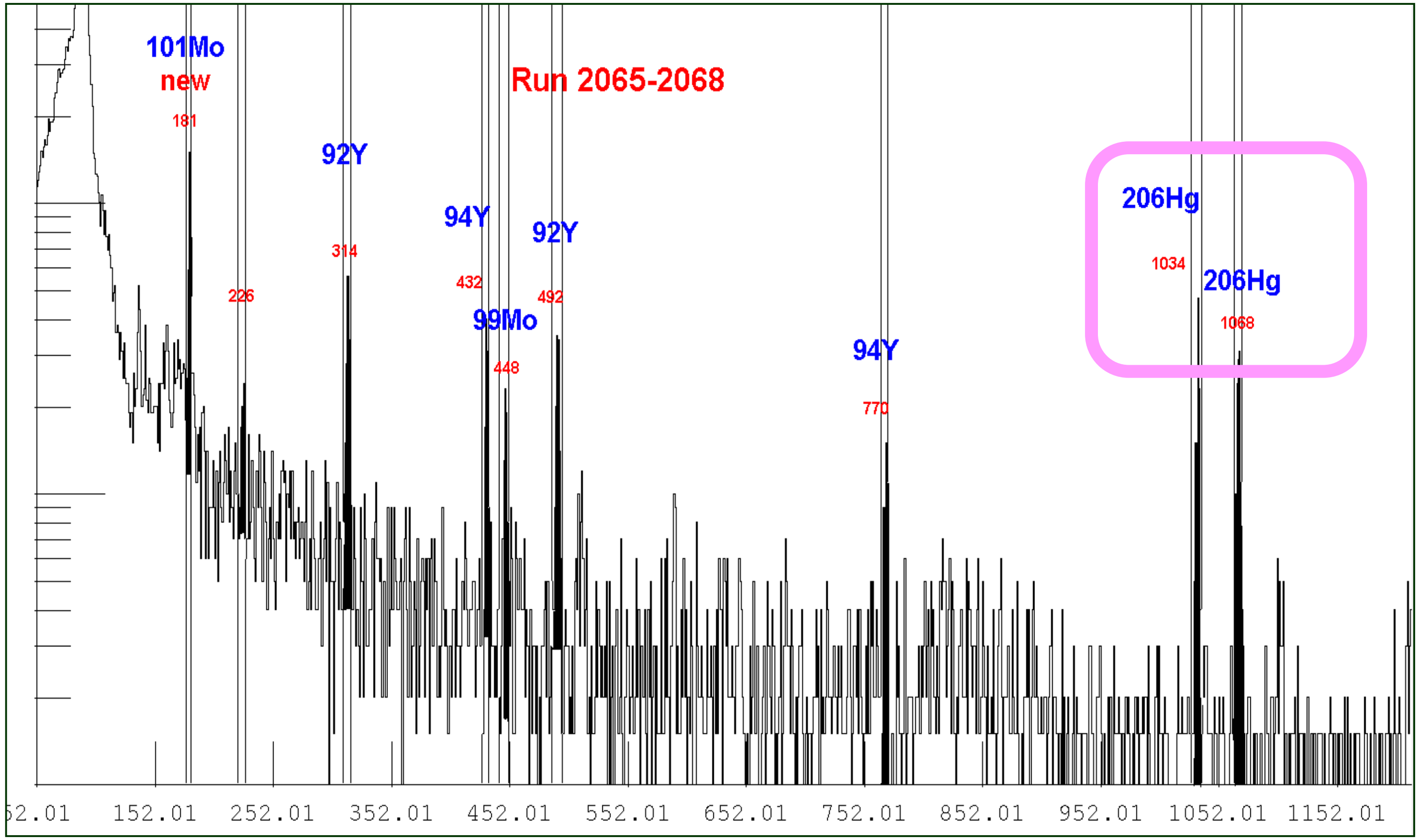


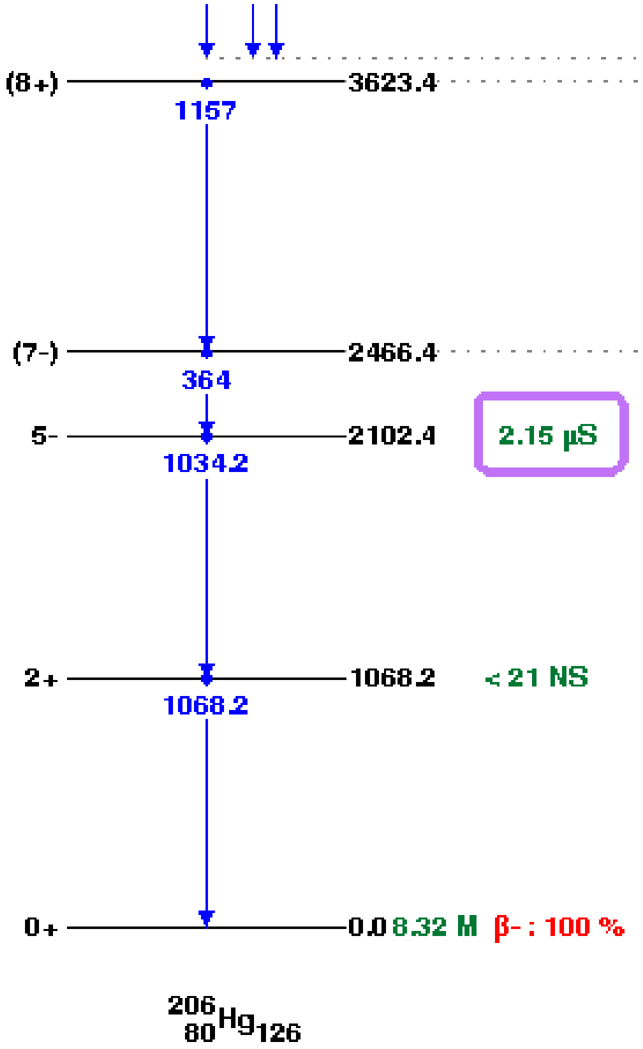


Stopped fragment tagging with isomeric gamma-rays

NSCL #05120

^{208}Pb (86 MeV/u) + Be





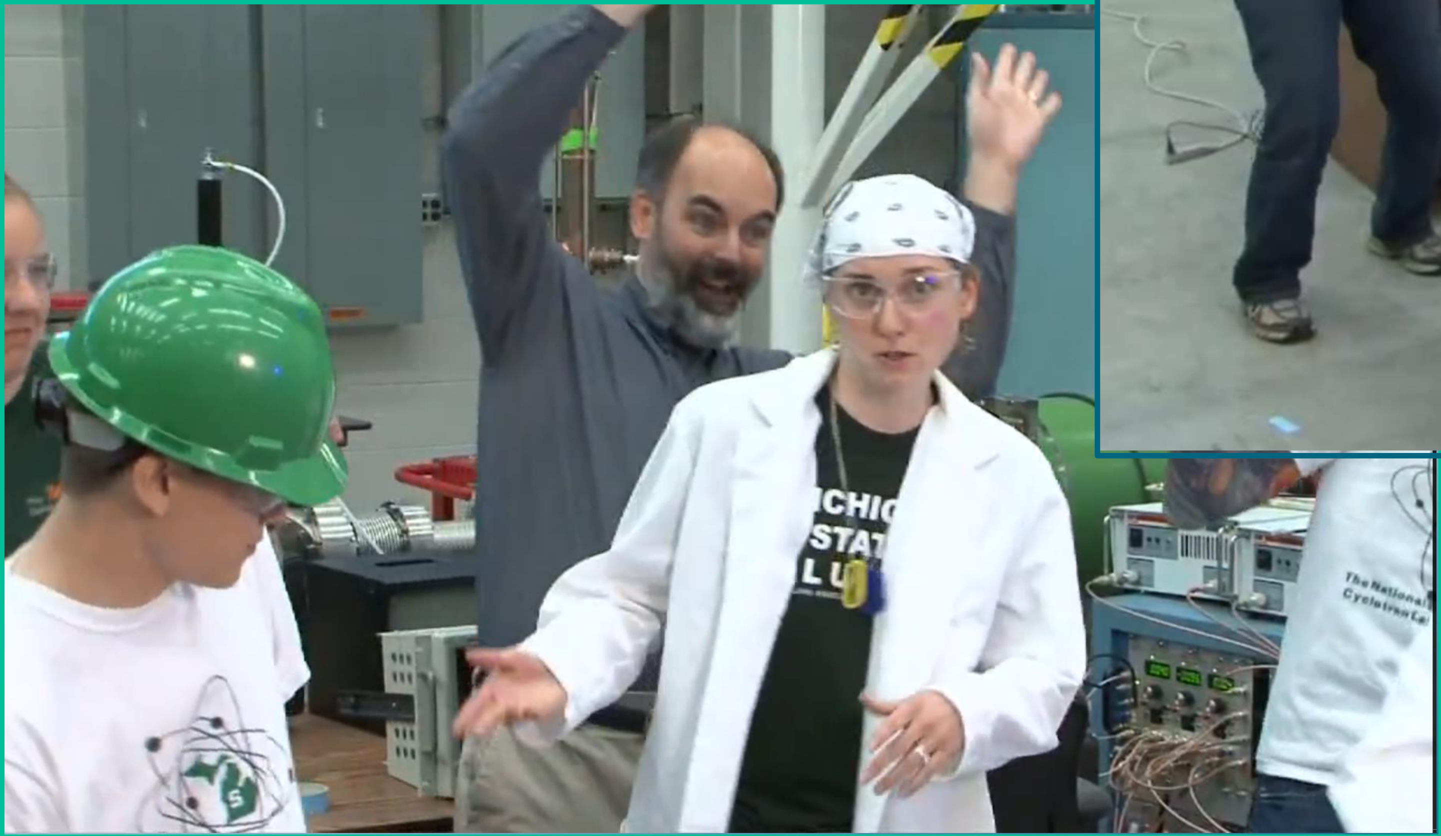
Gamma Information

Nucleus	Elevel(keV)	Jπ	T1/2	Eγ(keV)	Iγ	γ mult.	γ mix. ratio	γ conv. coeff.
206HG	1068.54 10	2+	< 21 ns	1068.54 10	100	E2		
206HG	2102.6 2	5−	2.15 µS 21	1034.01 10	100	E3		

Yes, we did it!

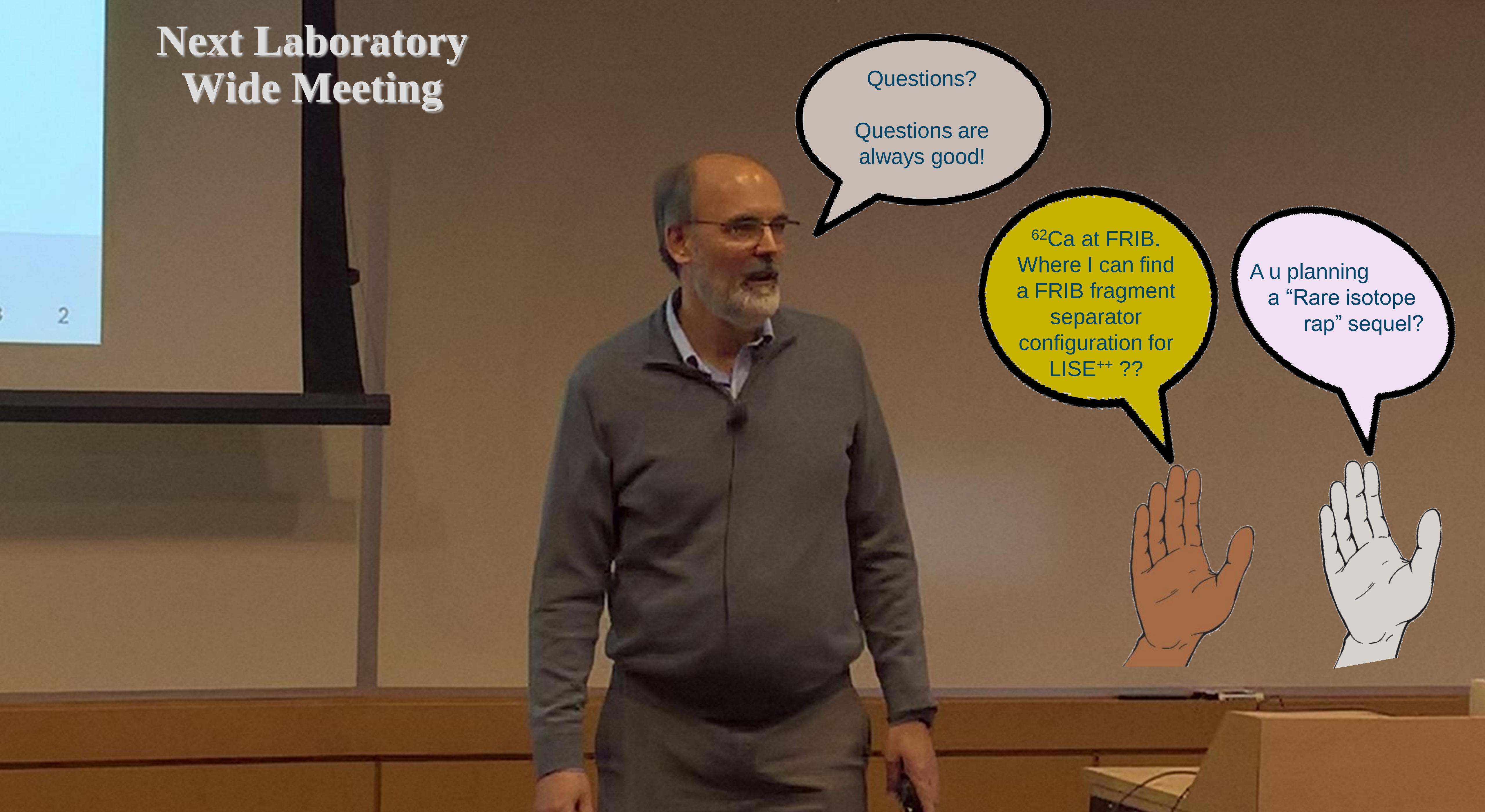
A link on this presentation can be found on the home page of the LISE^{++} site.

There you can also find the “First steps” manual and the detailed course of lectures "Production of Fast Rare Ion Beams”.



Almost finished!

Next Laboratory Wide Meeting



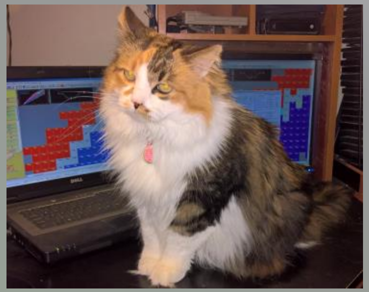
"How to Make Rare Isotope Beams at Home"

Directed by	Oleg Tarasov
Produced by	NSCL/MSU, NSF
Story by	Oleg Tarasov Brad Sherrill
Written by	Oleg Tarasov
Consulted	Brad Sherrill Alexandra Gade

Starring

Brad Sherrill

Cat "Varya"



Production Company	LISE^{++} pictures studio
Distributed by	"FRIB/NSCL Staff Information Talk" group
Release date	April 4, 2018 (United States)
Running time	30 minutes

Images from Rare Isotope Rap by "alpinekat" @ youtube
https://www.youtube.com/watch?v=677ZmPEFIXE were used

The End

Theatrical Release poster