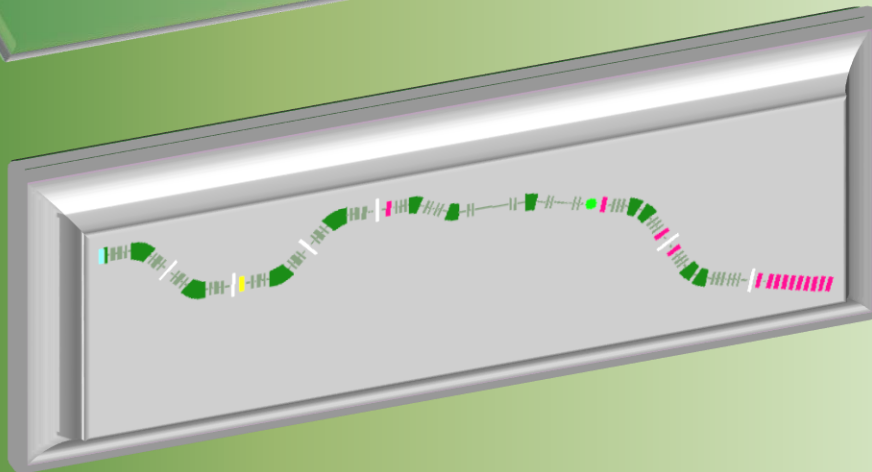


Oleg B. Tarasov  
FRIB / MSU

**LISE<sup>++</sup><sub>cute</sub>**, the latest generation of the  
**LISE<sup>++</sup>** package, to simulate rare isotope  
production with fragment-separators

The 19th International Conference on Electromagnetic  
Isotope Separators and Related Topics

LISE<sup>++</sup>



LISE<sup>++</sup>



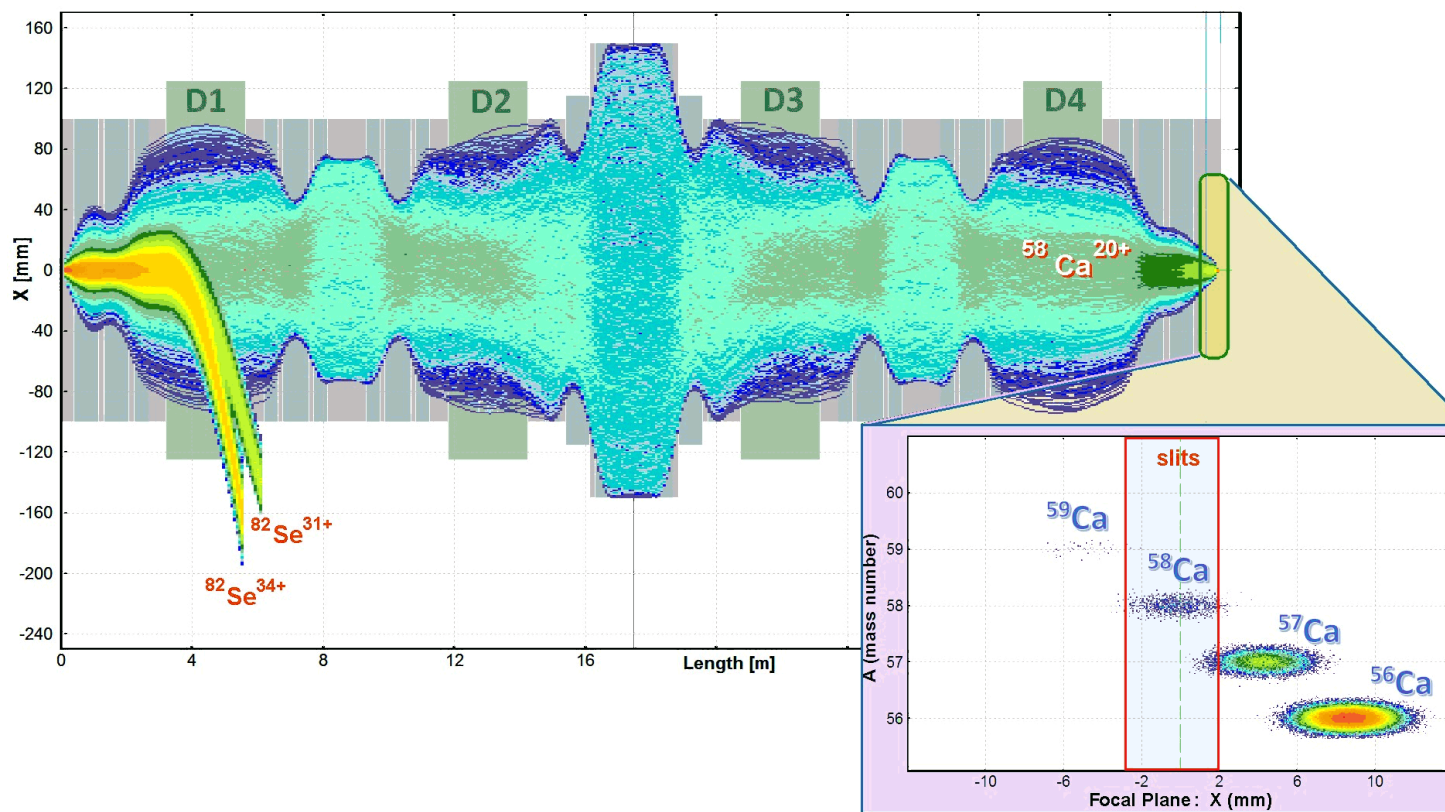
1. Rare Isotope Beam Production with Fragment Separators
2. LISE package transportation
3. New features
4. New code implementation
5. Reaction mechanism models development updates
6. Summary, transportation team

- The program LISE<sup>++</sup> is designed to predict the intensity and purity of rare isotope beams (RIB) produced by In-flight separators
- The program is constantly expanding and evolving from the feedback of its users around the world
- Many “satellite” tools have been incorporated into the LISE<sup>++</sup> framework
- It can be freely downloaded from the following internet addresses:  
<http://lise.nslc.msu.edu>



- predict the fragment separator settings necessary to obtain a specific RIB
- predict the intensity and purity of the chosen RIB
- simulate identification plots for on-line comparison
- provide a highly user-friendly graphical environment

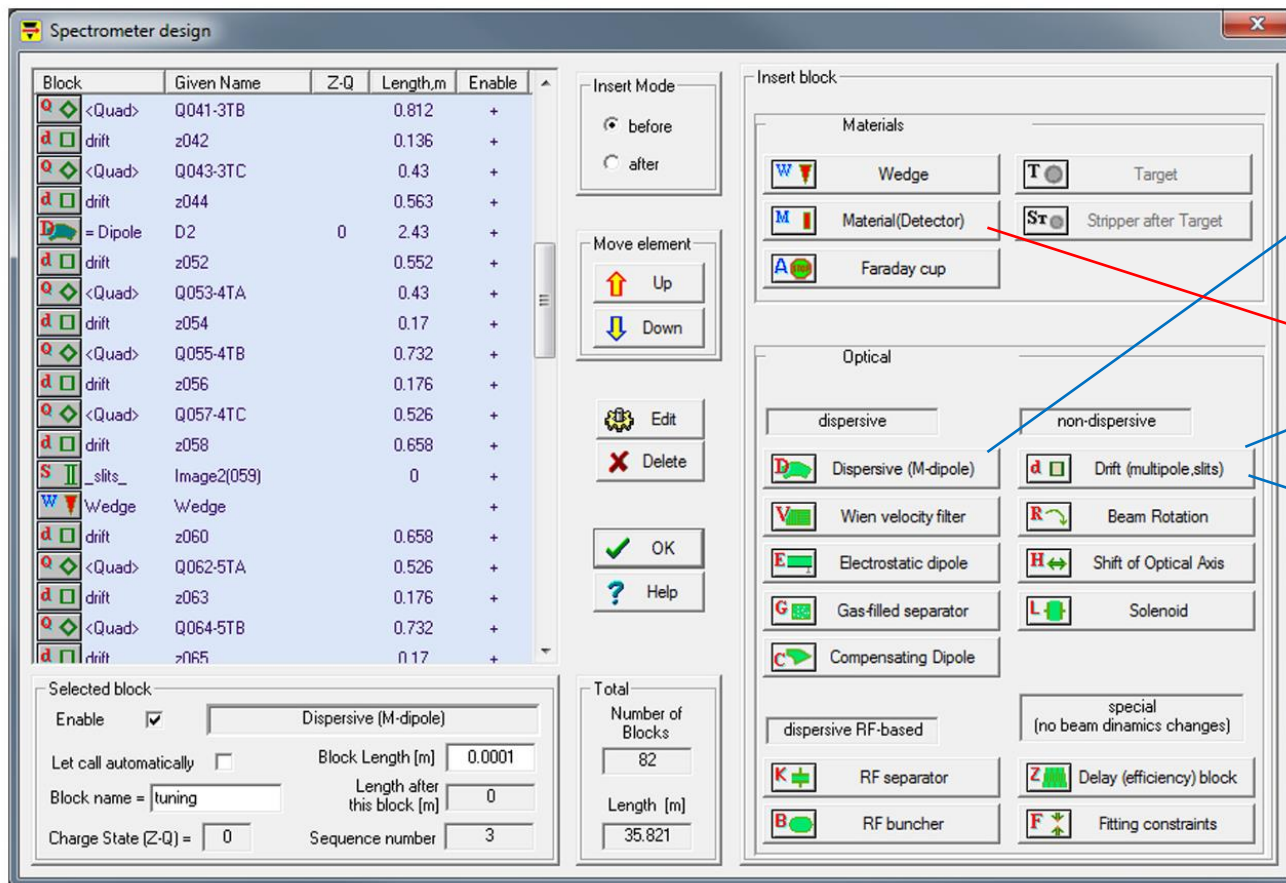
X-envelope  
 $^{82}\text{Se} \rightarrow ^{58}\text{Ca}$  @ A1900



“wedge” selection



- 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.

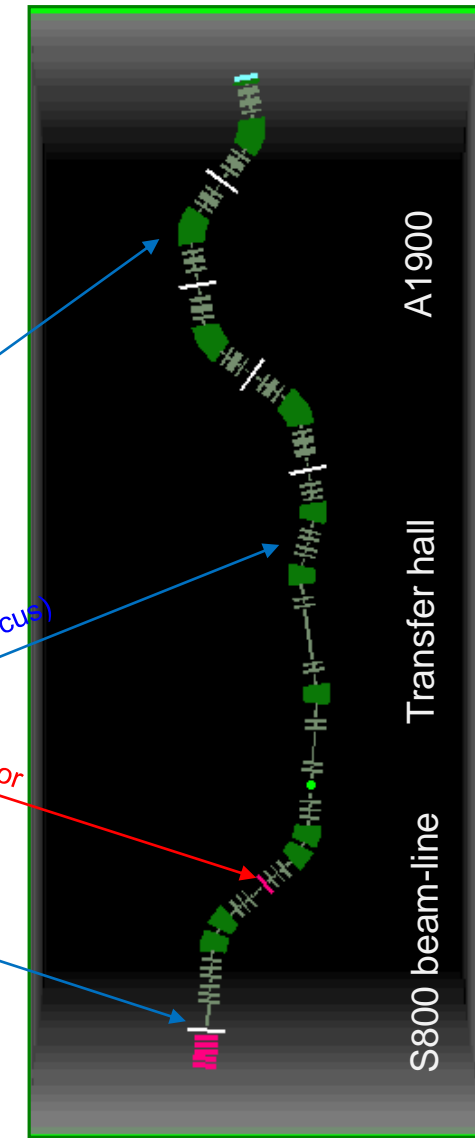


Magnetic dipole (to bend)

Magnetic quadrupole (to focus)

Detector

Slits (to select)



Configuration: A1900\_S800BL (2nd order) 164 blocks

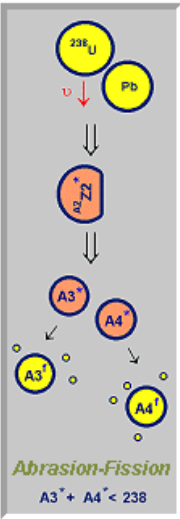
Fig. 1. Updated view of the "Spectrometer Design" dialog window.

- Not only using classical reaction mechanism models, but actively developing fast and accurate in-house models of rare isotope production
- Includes secondary reactions in target
- Includes fragment production in materials (wedges, detectors)

Production Mechanism

$^{238}\text{U} (163.0 \text{ MeV/u}) + \text{C} \rightarrow ^{78}\text{Ni}$

Reactions Energy Loss, Straggling Charge states Databases: Masses, Isomers



Reactions

Settings  Projectile Fragmentation  additionally calculate yields for the next reactions

Settings  Fusion  $\rightarrow$  Residual

Settings  Fusion  $\rightarrow$  Fission

Settings  Coulomb fission

Settings  Abrasion-Fission

Two Body Reactions

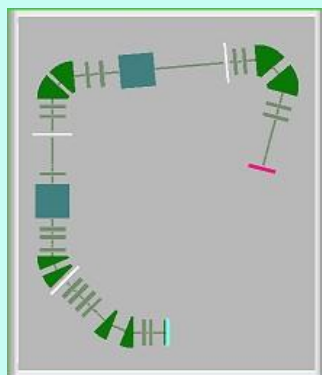
ISOL mode

Make default

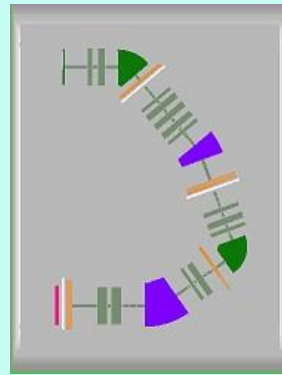
OK Cancel Help

O.B.Tarasov	Analysis of momentum distributions of projectile fragmentation products	NPA 734 (2004) 536-540
O.B.Tarasov, D.Bazin	Development of the program LISE: application to fusion–evaporation	NIM B204 (2003) 174-178
O.B.Tarasov, A.C.C.Villari	Fusion–fission is a new reaction mechanism to produce exotic radioactive beams	NIM B 266 (2008) 4670-4673
O.B.Tarasov	LISE <sup>++</sup> development: application to low-energy fission of projectiles at relativistic energies	ENAM2004: EPJ A25 (2005) 751
O.B.Tarasov	LISE <sup>++</sup> development: Abrasion-Fission	Preprint NSCL MSU, MSUCL-1300, 09.2005

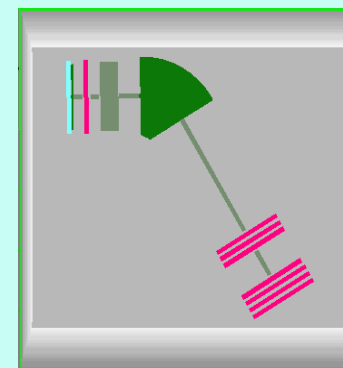
The LISE++ code may be applied at low, medium, and high-energy facilities (fragment- and recoil-separators with electrostatic and/or magnetic selections)



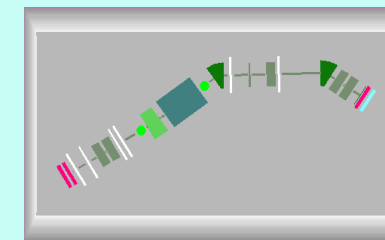
SECAR, MSU



DRAGON, Canada

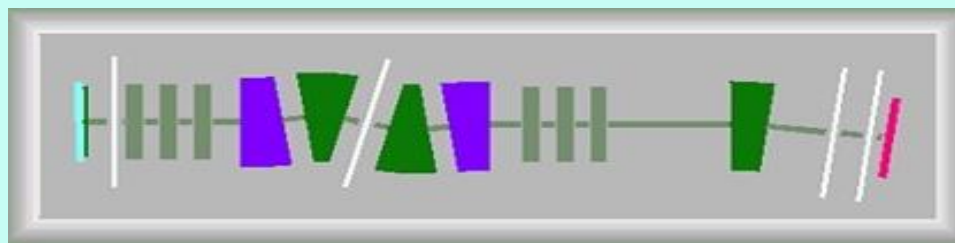


PRISMA, Italy

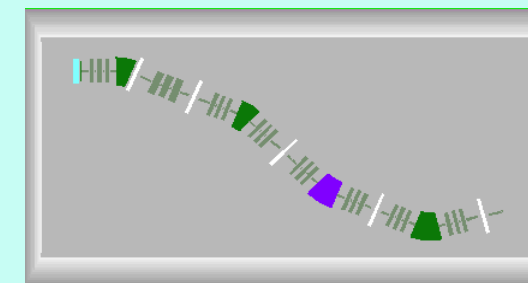


MARS, TAMU, USA

The LISE++ package includes configuration files for most of the existing fragment and recoil separators



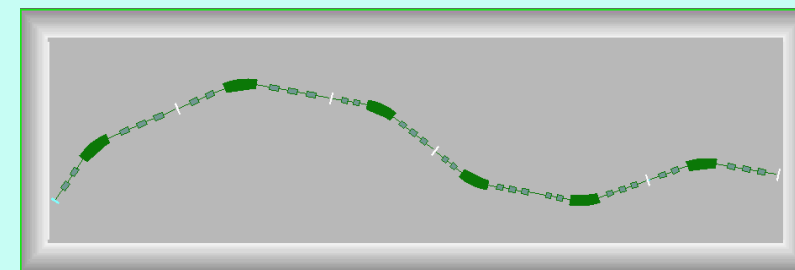
SHELS, Russia



S<sup>3</sup>, France



BigRIPS+ZeroDegree, Japan



SuperFRS\_HEB, Germany

Besides analytical calculation of the transmission and yields of fragments

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

#### LISE<sup>++</sup> calculators:

- "Physical Calculator",
- "Relativistic Kinematics Calculator",
- "Evaporation Calculator",
- "Radiation Residue Calculator" (*new*),
- "Ion Mass calculator" (*new*),
- "Matrix calculator"
- "Initial Fissile Nuclei analyzer" (*new*)

#### Implemented codes:

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

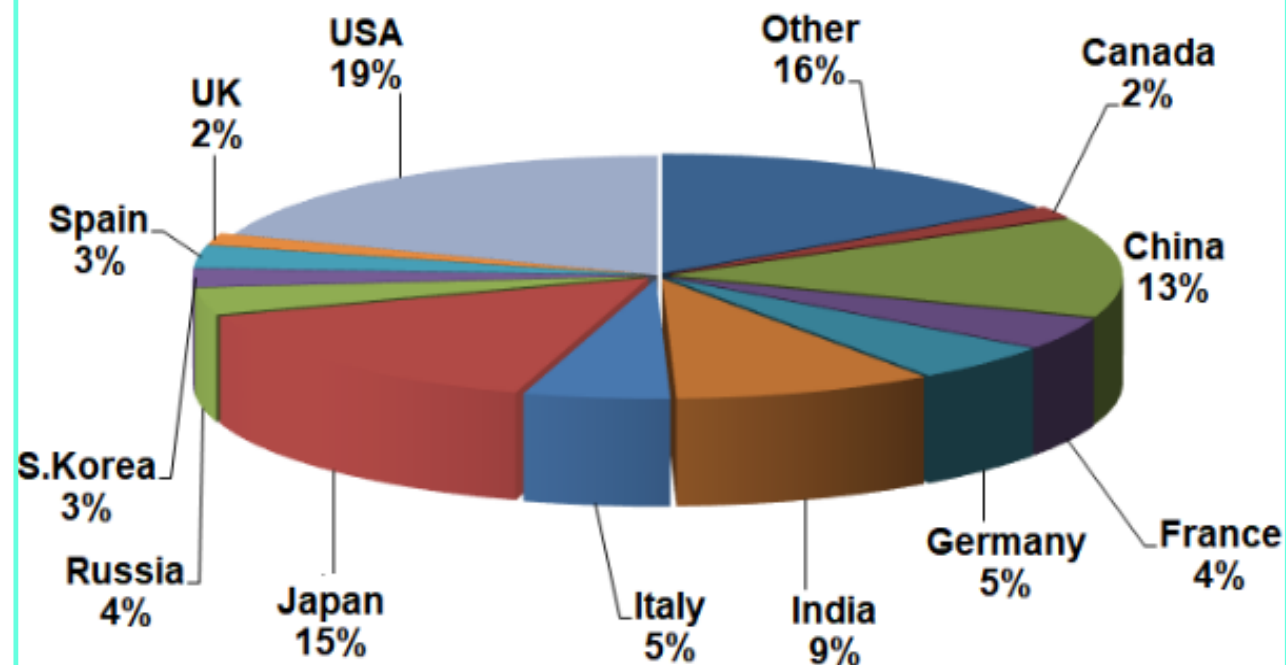
#### LISE<sup>++</sup> Utilities:

- 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)

The LISE<sup>++</sup> code geography (2021 year)

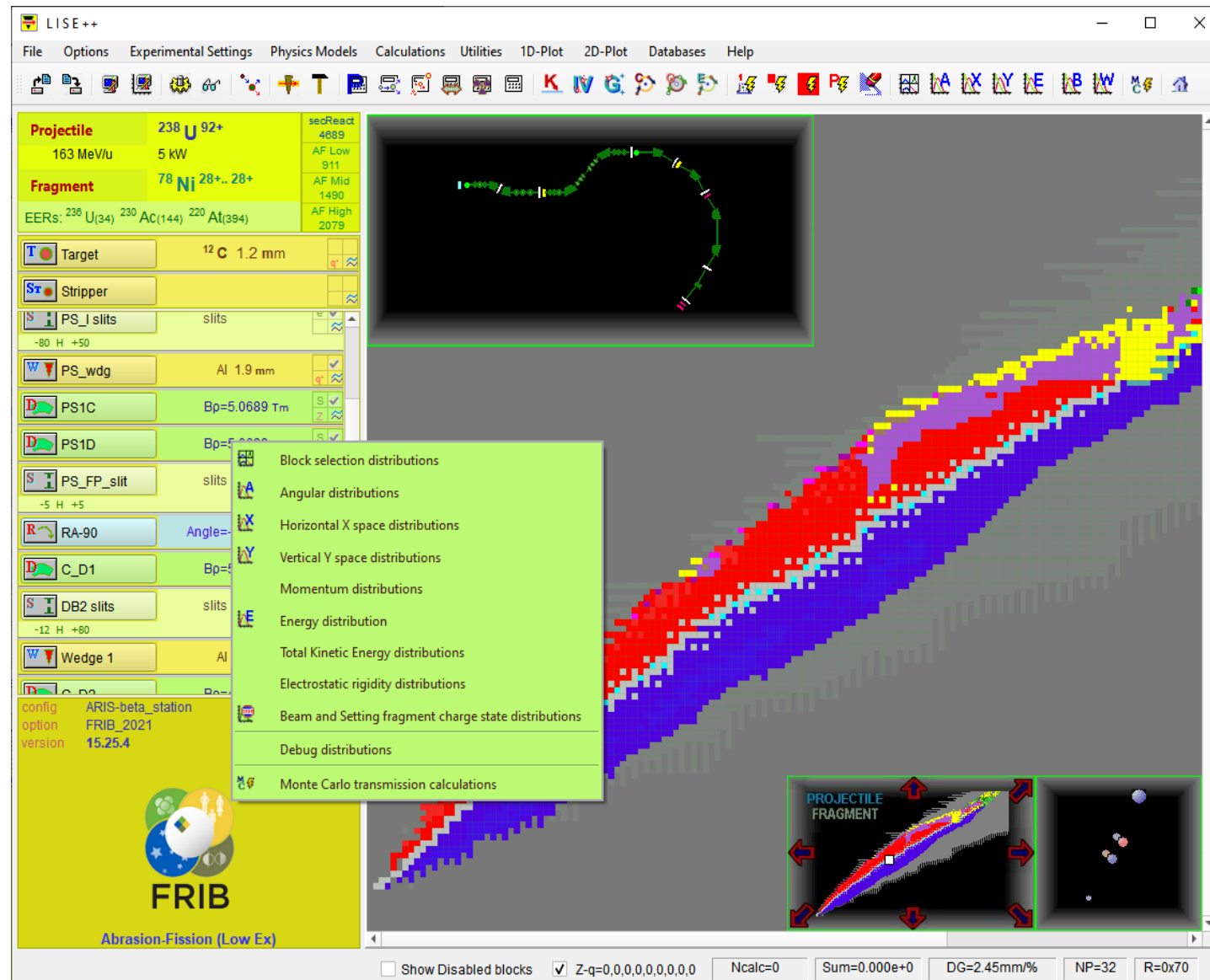


PORTING: 03/20 – 11/21

*COVID19: No bad without good...*



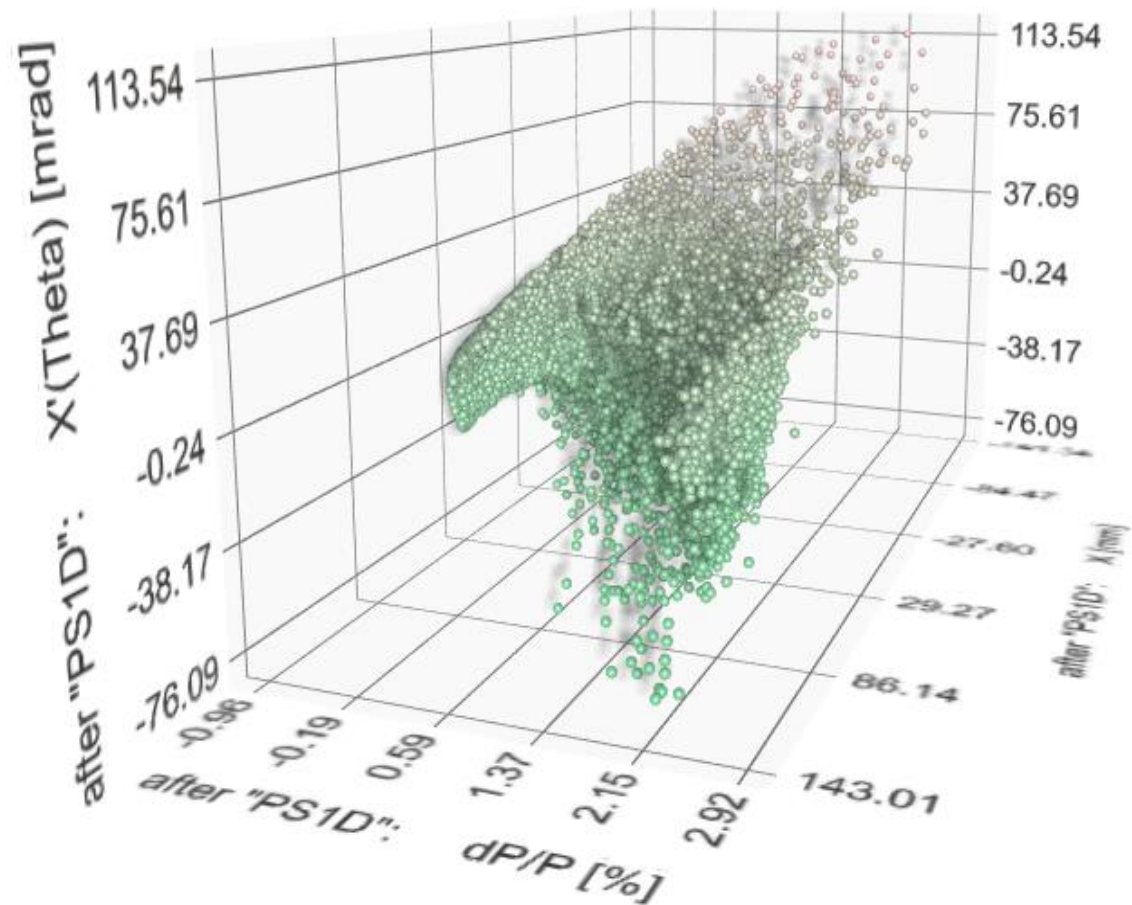
- The LISE<sup>++</sup> code (v.6-13) was developing at Borland C++ 5.02 IDE (integrating development environment), which is not compatible with the next Borland (Builder, Embarcadero C++) generations
- The LISE<sup>++</sup> software suite was recently ported to Qt-framework in order to
  - Aid in sustainability of the code
  - Support modern compilers and computing methods:
    - ✓ 64-bit operation
    - ✓ cross-platform compatibility (Windows, Mac, and Linux versions)
    - ✓ the ability to take advantage of computational progress (for example parallel computing methods)
    - ✓ integration with control systems



LISE<sup>++</sup> version (currently 16.7), created using the Qt framework, is named LISE<sub>cute</sub><sup>++</sup> to indicate a new generation different from the previous Borland-based versions.

X-X'-dP/P  
in ARIS preseparator  
focal plane

53Ar : Monte Carlo Transmission Plot

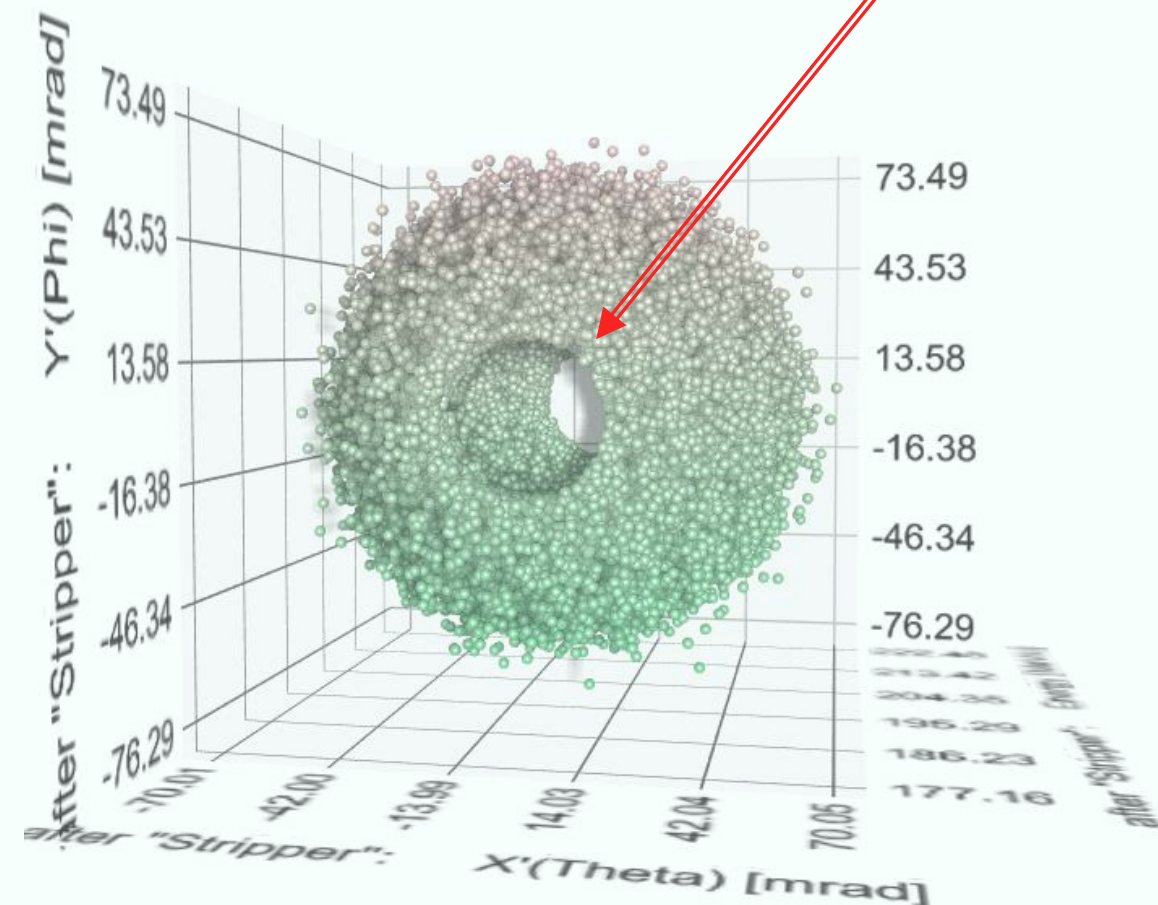


Projectile 238 U 92+  
200 MeV/u 1 pA  
Fragment 132 Sn 50+.. 50+  
EERs: 237 U(34) 232 Th(108) 222 Rn(394)  
Target 12 C 0.01 g/cm<sup>2</sup>

X'-Y'-E  
after target  
using the angle gate

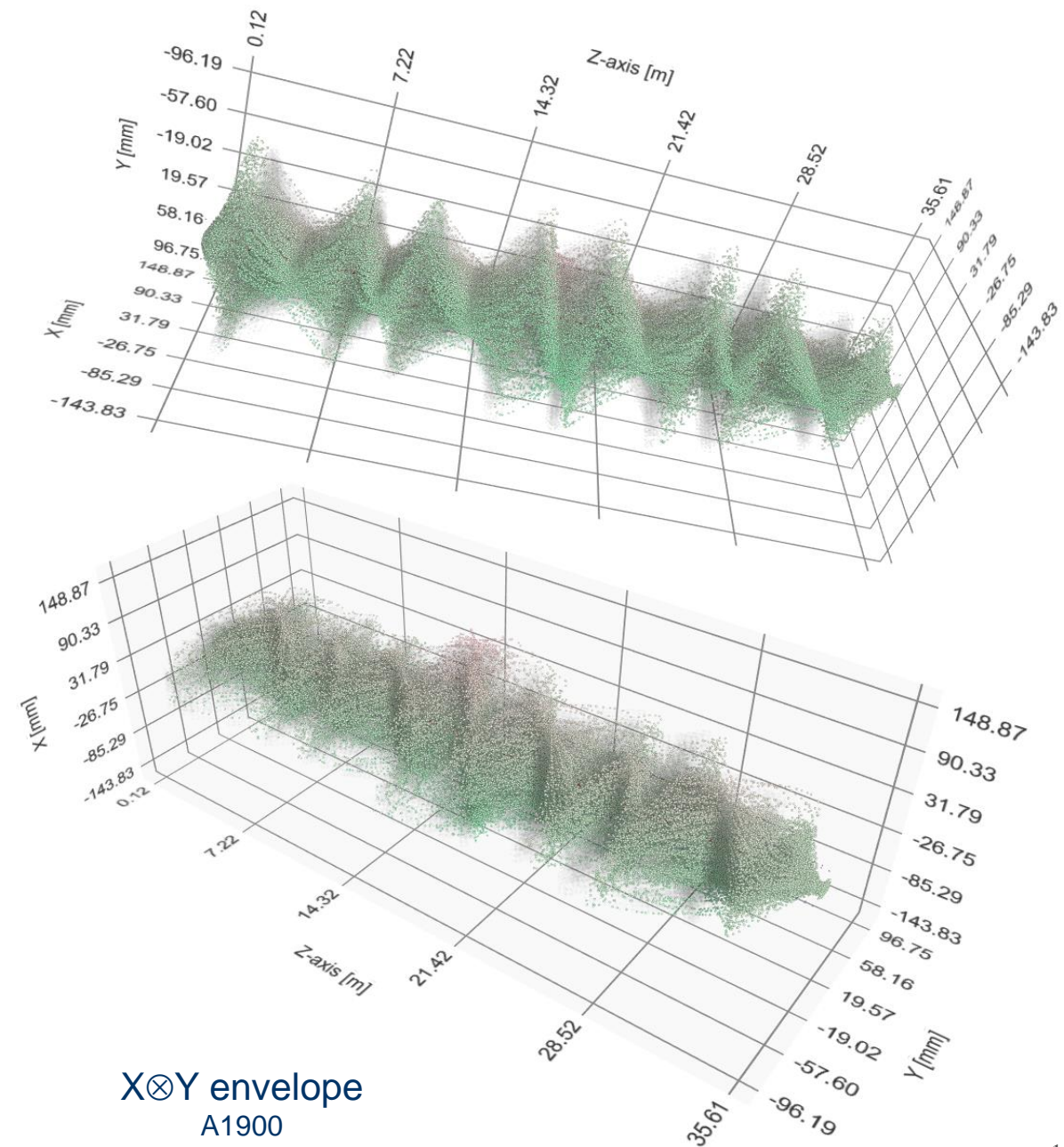
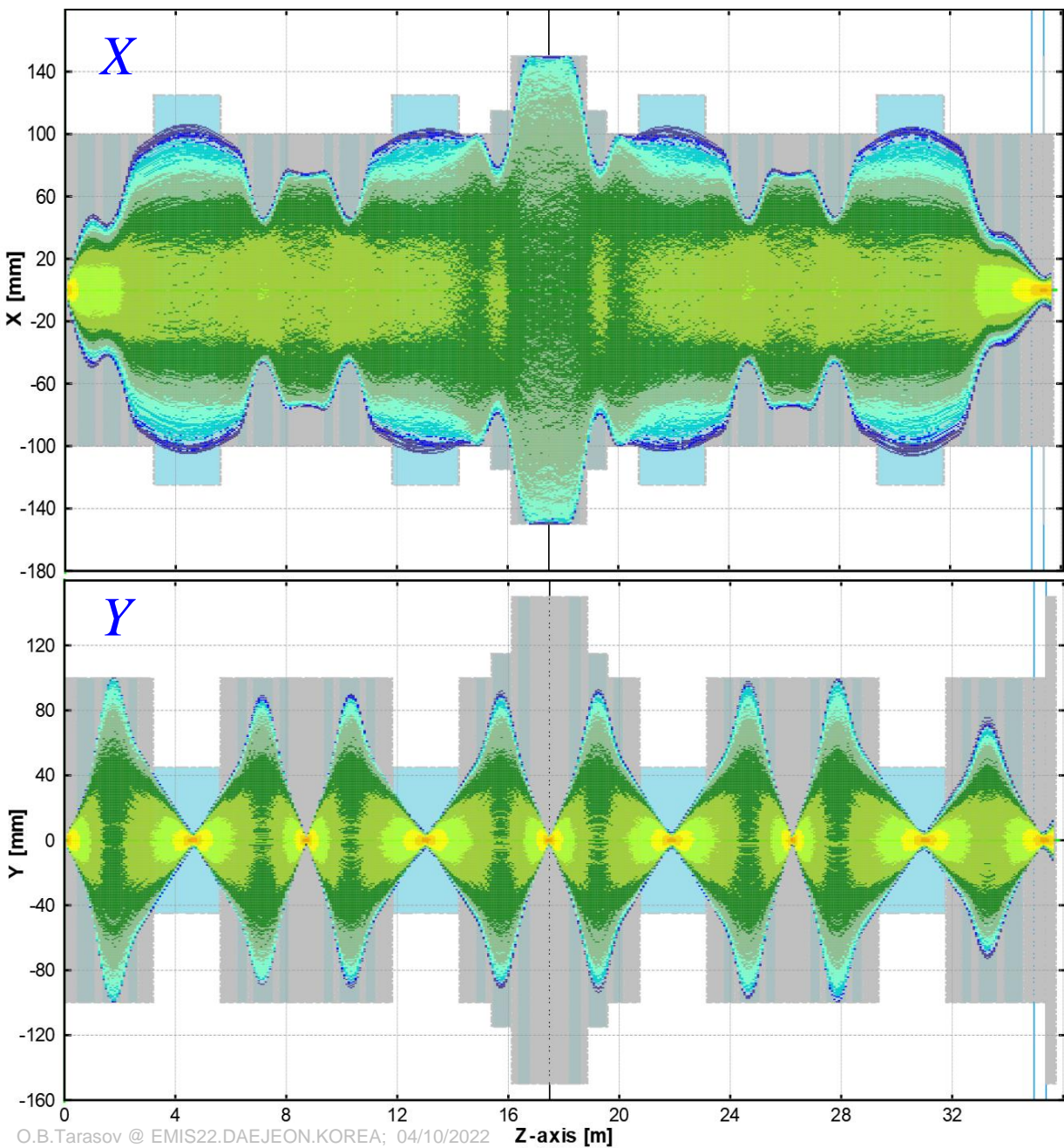
Fission products  
in 3-D

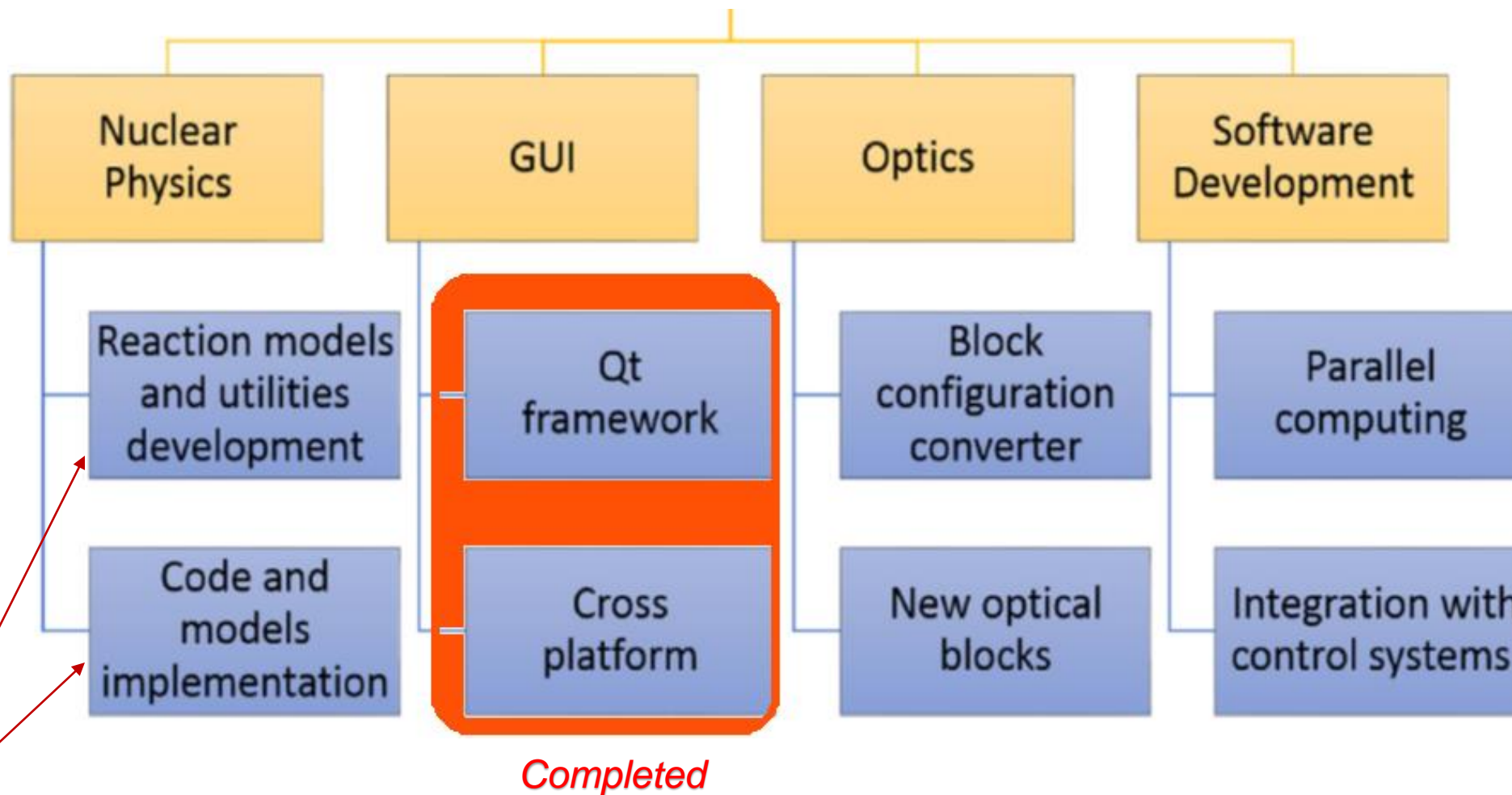
132Sn : Monte Carlo Transmission Plot





# 3-D Monte Carlo Envelope Plots





*Next Slides*

**Fig.** A schematic diagram of the LISE<sup>++</sup> development plans.

*M.P. Kuchera et al./Nuclear Instruments and Methods in Physics Research B 376 (2016) 168–170*



We are very grateful to Dr. Toshiyuki Sumikama (RIKEN) for the fast and quality analysis of bug locations during the porting process

## About "ETACHA"

# ETACHA

### calculating charge state distributions

E.Lamour, P.D.Fainstein, M.Galassi, C.Prigent, C.A.Ramirez, R.D.Rivarola, J.-P.Rozet, M.Trassinelli, and D.Vernhet

PHYSICAL REVIEW A 92, 042703 (2015)

**Version 4.4.3**  
**30-SEP-2021**

This program has been converted to C++ and ported to MS Windows GUI by O.B.Tarasov (NSCL/MSU) with the framework of the LISE++ program.

This program has been made into a cross-platform application in the Qt framework by K.V. Tarasova

The GUI-version is currently maintained by O.B. Tarasov

ETACHA [www.insp.jussieu.fr/ETACHA4-a-code-to-predict-the.html](http://www.insp.jussieu.fr/ETACHA4-a-code-to-predict-the.html)

LISE++ <http://lise.nslc.msu.edu>

ETACHA4 - eUntitled

File Execute Help

**Projectile**

A	Element	Z	Q
207	Pb	82	64

Energy (MeV/u): Initial 28.9, Final 28.162  
Stopping power (MeV/mg/cm<sup>2</sup>): 75.905, 76.772

Last orbital of:  
Neutral atom = 6 p 2  
Ion in ground state = 3 p 6

Use Energy Loss Calculations

**Version**

- v.23 Y(1s,2s,2p),Y(3s),Y(3p),Y(3d)
- v.3 + Y(12,3) *fast, for high E*
- v.3.4 + Y(4) *do not use*
- v.4 + Y(123, 4) *default*
- v.4.5 + Y(5) *beta*

**Target**

A	Element	Z
12	C	6

1,004e+20 atoms/cm<sup>2</sup>  
Thickness = 2 mg/cm<sup>2</sup>  
Density = 2.26 g/cm<sup>3</sup>

**Integration model**

- ODE ISBN: 0716704617 (ordinary differential equation solver)
- RKF45 (Runge-Kutta-Fehlberg ODE solver)
- Euler's method

**Steps & Numerical uncertainties**

Absolute = 1.00e-12  
Relative = 1.00e-5  
Minimum step = 1 μg/cm<sup>2</sup>  
Maximum step = 200 μg/cm<sup>2</sup>

**Reaction characteristics**

perturbation Kp (n=1) = 0.18  
parameter Kp (n=3) = 0.02  
projectile velocity Vp = 33.364 au

**Corrections for PWBA (parameter "lbin")**

- 0: empirical saturation correction (default)
- 1: binding correction included (not recommended)
- 2: no empirical correction and no binding correction

**Show Results**

Event Logs

- Intermediate output of cross sections
- Debug mode
- Plots

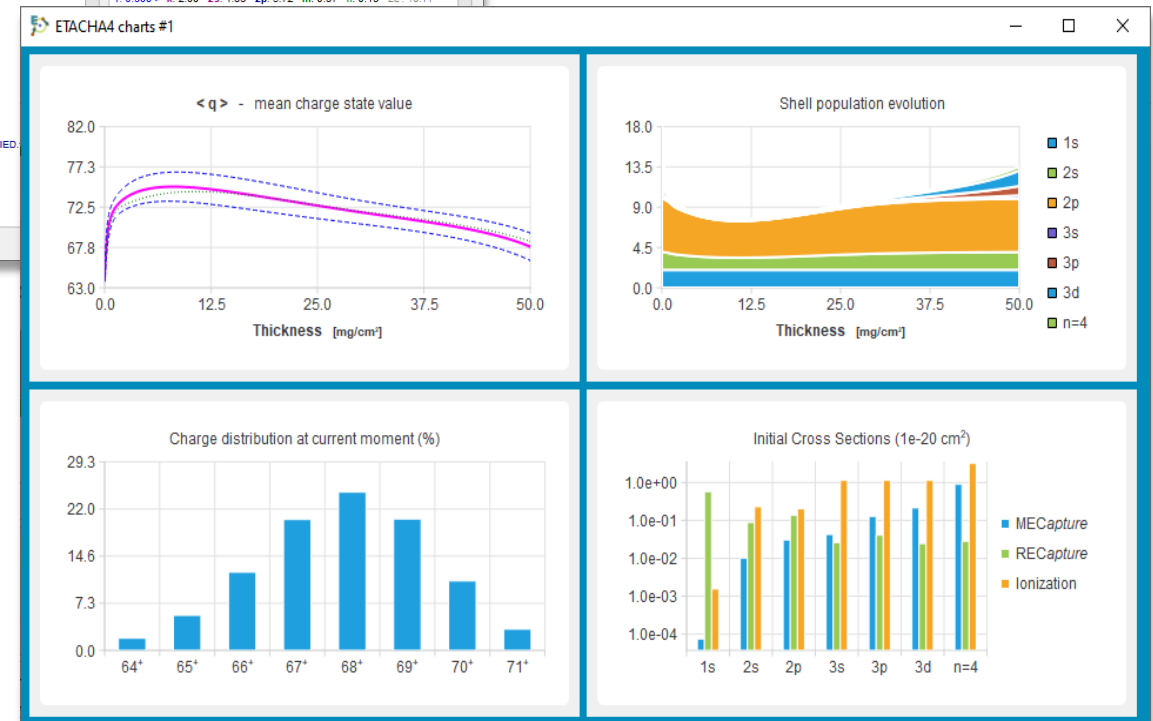
Finished at 02:00:16  
Elapsed time is 00:00:27 (or 27 863 sec)

Final energy : 28.162 (MeV/u)

output data in files:  
00 to 09 EE- charge states in C:/Users/taras/Documents/LISEoute/results/e/Untitled\_Eta0009.bt  
10 to 19 EE- charge states in C:/Users/taras/Documents/LISEoute/results/e/Untitled\_Eta1019.bt  
20 to 29 EE- charge states in C:/Users/taras/Documents/LISEoute/results/e/Untitled\_Eta2029.bt  
30 to 39 EE- charge states in C:/Users/taras/Documents/LISEoute/results/e/Untitled\_Eta3039.bt  
40 to 49 EE- charge states in C:/Users/taras/Documents/LISEoute/results/e/Untitled\_Eta4049.bt  
50 to 59 EE- charge states in C:/Users/taras/Documents/LISEoute/results/e/Untitled\_Eta5059.bt  
bare, 1s,2s,2p,1s2,1s2s,1s2p,1s2,2s,1s2+2p ions and sum of these in C:/Users/taras/Documents/LISEoute/results/e/Untitled\_ETAPIED.mean,1s,2s,2p,3s,3p and 3d populations in C:/Users/taras/Documents/LISEoute/results/e/Untitled\_POPMEAN.bt

WARNING! Next calculation will overwrite these files. Consider saving or renaming these results !

FINAL achieved >> T=2.000 mg/cm<sup>2</sup> <Q>=73.264 dQ=1.303 E=28.162 dSum=0.000



ETACHA cross sections

Capture and ionization				Excitation								
(sub) shell	MEC (capture)	REC (capture)	ionization	From / To	2s	2p	3s	3p	3d	n=4		
1	1s	7.4753e-5	5.7628e-1	1.5660e-3	1	1s	3.4723e-3	5.9665e-3	5.6845e-4	8.6390e-4	7.3594e-5	5.1577e-4
2	2s	1.0215e-2	8.8511e-2	2.2976e-1	2	2s		6.8601e+0	1.3095e-1	1.2979e-1	4.7504e-1	1.3828e-1
3	2p	3.0644e-2	1.3817e-1	2.0481e-1	3	2p		1.4638e-2	1.5797e-1	5.8280e-1	1.3981e-1	
4	3s	4.2868e-2	2.6225e-2	1.1414e+0	4	3s			2.5257e+1		4.4038e+0	
5	3p	1.2860e-1	4.0938e-2	1.1414e+0	5	3p				1.1368e+1	4.8968e+0	
6	3d	2.1434e-1	2.4563e-2	1.1414e+0	6	3d						6.5730e+0
7	n=4	9.0063e-1	2.8335e-2	3.1926e+0								

Version 4      Ionization: CDW-EIS      Excitation: SE

<sup>209</sup>Pb (28.9MeV/u) + C

Table cells can be edited. All cross sections in 1e-20 cm<sup>2</sup>

Accept      Continue

**About GEMINI++**

**GEMINI++**  
statistical decay code

R. J. Charity

R.J. Charity, Phys. Rev. C 82 (2010) 014610  
D. Mancusi, R. J. Charity, J. Cugnon, Physics Review C 82 (2010) 044610

Version 2.7.3  
12-JUL-2021

GEMINI++ has been ported to a GUI application using Qt within the LISE++ framework by M.P. Kuchera, and updated by O.B. Tarasov  
The GUI-version is currently maintained by O.B. Tarasov

GEMINI++ <http://lise.nscf.msu.edu/gemini.html>  
LISE++ <http://lise.nscf.msu.edu> **LISE++**

**Gemini**

File About

Execute Open Save About

Compound Nucleus Decay Fusion reaction

**Projectile**  
A = 16 N = 8  
Z = 8 <sup>16</sup>O  
ME (MeV) = -4.737

**Target**  
A = 12 N = 6  
Z = 6 <sup>12</sup>C  
ME (MeV) = 0

**Compound**  
A = 28 N = 14  
Z = 14 <sup>28</sup>Si  
ME (MeV) = -21.4928

**Beam Energy**  
Lab Energy (MeV) 160

**Calculation**  
Q<sub>CN</sub> = 16.7558  
E<sub>CM</sub> = 68.5714  
E<sub>x</sub> = 85.3272

**Spin**  
 Input max spin 23  
 Max spin from Bass Model

**Local settings**  
Diffuseness of fusion spin distribution (ħ) 2  
Number of fusion events 500

**Masses**  
 Traditional Gemini  
 AME2016 database

**Evaporation mode**  
 0 = widths (& KE) calculated from Weisskopf, S & L from H.F.  
 1 = Hauser-Feshach formalism (H.F.)  
 2 = Switches between options 0 and 1 depending of the ratio of rotational to thermal energy

**IMF emission**  
 use in calculations  
 enhanced IMF emission

**Gemini**

Save Print

**Gemini**  
Statistical Decay Code

**Starting Conditions**

	Z	N	A	<sup>A</sup> EI
Projectile	8	8	16	<sup>16</sup> O
Target	6	6	12	<sup>12</sup> C
Compound nucleus	14	14	28	<sup>28</sup> Si

Bombarding energy (MeV) 160.00  
Center of Mass energy (MeV) 68.571  
Compound nucleus Excitation energy (MeV) 85.33  
Q-value of reaction (MeV) 16.756  
Compound nucleus recoil energy (MeV) 91.429  
Compound nucleus recoil velocity (cm/ns) 2.512e+00  
Compound nucleus recoil (β) 8.373e-02  
Beam velocity (cm/ns) 4.396e+00  
Beam velocity (β) 1.465e-01

diffuseness 2.00 ħ  
Fusion cross section 655.27 mb  
Bass L 21.02 ħ  
L0 20.85 ħ  
Bass cross section 675.84 mb  
Excitation energy 85.33 MeV  
Critical spin 21.0 ħ

**Fusion Product Summary**

Result	Number
Intermediate Mass Fragments	268
Symmetric Fission	0
Residual Nuclei	232
TOTAL	500

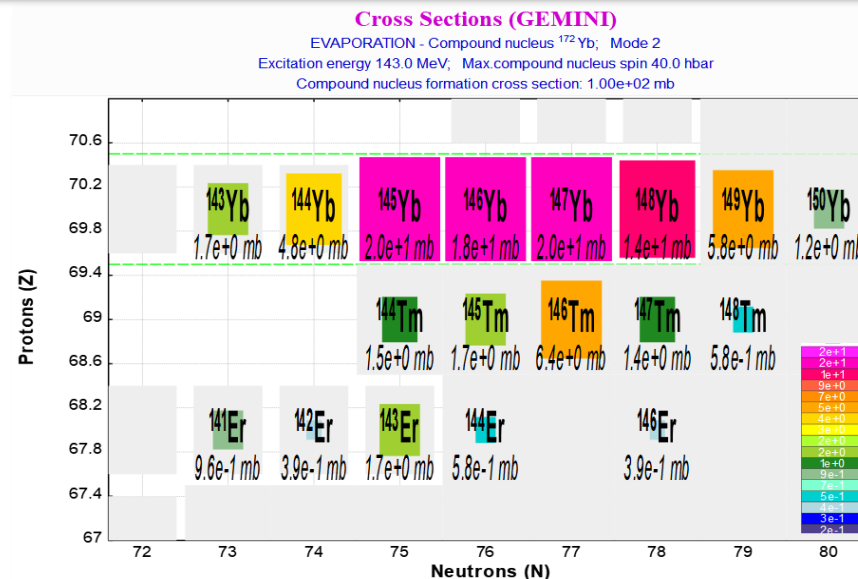
**Yields of Residual Nuclei**

Z	Name	Events	Percent	x-section (mb)	err(mb)
12	<b>24Mg</b>	11	4.7%	31.07	9.368
12	<b>23Mg</b>	28	12.1%	79.08	14.95
12	<b>22Mg</b>	44	19.0%	124.3	18.74

The Gemini++ code was implemented to the LISE++ package after porting to a GUI application using the Qt graphics framework.

The code was updated to use the AME2016 database and to plot calculation results with the LISE++ code.

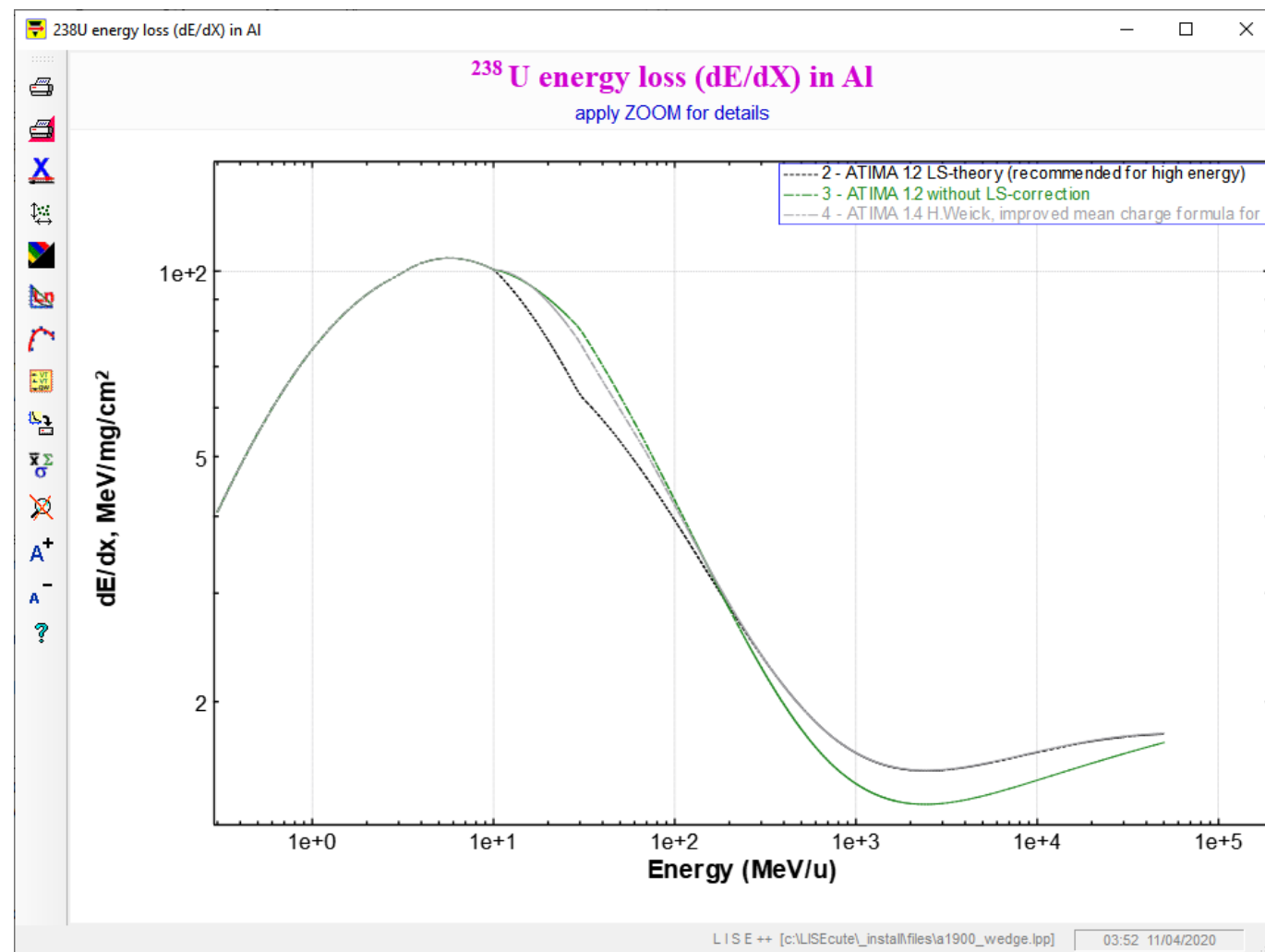
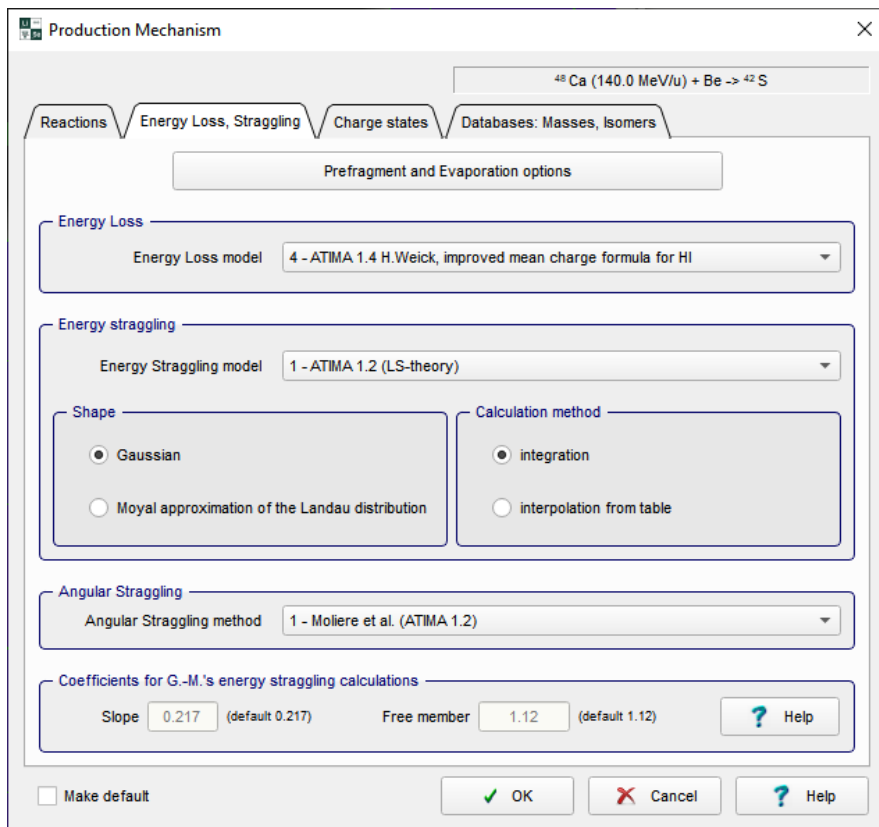
<http://lise.nscf.msu.edu/gemini.html>



## Implementation of ATIMA1.4 (catima1.5)

Complete agreement with ATIMA14  
site results were obtained

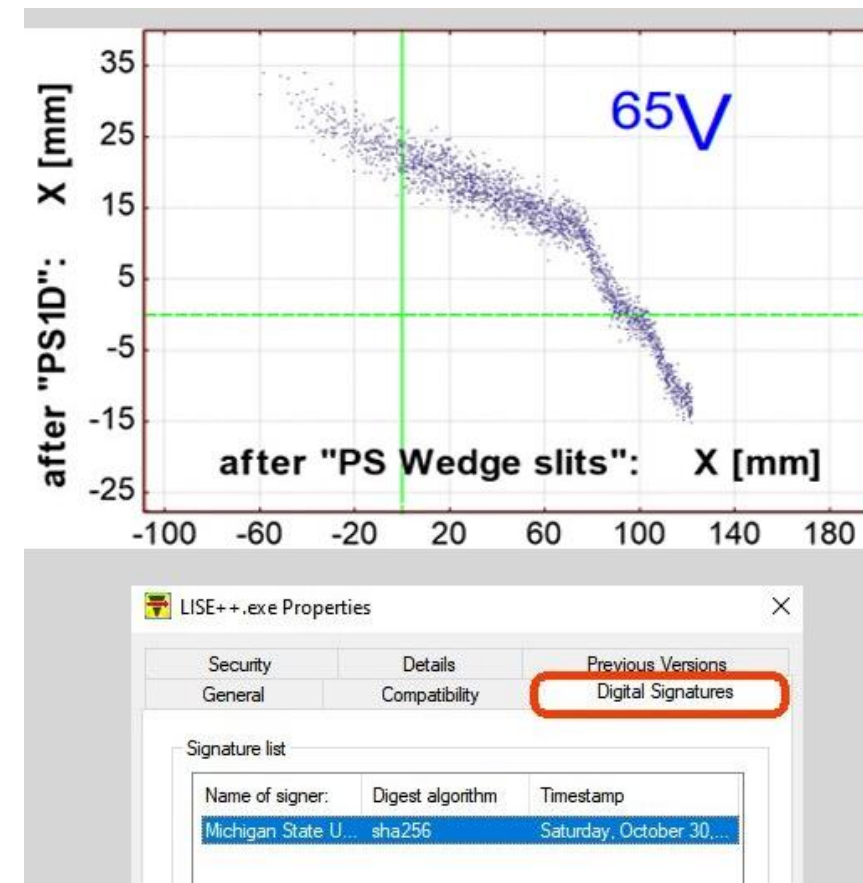
ATIMA 1.4 is set as  
default Energy loss model in version 15



Acknowledgements to Drs. H.Weick and A.Prochazka

ATIMA website: <http://web-docs.gsi.de/~weick/atima/>

- The new utility “Power deposition and rate analysis in blocks”
- The new utility “Beam energy scanning” determines optimal beam energy for current given separator settings
- Shape calculation of two angle wedge to pass neighbors isotopes besides a setting fragment in the case of thick momentum compression degrader
- The LISE package installer on Windows has been signed with the MSU digital certificate, thereby eliminating the “unknown publisher” message
- New LISE<sup>++</sup> file type → FILES LIST (\*.liselst) : set of lise files to compile a final configuration
- Account for material lengths in optics
- Angular straggling contribution to ion optics



*Please find more details of v.16.3-7 updates on the LISE<sup>++</sup> site*



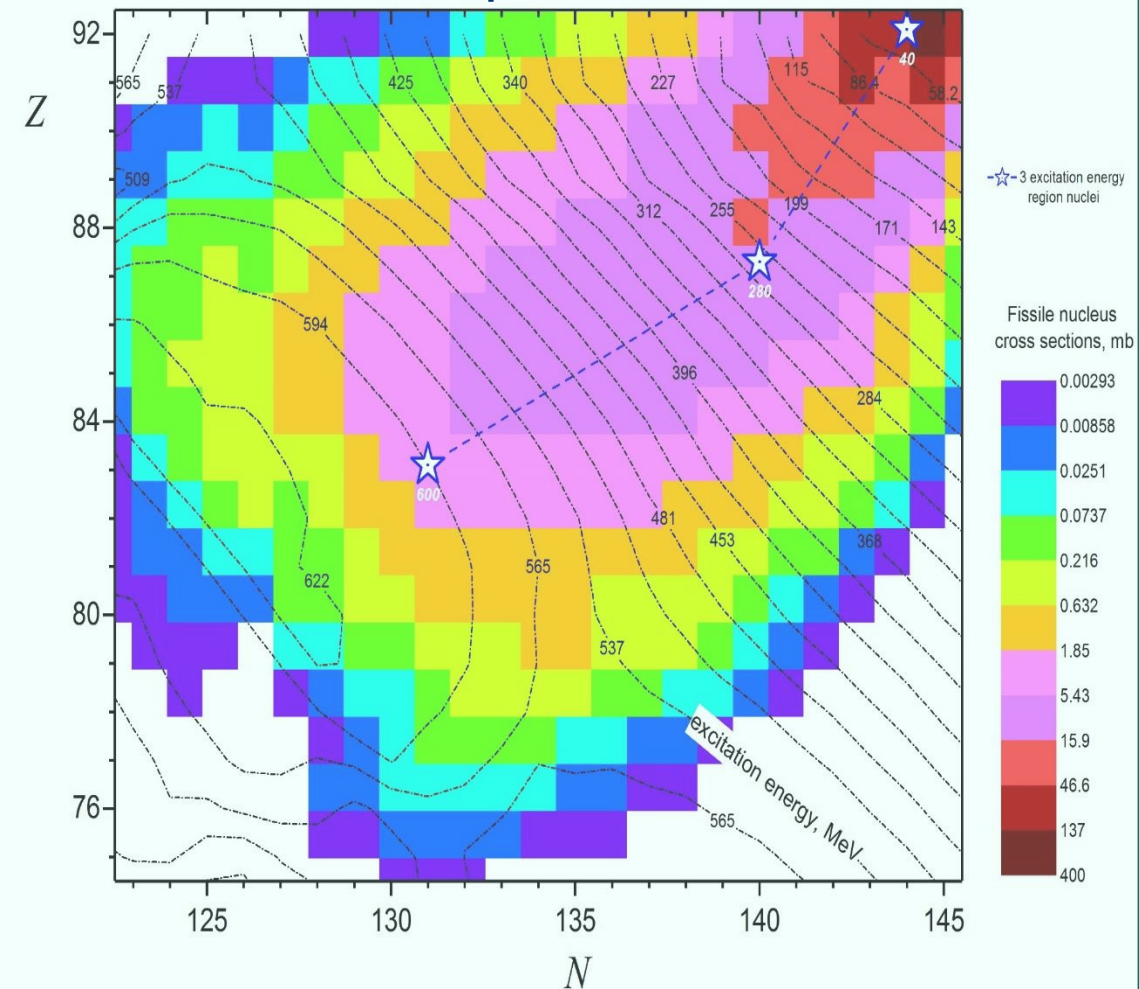
REACTIONS

- ❑ The standard LISE 3EER (excitation energy region) model uses only 3 fissile nuclei to calculate fission fragment cross sections. Fast, but there is a large discrepancy for exotic nuclei production, as it is aimed at obtaining the main fission yield.
- ❑ The new utility, Initial Fissile Nuclei (IFN) Analyzer, calculates the contribution from all possible parent fissile nuclei to the final fission fragment, which allows to calculate
  - fission fragment production cross section,
  - more likely fissile nucleus,
  - fragment velocity in CMS,
  - excitation energy of the initial fission fragment,
  - number of nucleons released to reach the final fission fragment.
- ❑ Knowledge of the parent fissile nuclei helps to choose a reaction to maximize production of the isotope of interest, transmission factor

## Abrasion-Fission 3EER model

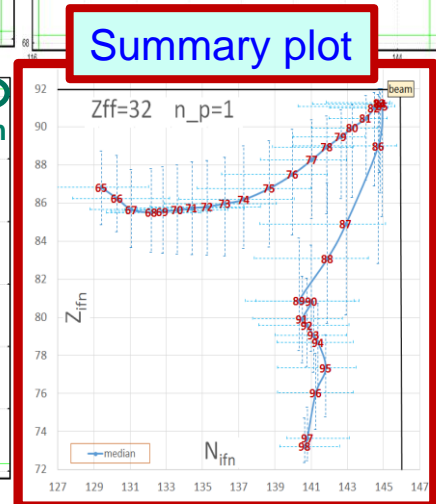
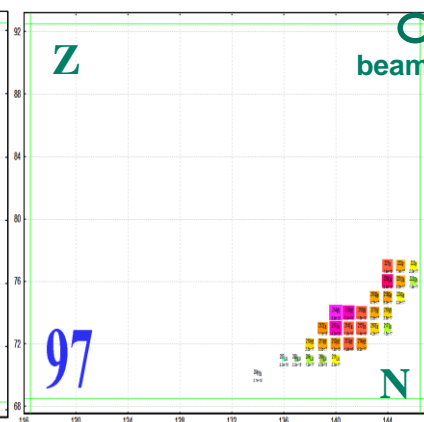
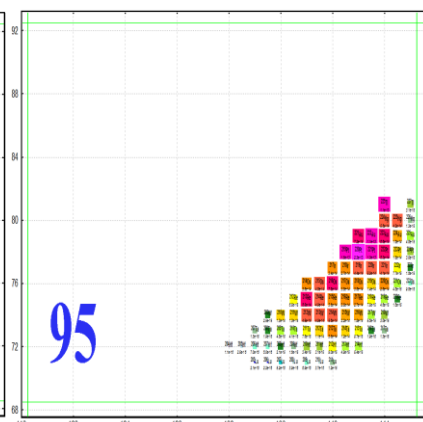
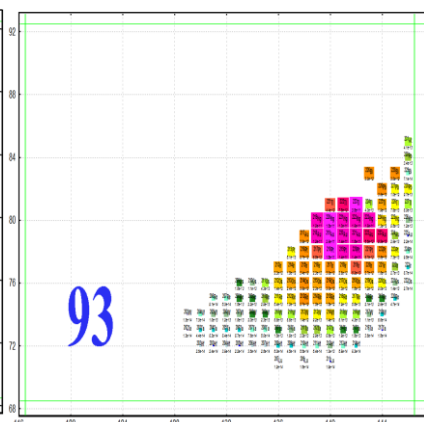
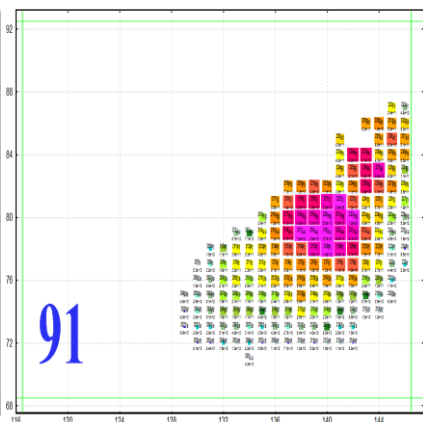
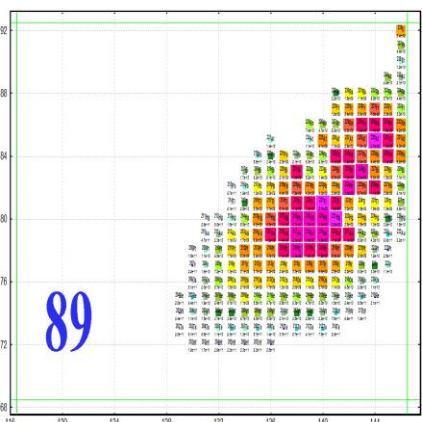
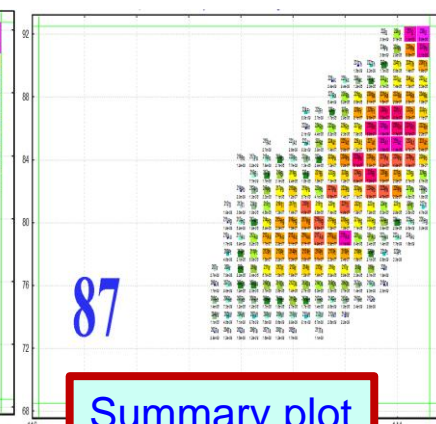
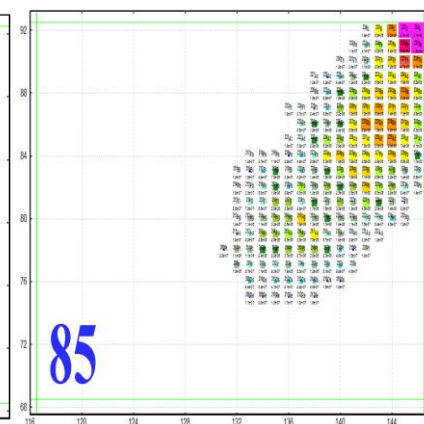
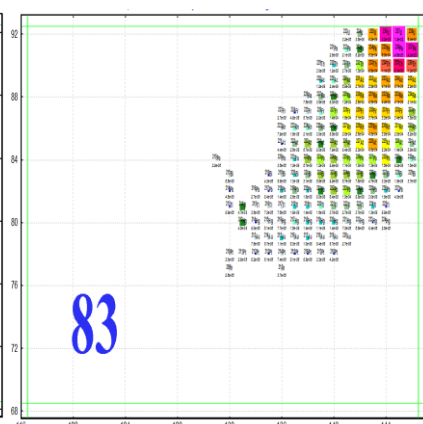
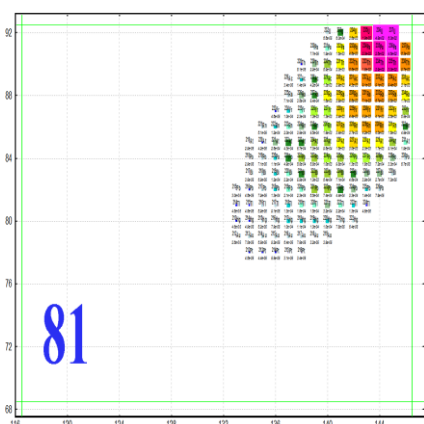
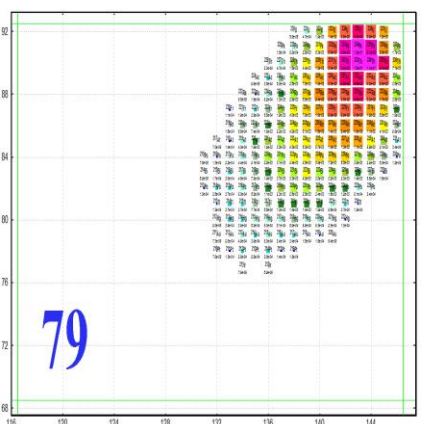
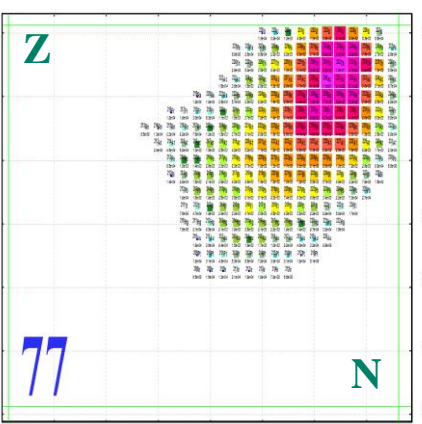
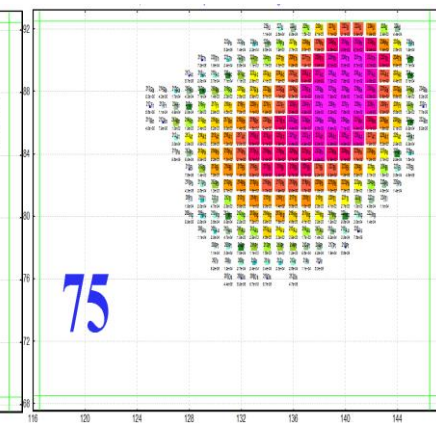
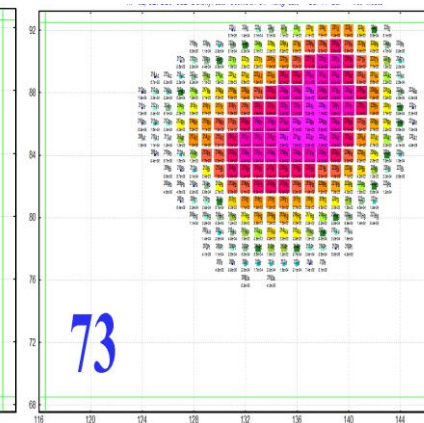
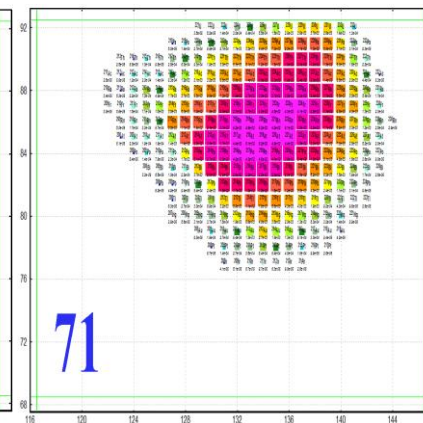
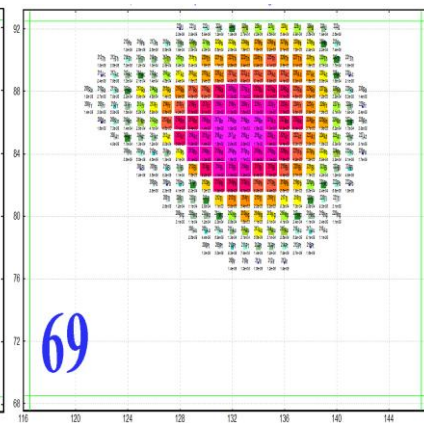
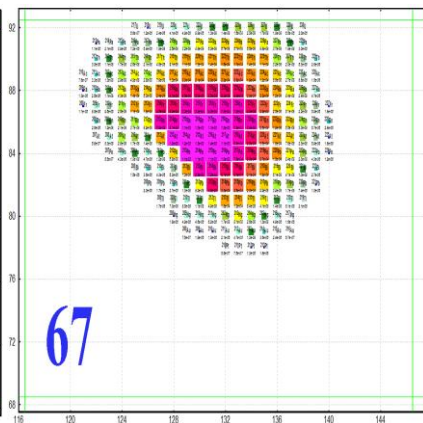
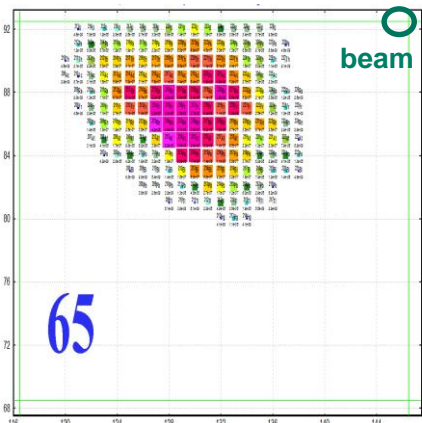
- Fast Analytical model
- Averaging  $\rightarrow$  substitution of more than 1000 fissile nuclei by 3 nucleus

### Fissile nuclei map after abrasion of $^{238}\text{U}$

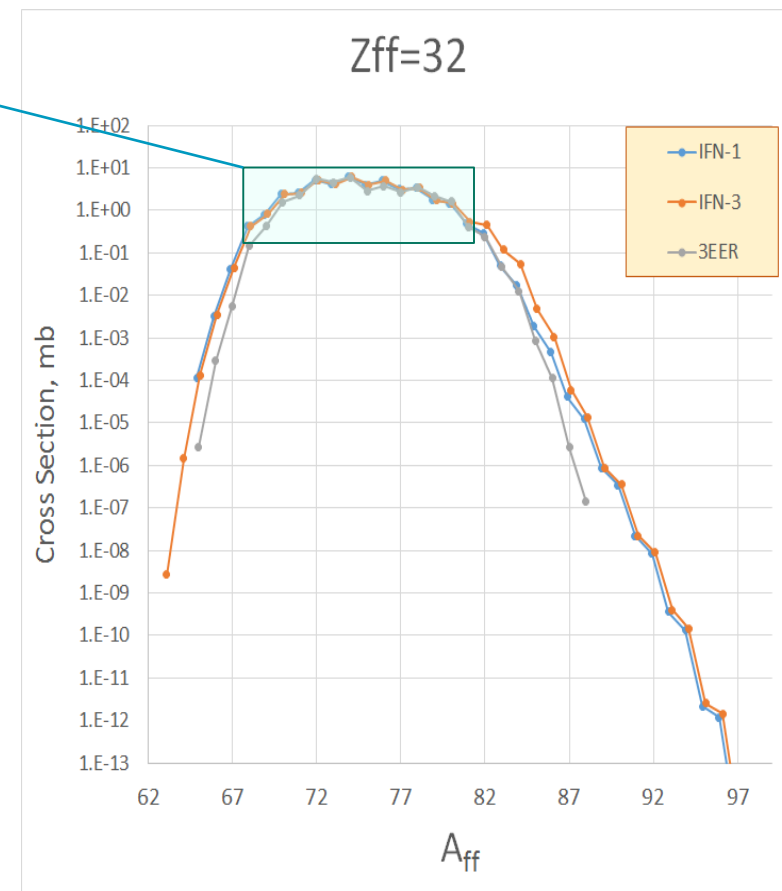
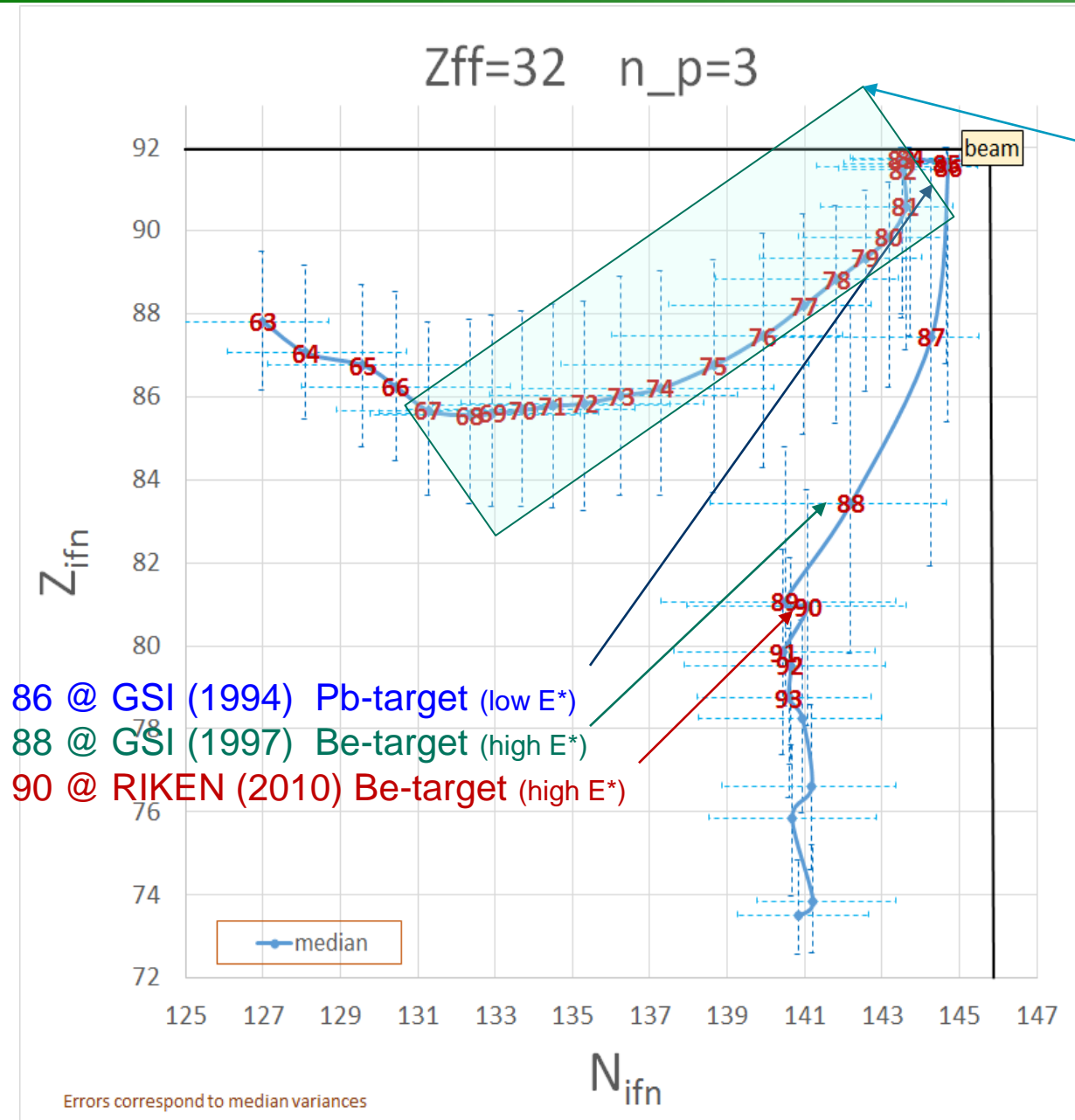




# Initial Fissile Nuclei (IFN) for final Ge-isotopes (Z=32)







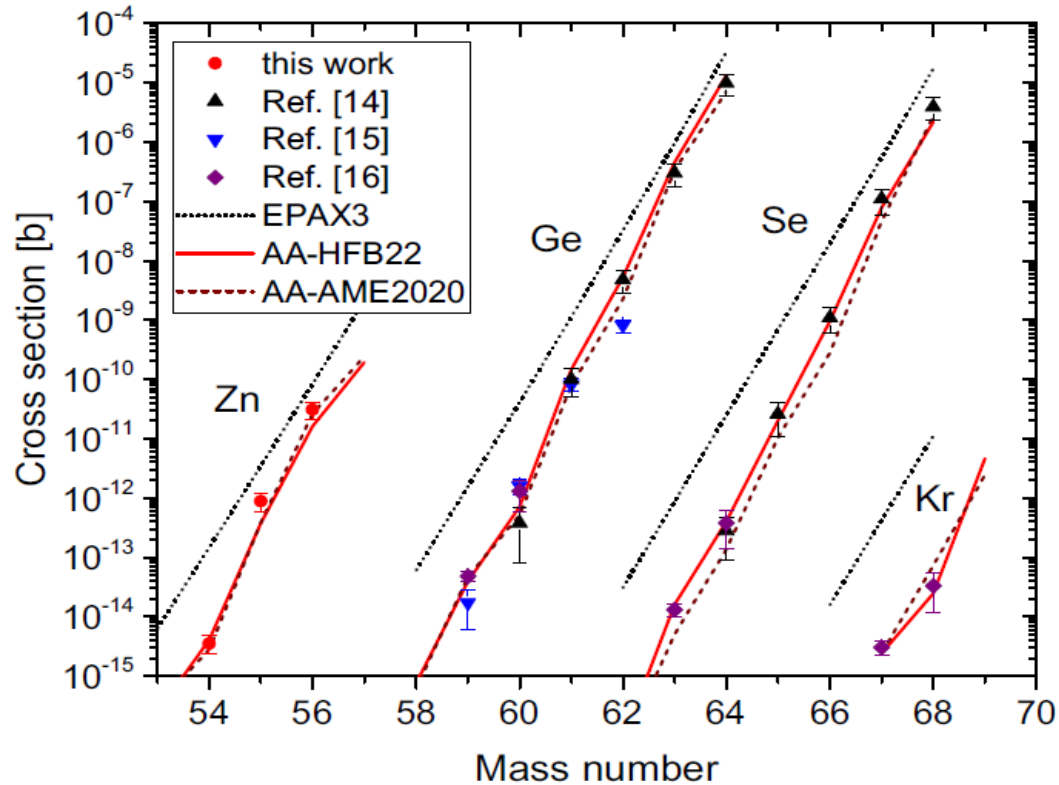
- sensitive to mass models
- Very neutron-rich isotopes produced in high excitation fission of nuclei with  $Z < 82$ .
- Light Z-target should be used to go far



The new minimization utility recently developed in the LISE code allows to deduce Abrasion-Ablation model parameters from comparison of AA-calculation results with experimental cross-sections with selection one from 28 mass models distributed with the LISE<sup>++</sup> suite. The utility is based on the levmar package using the Levenberg-Marquardt nonlinear least square algorithm.

Abrasion-Ablation: <http://lise.nsl.msui.edu/AA.html>

A.Kubiela et al., Phys.Rev.C 104, 064610 (2021)



User Cross-Section analysis using the Abrasion-Ablation model: MINIMIZATION ==> 78Kr\_2n\_ame2016.mfit

This utility can be used if:

- "Projectile Fragmentation" reaction mode is selected
- Abrasion-Ablation is the selected cross-section method
- "File" cross section option is set to "on"
- There are more than 2 user cross-sections in memory for this reaction.

Make items 1-3

Local line to analyze:  Z = 30

Calculate down to Z =

Universal analysis value

Analysis value	X <sup>2</sup>	LoD
Local	3	2
Global	0.5	1

Weights

Analysis value	X <sup>2</sup>	LoD
Local	3	2
Global	0.5	1

Use experimental CS errors in analysis  
 Use Reduced chi-square (divide by "n-p")

if exp error is absent, then error=coef\*CS, where coef is

E\*: quadratic polynomial  
 <E\*> - excitation energy per abraded nucleon (MeV)

0	1	2
0	+ 12.481	+ 0.137

\* d\_abr \* d\_abr<sup>2</sup>

Use in Fitting process

Use Bounds constraints

Lower bound 0 10 -2  
 Upper bound 15 30 2

sigma(E\*): quadratic polynomial  
 Excitation energy std deviation

0	1	2
0	+ 7.014	+ 0.082

\* d\_abr<sup>(1/2)</sup> \* d\_abr

AAX-sections

Amplitude factor	Time Coefficient	Effective Coulomb barrier
0.446	1.65	5.062

Operations

Evaporation Settings

Prefragment excitation energy

Analysis Log-file

78Kr\_2n\_ame2016

Fitting

N iterations =

Plot Product values from the chi2-table

Target value =

N CS points =

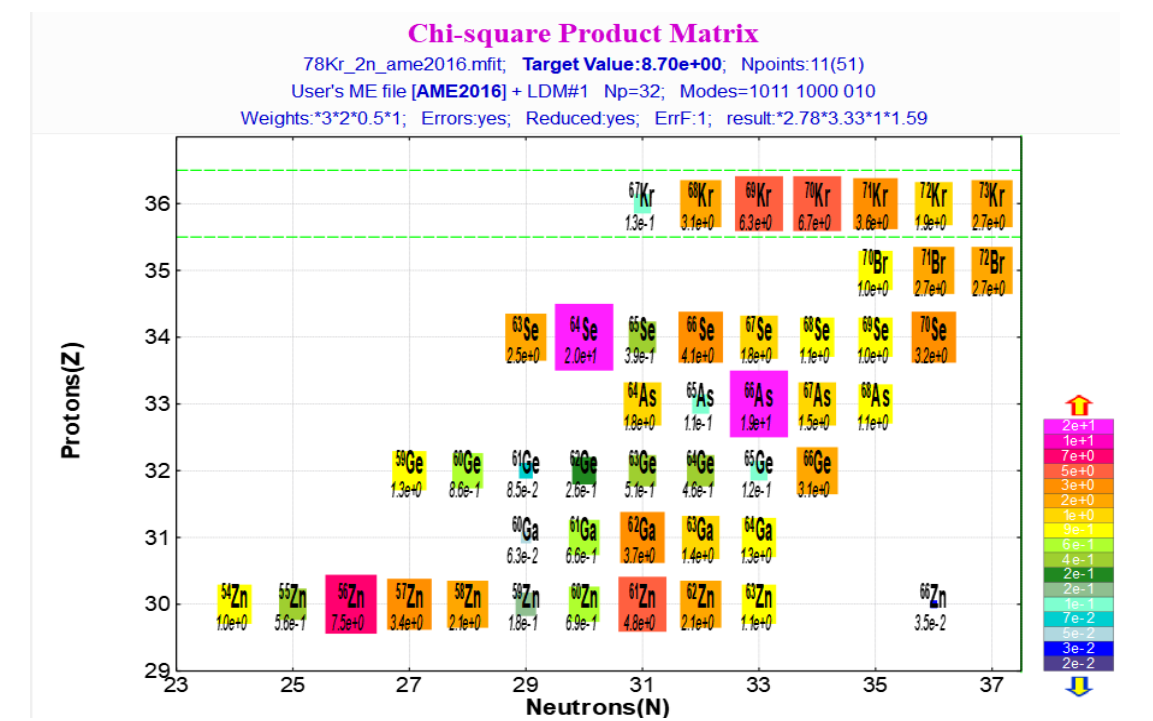
mass model

User's ME file [AME2016] + LDM#1

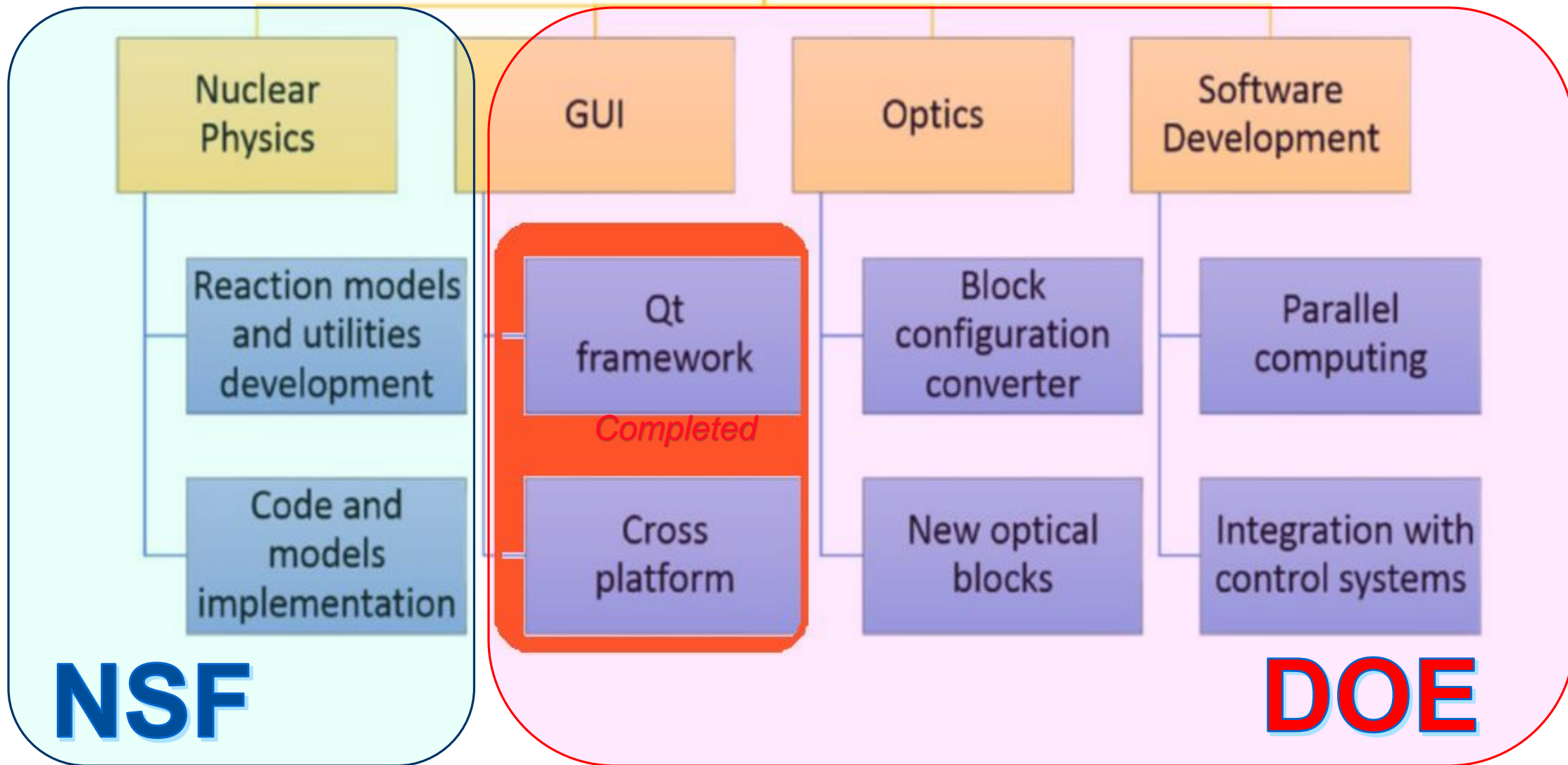
decay channels info

Np=32; Modes=1011 1000 010

Make default



PLANS

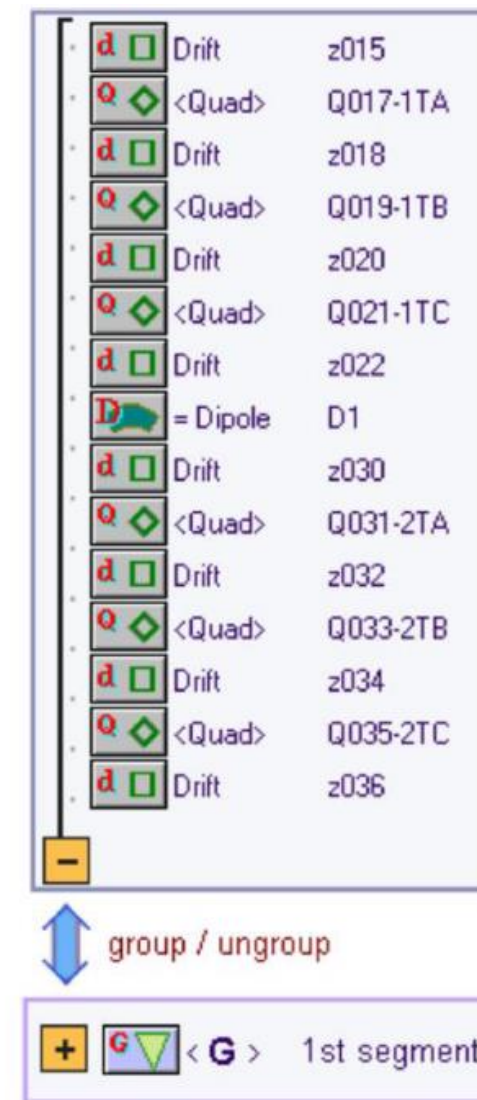
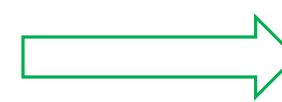


- Creation of fast and accurate Abrasion-Fission model based on the IFN Analyzer tables
- Abrasion-Ablation:
  - Improvement of the fast model for multi-step reactions (implementation of the AA for second step)
  - Intermediate Dissipation step in the Abrasion-Ablation model
  - Theoretical study of prefragment excitation energy
  - Development and implementation of the new (log-normal) excitation distribution shape after abrasion based on the BeAGLE calculations (in collaboration with the EIC/BNL exotic nuclei group)
- Implementation in LISE<sup>++</sup> code for transmission and cross section calculations
  - ETACHA4: Low-energy non-equilibrium charge state evolution
  - PACE4: Projection Angular-momentum coupled evaporation
  - INC: intranuclear cascade model to use at higher energies with light targets
- Systematization of experimental production cross-sections
- Creation of Monte Carlo de-excitation cascade utility to benchmark the analytical LISE<sup>++</sup> cascade subroutine and to create condition (gating) options
- Investigate charge-exchange and pick-up reactions in RIB production



## In the near future:

- The creation of a LISE<sup>++</sup><sub>core</sub> library
  - ❖ This library will allow to integrate LISE<sup>++</sup> calculations within control systems, in order to directly assist the tuning of fragment separators.
  - ❖ LISE for Excel-64
- The code parallelization will be undertaken
  - ❖ To take advantage of modern computing architecture, parallel computing methods are essential in achieving faster computation. As a first step, the LISE<sup>++</sup> code parallelization process will be implemented on the Monte Carlo and “Distribution” analytical methods for fragment transmission calculation.
- Block configuration converter
  - ❖ This new tool will be built around a new type of block, labeled G (Group), which allows the grouping and ungrouping of E blocks. The tool can be applied to create sector configurations for fast analytical calculations.



The new LISE<sup>++</sup> feature for converting a series of extended blocks to a single segmented block.

- The program LISE<sup>++</sup> is **designed to predict the intensity and purity** of rare isotope beams (RIB) is widely used at heavy ion collision facilities
- The program is **constantly expanding and evolving from the feedback** of its users around the world
- Fast and accurate models of rare isotope production mechanism are being developed in the LISE<sup>++</sup> framework
- The LISE<sup>++</sup> software suite **has been transferred to a new graphics framework**, Qt, to use with modern compilers, that **provides cross-platform functionality, 64-bit operations**
- New code capabilities such as **parallel computing**, and integration with control systems are planned, so the next step to be undertaken will be the **creation of a LISE<sub>core</sub> library**. This library will allow the integration of LISE<sup>++</sup> with control systems for direct assistance in the tuning of fragment separators. These developments are planned to be tested at FRIB in the near future
- Computational speedup is requested from users at many facilities, and becomes more crucial with the new large-scale nuclear physics facilities under construction, such as FRIB and FAIR, that have keen interest in integrating the LISE<sup>++</sup> software with their control systems

# The LISE<sup>++</sup> Transportation Team

Members working on the transportation of the LISE<sup>++</sup> Software Suite to Qt.

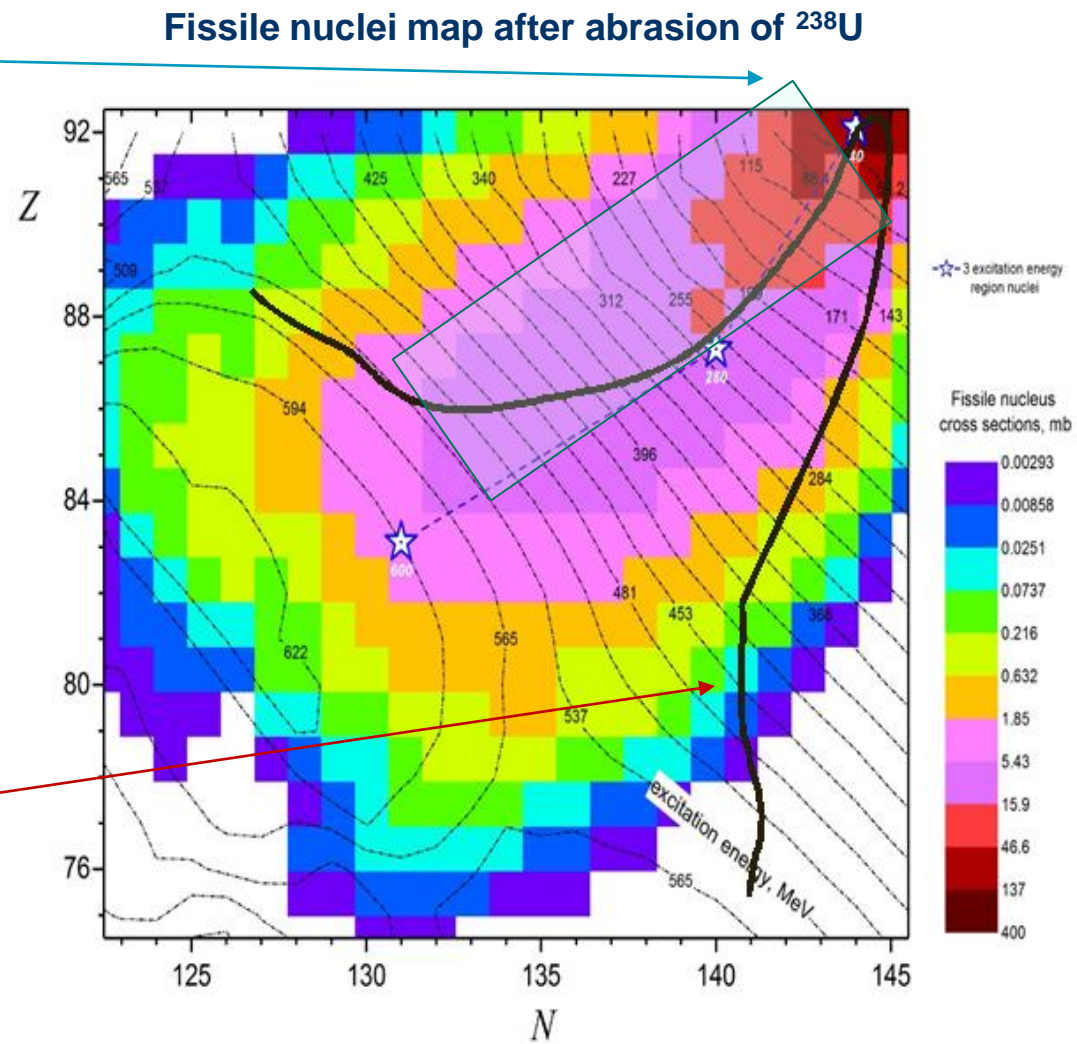
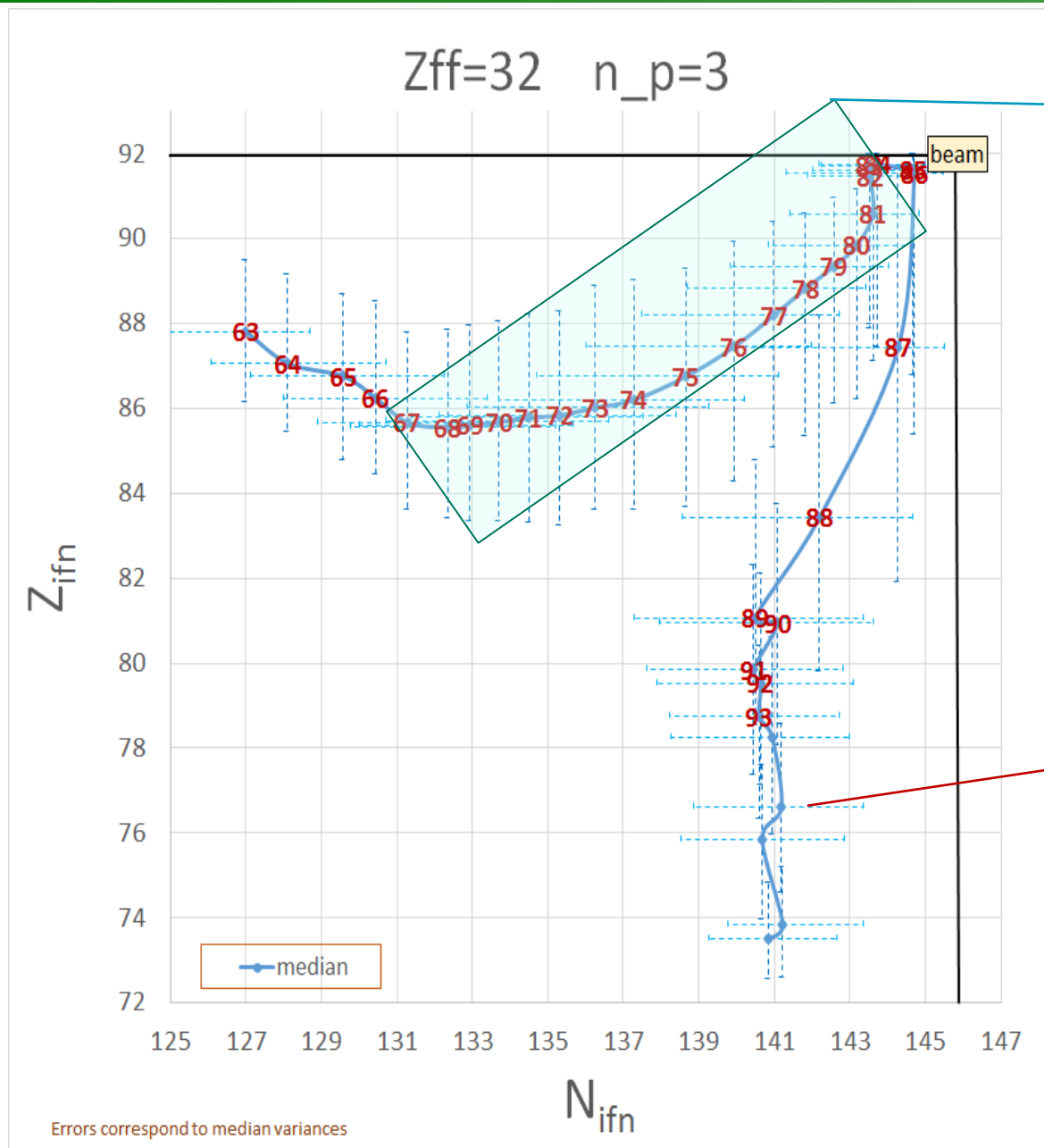
<b>D. Bazin</b>	physics & ion optics consulting, benchmarks, adaptation to macOS
<b>M. Hausmann</b>	physics & ion optics consulting, benchmarks
<b>M. Kuchera</b>	source porting, development of porting process base
<b>P. Ostroumov</b>	supervision, funding acquisition
<b>M. Portillo</b>	physics & ion optics consulting, benchmarks
<b>B. Sherrill</b>	supervision, funding acquisition
<b>O.B. Tarasov</b>	leading porting process worker
<b>K.V. Tarasova</b>	source porting, benchmarks
<b>T. Zhang</b>	process administration, IT consulting, adaptation to Linux

This work was supported by the U.S. National Science Foundation under Grants No. PHY-1565546, PHY-2012040, and by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB), which is a DOE Office of Science User Facility, operated by Michigan State University, under Award Number DE-SC0000661

BACKUP



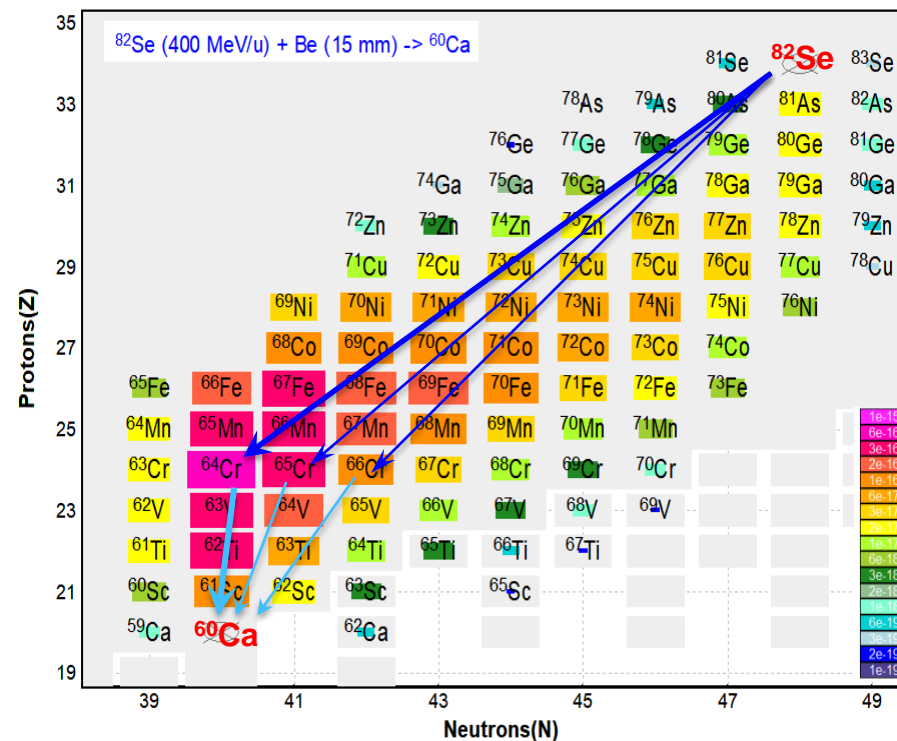
# IFN-analysis for final Ge-isotopes (Z=32)



New Fast Abrasion-Fission model based on pre-calculated  $V_{cm}$  tables is under construction

- Multi-step reactions in thick targets is process then the projectile undergoes a series of successive reactions until the fragment of interest is produced
- For the second and next reactions we assume always a projectile fragmentation mechanism and uses the EPAX parameterization to speed up calculations

Parent nuclei: multistep production probability



LISE++ → <sup>64</sup>Cr is more probable second-step projectile to produce <sup>60</sup>Ca with a <sup>82</sup>Se beam (400 MeV/u) on Be (15 mm).

Total Multi-step reaction factor is equal to 10.1

- The study (experimental and theoretical) of the charge-exchange mechanism as a **step for rare isotope production**

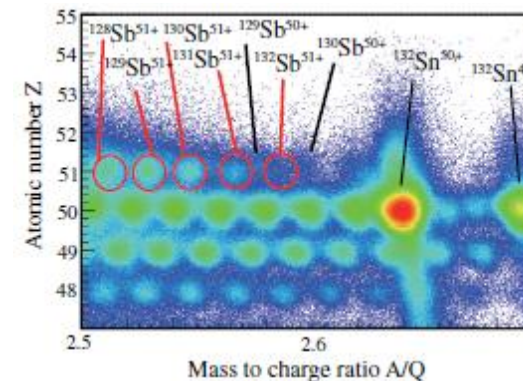
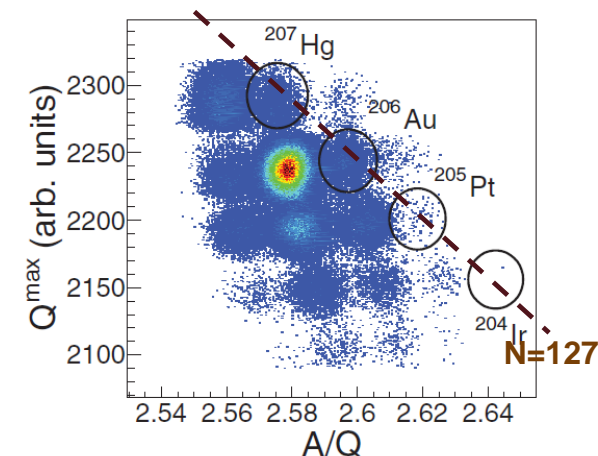
- (p,n)

- A. I. Morales, J. Benlliure et al.,  
PRC84, 011601(R) (2011)  
 $^{208}\text{Pb}_{126}$  (1 AGeV) + Be

- (n,p)

- J. Yasuda, M. Sasano, et al.,  
PRL 121, 132501 (2018)  
 $^{132}\text{Sn}$  (200 MeV/u) + H  $\rightarrow$   $^{**}\text{Sb}$

- D.Kostyleva, I.Mukha et al.,  
PRL 123, 092502 (2019)  
 $^{31}\text{Ar}$  (620 MeV/u) + Be  $\rightarrow$   $^{31}\text{K}$



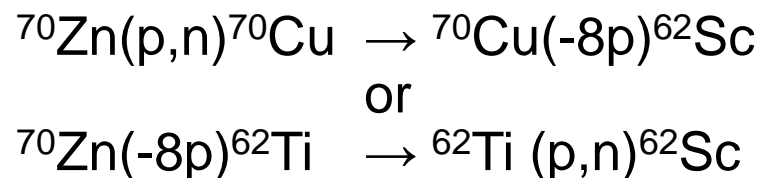
- The study (experimental and theoretical) of the multi-step reactions:
  - the development of a fast model for multistep reactions
  - the measurement of experimental secondary cross sections
- Important to approach the nucleon drip-lines
  - So, more probable path for  $^{70}\text{Ca}$  production at FRIB is a three-step process:
    1. Abrasion of  $^{238}\text{U}$  to low-excited  $^{237}\text{U}$  ( $E^* \sim 32$  MeV) with sequential fission to  $^{81}\text{Ga}$  ( $2e-2$  mb)
    2. First projectile fragmentation step :  $^{81}\text{Ga} \rightarrow ^{76}\text{Fe}$  ( $-5p$ ,  $\sim 1e-5$  mb)
    3. Second projectile fragmentation step :  $^{76}\text{Fe} \rightarrow ^{70}\text{Ca}$  ( $-6p$ ,  $\sim 1e-6$  mb)
- MSU-RIKEN collaboration recent experiments with multi-step reactions analysis in process:
  - Production of neutron-rich isotopes around  $^{60}\text{Ca}$  by projectile fragmentation of a beam of  $^{70}\text{Zn}$  at 345 MeV/u (*O.Tarasov et al., PRL 121 (2018) 022501*)
  - Production of very neutron-rich Pd isotopes around  $N = 82$  by projectile fragmentation of a RI beam of  $^{132}\text{Sn}$  at 280 MeV/u (*H.Suzuki et al.*)



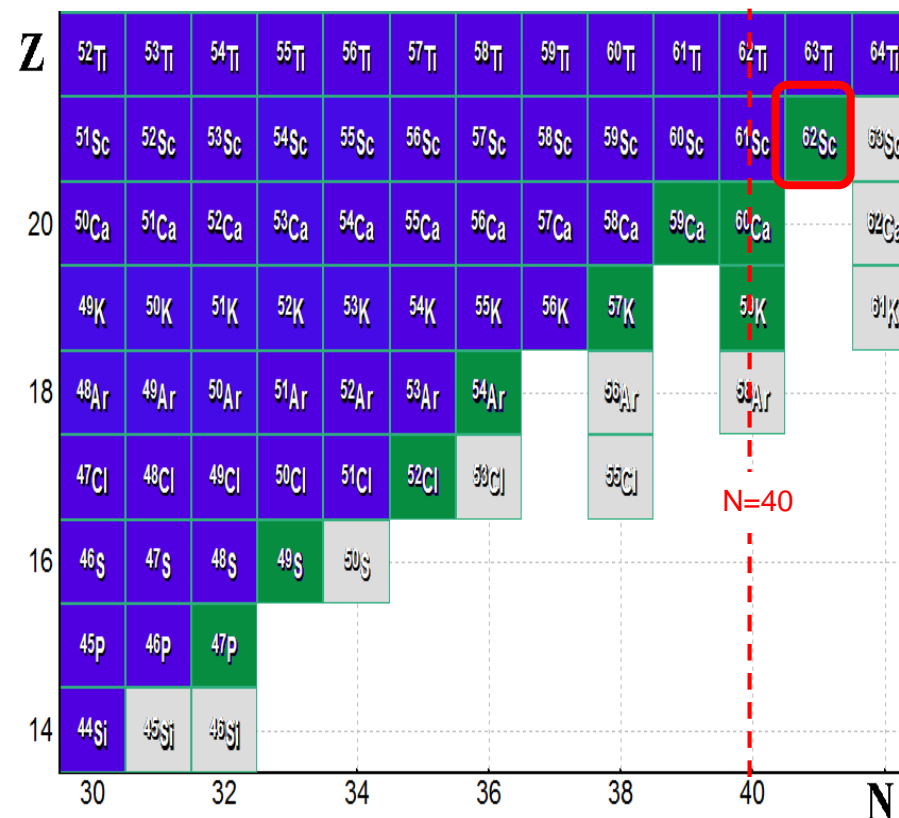
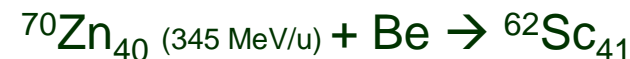
## Recent “ $^{60}\text{Ca}$ ” experiment at RIKEN

O.Tarasov et al., PRL 121 (2018) 022501

- Production of  $^{62}\text{Sc}$  is  $-9p,+1n$
- Pickup is suppressed at these energies
- Two-step reactions through a charge-exchange channel?



- Cross sections are under analysis
- Charge-exchange reactions become an important mechanism for the Rare Isotopes production

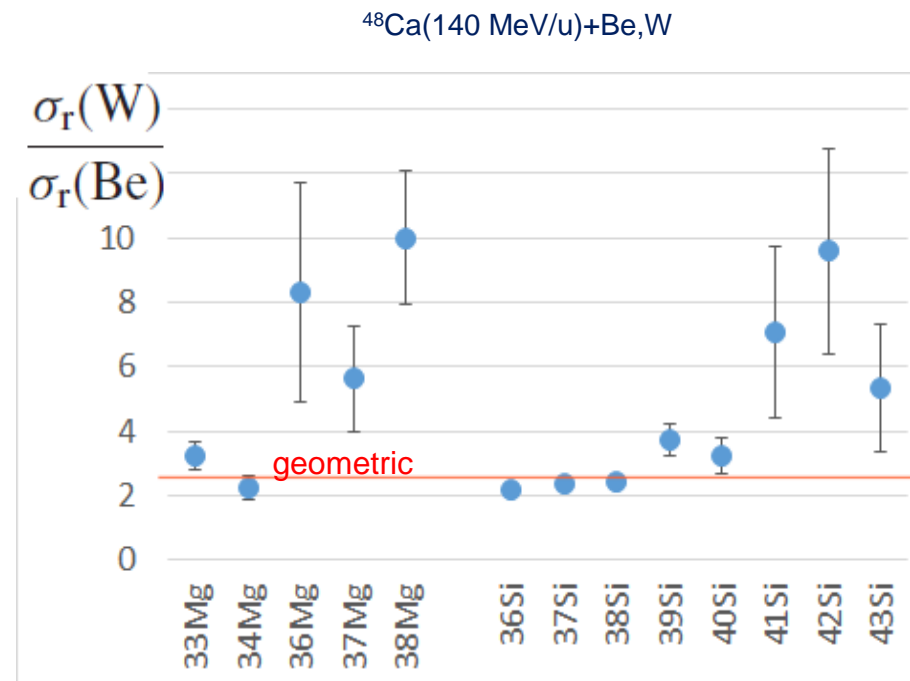


- The study of the target factor in rare isotope yields for energies 50–150 MeV/u

## ■ $^{48}\text{Ca}(140 \text{ MeV/u}) + \text{Be}, \text{W}$

- $^{40}\text{Mg}$ ,  $^{42,43}\text{Al}$ :  
T. Baumann, et al.,  
Nature 449 (2007) 1022
- $^{44}\text{Si}$ :  
O.B.Tarasov, et al.,  
PRC75 (2007) 064613

- $^{198}\text{Pt}(85 \text{ MeV/u}) + \text{Be}, \text{Ni}$   
NCSL/MSU, 2019  
O.Tarasov et al, under analysis



The cross sections for reaction with the tungsten target are larger than those with beryllium by factors that range from approximately 2.5 at  $A = 36$  ( $Z=14$ ) to about 10 at  $A = 42$ , values that become significantly larger than the ratio of the geo-metric reaction cross sections equal to 2.66