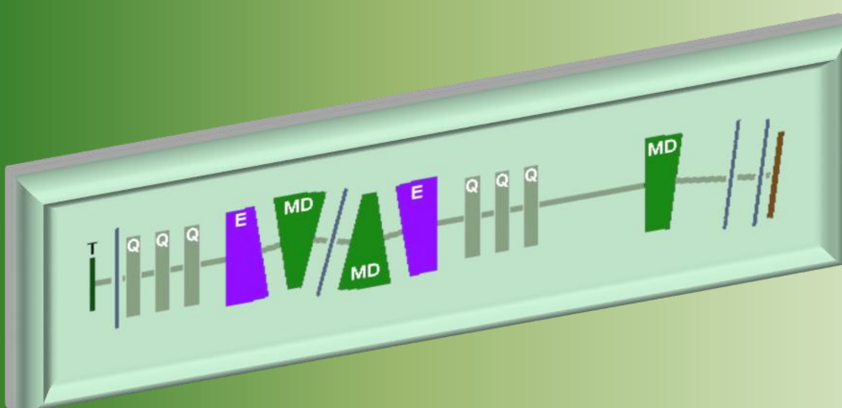
Oleg B. Tarasov
NCSL / MSU

Using LISE++ for heavy ion reactions at low energies

SHE . symposium @ TAMU . USA
04/02/2015

LISE++



LISE++

1. Introduction : Production & Separation
2. Fusion-Fission experiment in inverse kinematics
3. Update of Fusion mechanism in LISE++
4. Ion beam optics : extended configurations
5. New configurations at low energies
6. Future development
7. Summary

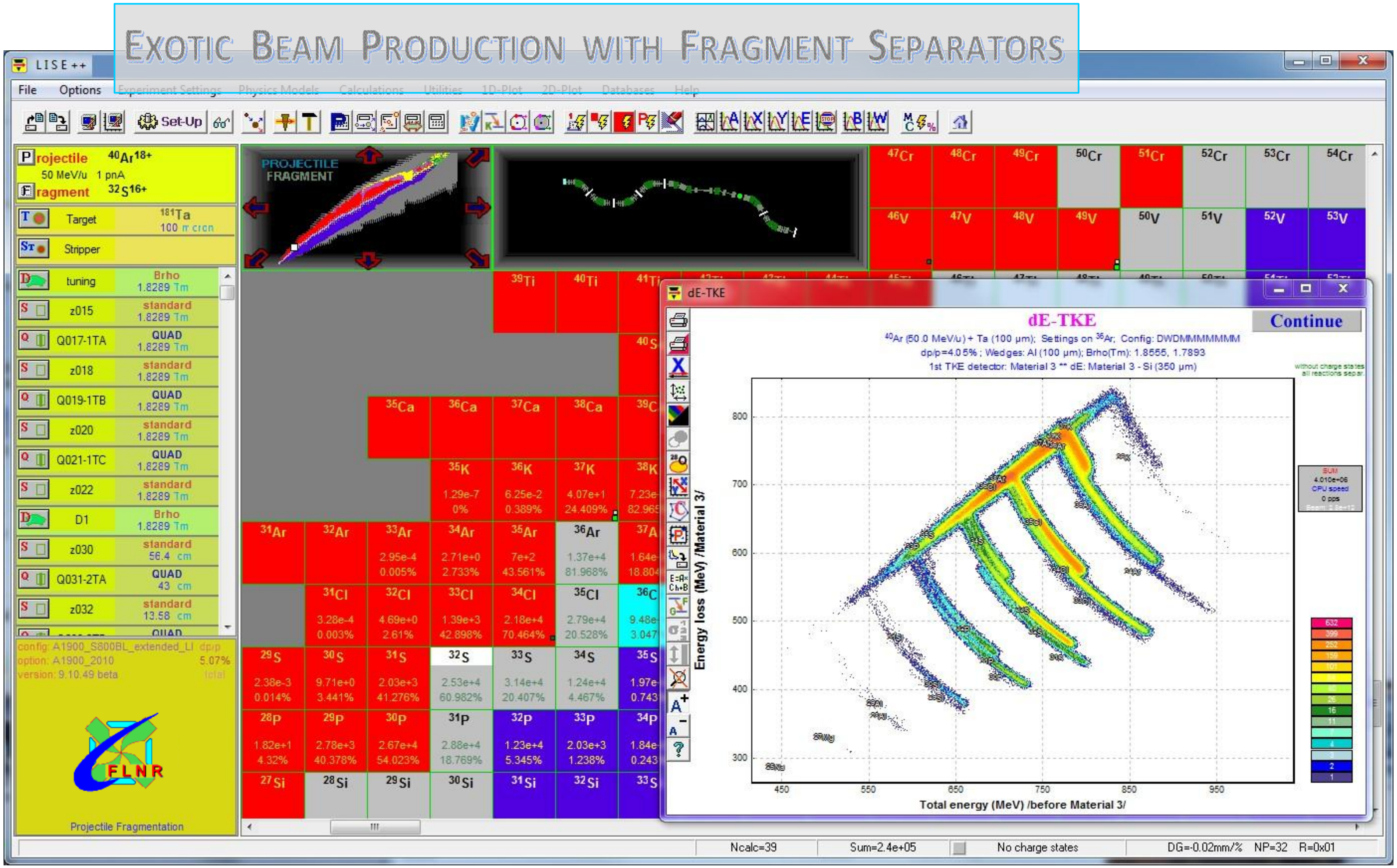
NSCL

MICHIGAN STATE UNIVERSITY

Introduction : Production & Separation

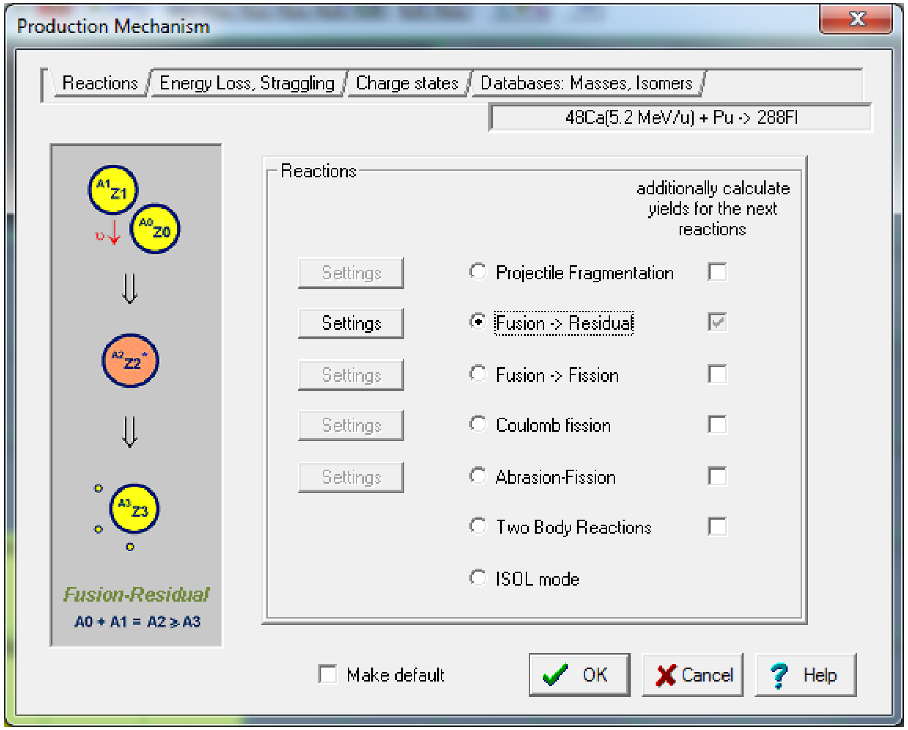
The program LISE^{++} is designed to predict intensities and purities for the planning of experiments with in-flight separators, as well as for tuning experiments where the results can be quickly compared to on-line data.

O. B. Tarasov and D. Bazin, Nucl. Instr. Meth. B 266 (2008) 4657



The LISE^{++} package which includes also the PACE4, Global, Charge, Spectroscopic calculator codes can be downloaded freely from the following site: **http://lise.nscl.msu.edu**.

LISE++ main features



Fast analytical calculations

(Monte Carlo calculations are available too)

Reaction mechanisms

- **Projectile Fragmentation**
- **Coulomb Fission**
- **Abrasion-Fission**
- **Fusion-Evaporation**
- **Fusion-Fission**

Beam Ion Optics

(calculated up to 2nd order, used up to 5th order)

Highly user friendly environment

Different selection methods

***Ion charge state distribution** (5 methods)*

***Range and energy loss in materials** (4 methods)*

***Fission barriers** (6 methods)*

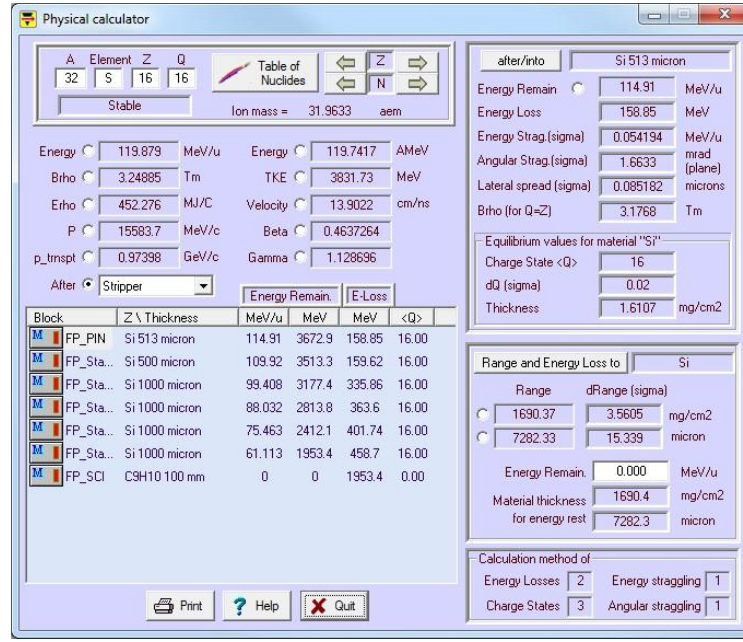
Fast and qualitative analytical de-excitation procedure

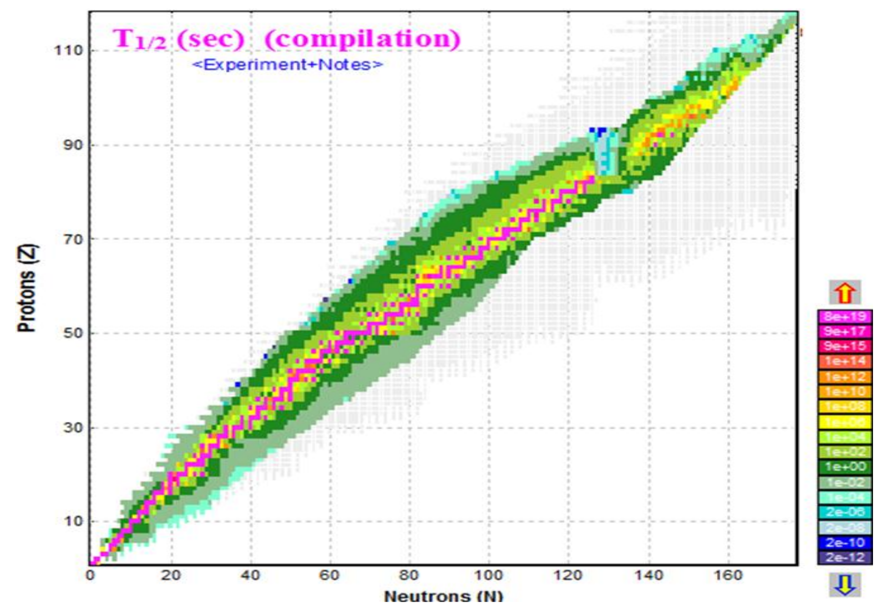
Contribution of secondary reactions in the target

***Fragment production in Material** (for example wedges)*

LISE++ utilities

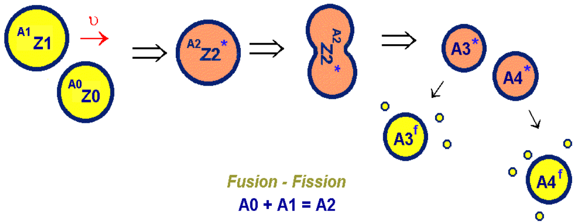
- Physical Calculator
- LISE for Excel
- Nuclide and Isomeric states databases & utilities
- Relativistic Reaction Kinematics Calculations
- Curved & custom degrader calculations
- PACE4 – evaporation MC code for Windows
- The spectrometric handbook of J.Kantele & Units converter
- Codes “Global” & “Charge” (charge state distributions)
- “MOTER” ray-tracing code with optimizer
- Stripping foil lifetime utility
- Range optimization utility (gas cell)
- “Brho” analyzer, Solenoid (Twinsol) & ISOL-catcher utilities
- Beam ion optics utilities
- “Evaporation” calculator
- Automatical search of two-dimensional peaks in experimental spectra





The LISE++ fusion-fission model [1] has been developed based on:

- ❑ The Bass algorithm to estimate complete fusion cross section [2],
- ❑ The fast analytical evaporation model LisFus [3] to calculate a fission channel value and de-excitation of fission fragments.
- ❑ The semi-empirical model of J.Benlliure [4] which describes fission properties of a large number of fissile nuclei are a wide range of excitation energies.



[1] O.T. and A.C.C.Villari, NIM B 266 (2008) 4670.
[2] R.Bass, Phys.Rev.Lett. 39 (1977) 265.
[3] O.T. and D.Bazin, NIM B 204 (2003) 174.
[4] J.Benlliure et al., Nucl.Phys. A628 (1998) 458.

Main features of the model:

- *Production cross-section of fragments*
- *Kinematics of reaction products*
- *Spectrometer tuning to the fragment of interest optimized on maximal yield (or on good purification)*

Towards the neutron drip-line via Fusion-Fission

Advantages of in-flight fusion-fission to explore neutron-rich 55 < Z < 75 region are comparing to AF & CF:

- *the heavier fissile nucleus competing with abrasion-fission (Z < 92),*
- *the higher excitation energy of a fissile nucleus competing with Coulomb fission of the ^{238}U primary beam.*

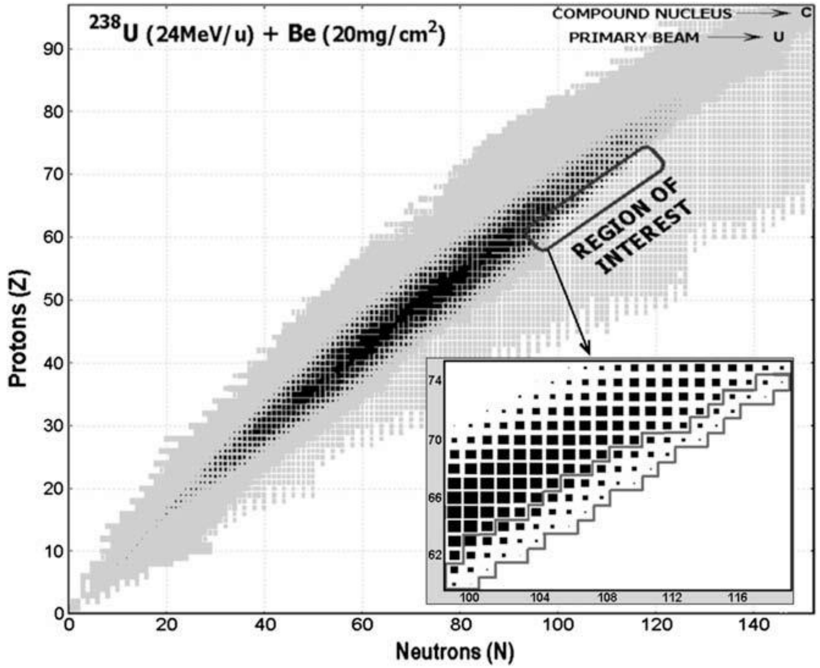


Fig. Two-dimensional yield plot for fragments produced in the ^{238}U (20 MeV/u,1pnA) + D (12 mg/cm^2) reaction and separated by SISSI + Alpha

Using low energy fusion-fission beams:

- *Several tens of new* isotopes are expected to be produced in the region 55 < Z < 75 using a ^{238}U beam with light targets according to the LISE^{++} Fusion-Fission model,*
- *Properties of these new nuclei allow to test nuclear models, in particular to understand the r-process abundance patterns,*
- *Reaction mechanism study.*

Open Questions:

- *What is optimal conditions, for example the energy of primary beam, the target material, thickness and so on?*
- *How reliable are simulations? Intensities, purification?*
- *What are contributions from other reaction mechanisms?*
- *Separation, Identification, Resolution?*

A experiment to show separation and identification of fusion-fission products has been performed using the LISE3 fragment-separator at GANIL.

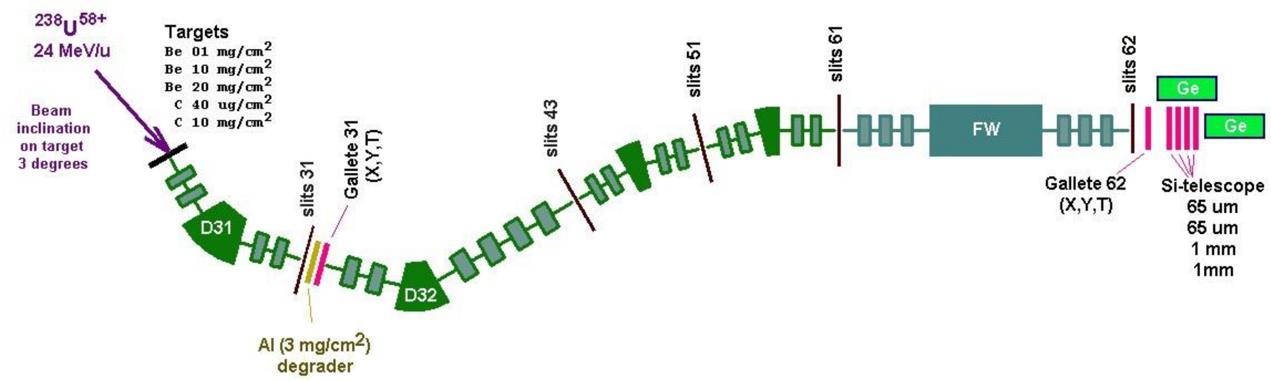
* *in 2008*

GANIL e547

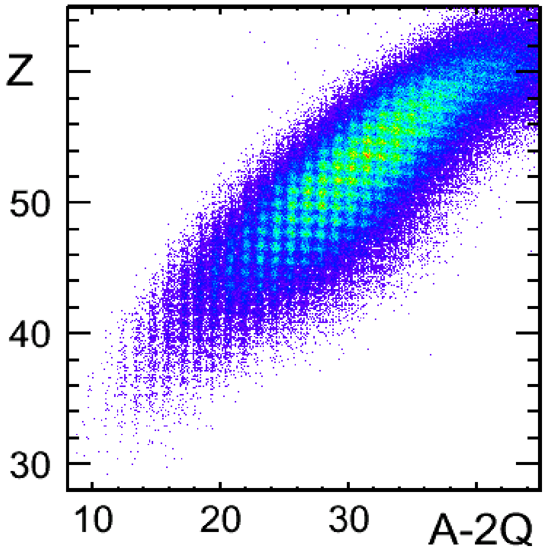
Spokesperson: O.Tarasov

Preliminary results in arxiv.org:1302.1981
By O. Delaune, F. Farget, et al.

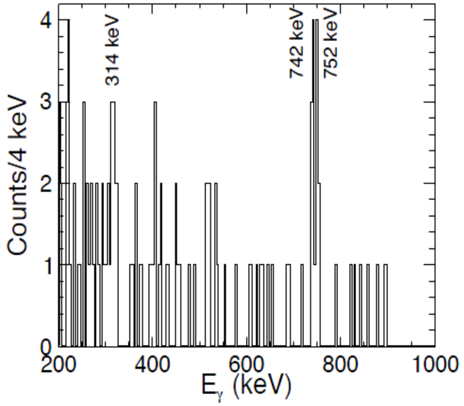
It will be submitted soon



- A ^{238}U beam at 24 MeV/u with a typical intensity of 10^9 pps was used to irradiate a series of Be & C targets
- The beam was incident at an angle of 3° in order not to overwhelm the detectors with the beam charge states
- Preliminary detectors calibration with the primary beam, then particle identification has to be proved by gamma from know isomers

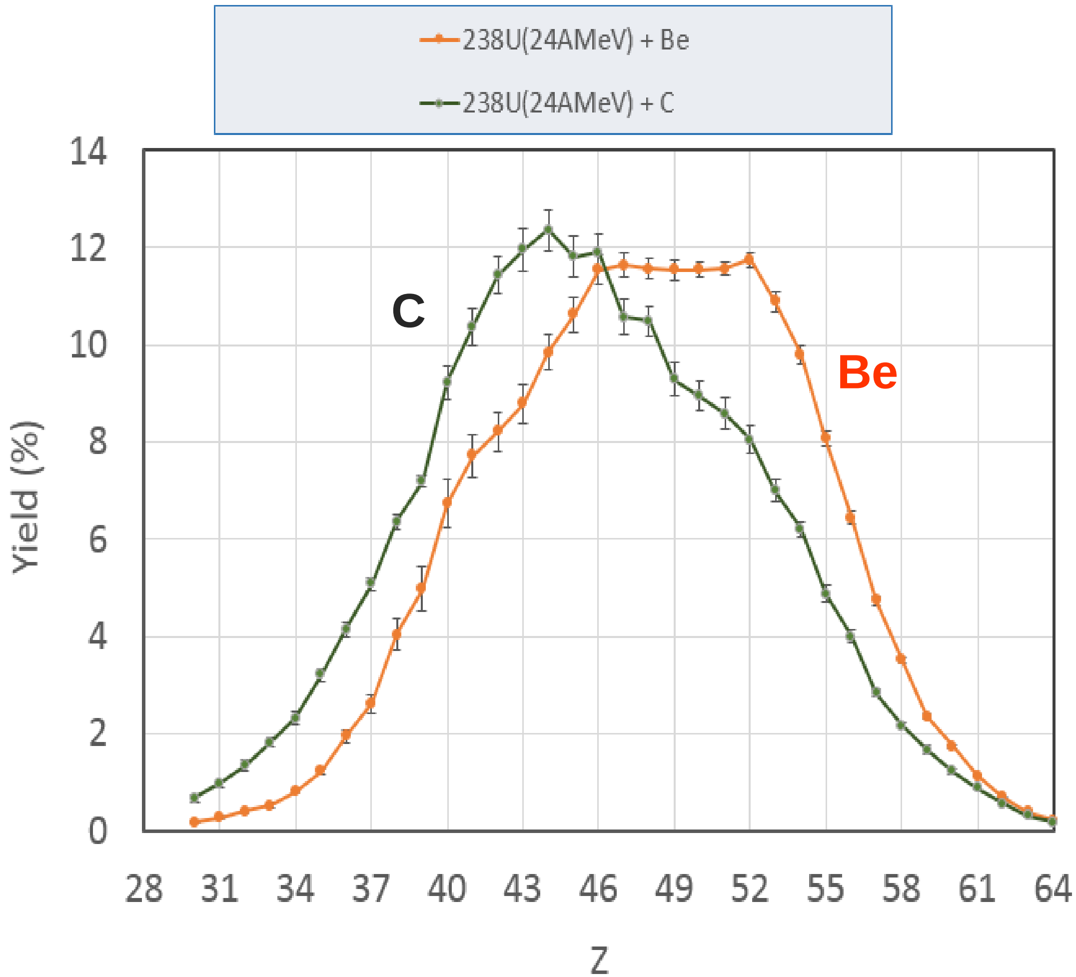


- The experiment demonstrated excellent resolution, in *Z*, *A*, and *q*.
- The results demonstrate that a fragment separator can be used to produce radioactive beams using fusion-fission reactions in inverse kinematics,
- In-flight fusion-fission can become a useful production method to identify new neutron-rich isotopes, investigate their properties and study production mechanisms.



Gamma-ray spectrum observed in coincidence with ^{128}Te. The characteristic gamma lines of 314, 742 and 752 keV sign the decay of the isomeric state of $T_{\frac{1}{2}} = 370$ ns

Preliminary!!!



^{238}U Energy	24 AMeV	24 AMeV
Target	Be	C
<Z>	**48.01**	**45.75**
d<Z>	0.22	0.21
sig(Z)	**6.03**	**6.40**
d(sig(Z))	0.17	0.16

Two light targets (A=9 & 12) at the same beam energy, but why so different distributions?

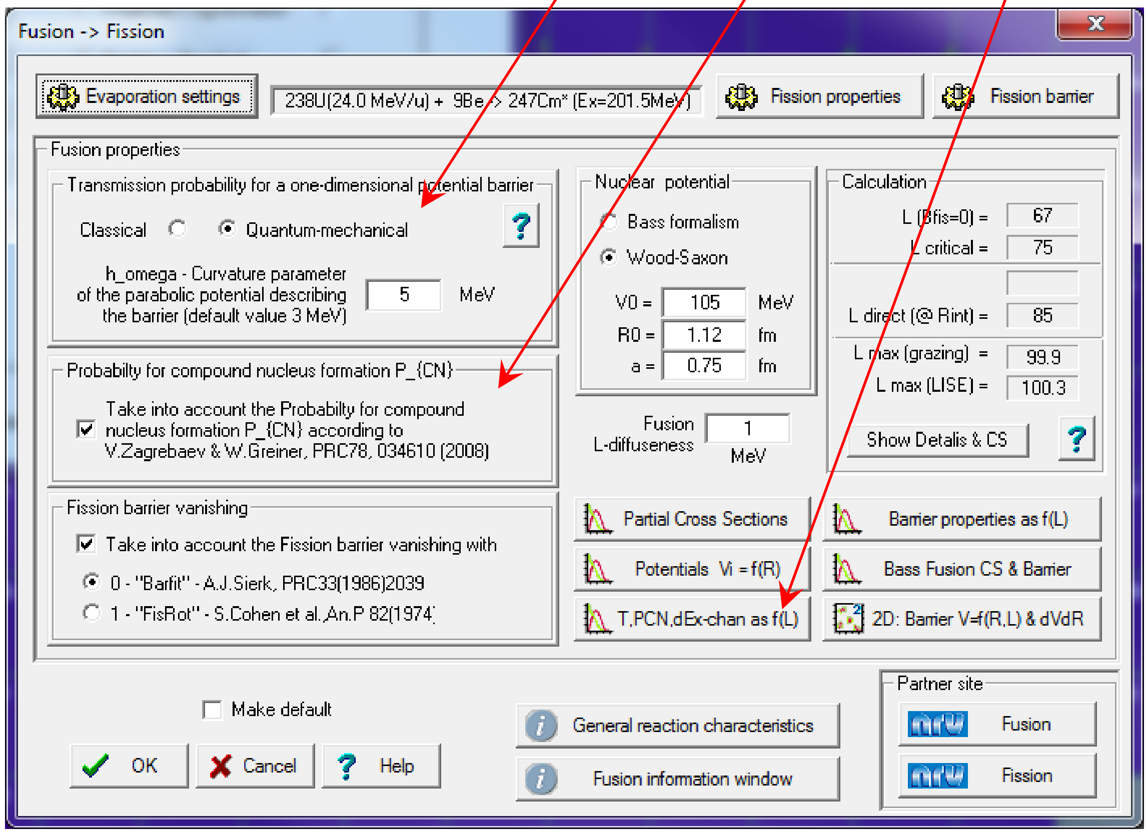
We need a fast analysis of partial cross sections!!

Update of Fusion mechanism in LISE^{++}

v.9.10.54
from 04/25/2015

Newest version, Documentation will be ready on two weeks

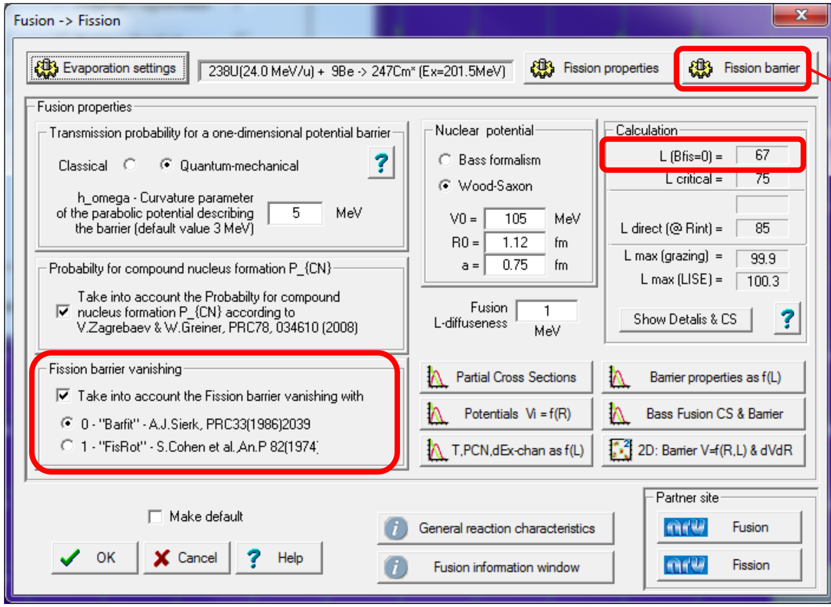
$$\sigma_{\mathrm{ER}}^{xn}(E) = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)P_{\mathrm{cont}}(E,l)P_{\mathrm{CN}}(E^*,l)\,P_{xn}(E^*,l)$$

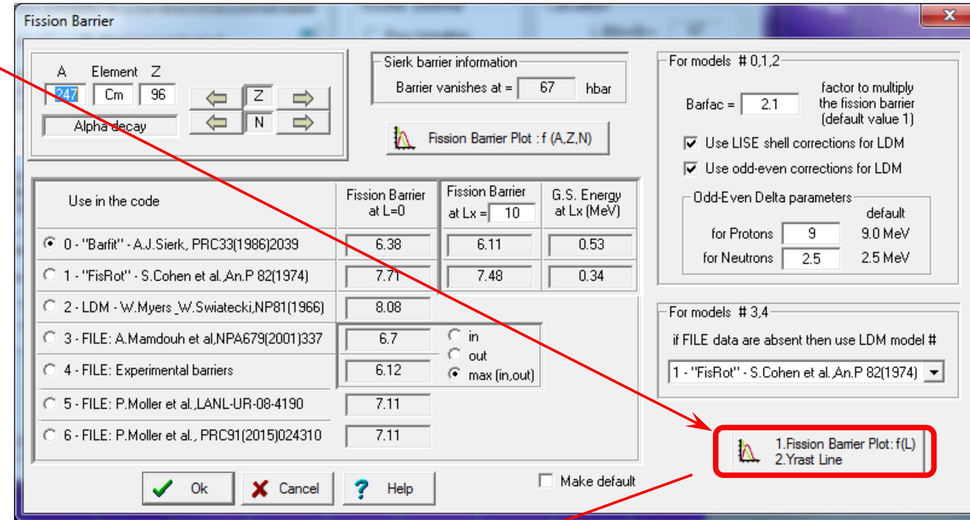


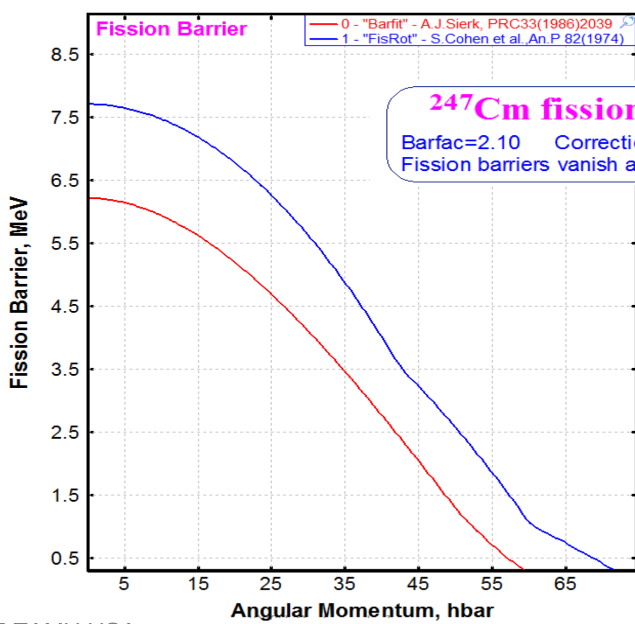
Projectile Fragmentation and Abrasion-Fission are dominated reaction mechanisms in LISE^{++} for rare beam production, where we are developing our own models

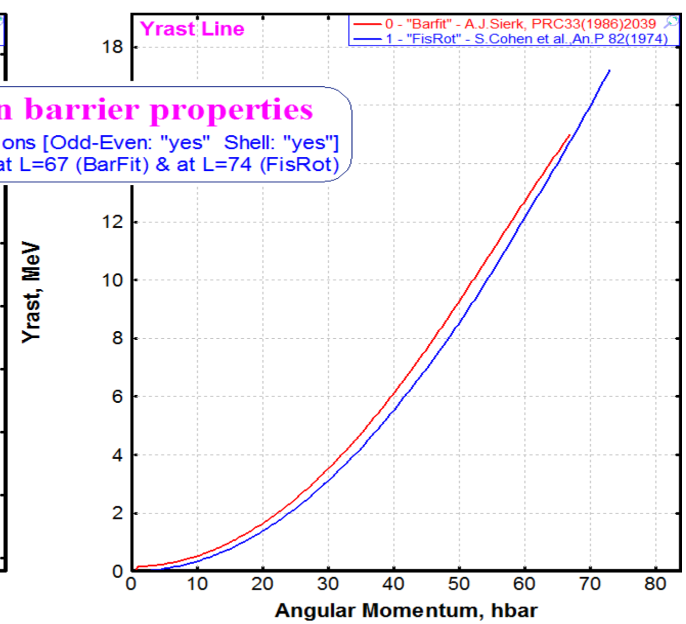
Do not hesitate to use Low-Energy reaction computing centers as NRV for more sophisticated solutions with Channel Coupling, Langevin equations and so on

Fission Barrier Vanishing as f(L)





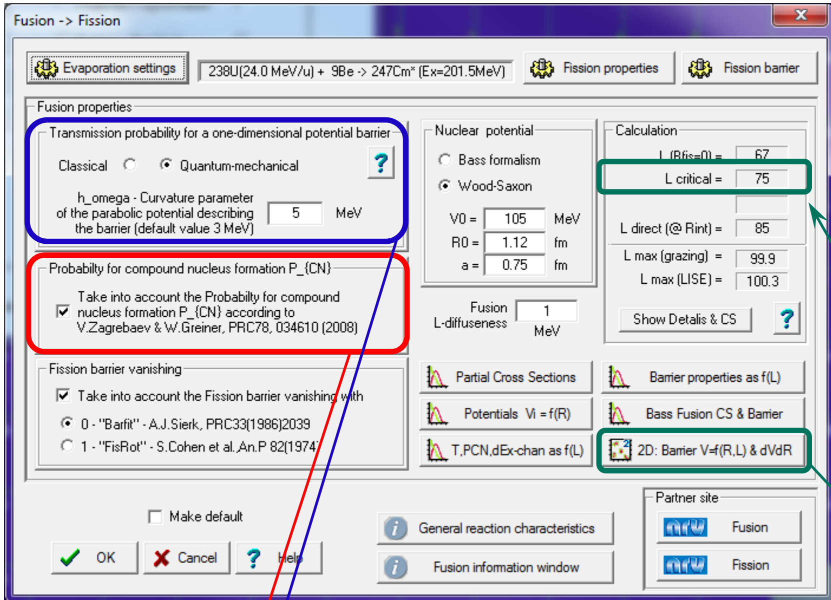




^{247}Cm fission barrier properties

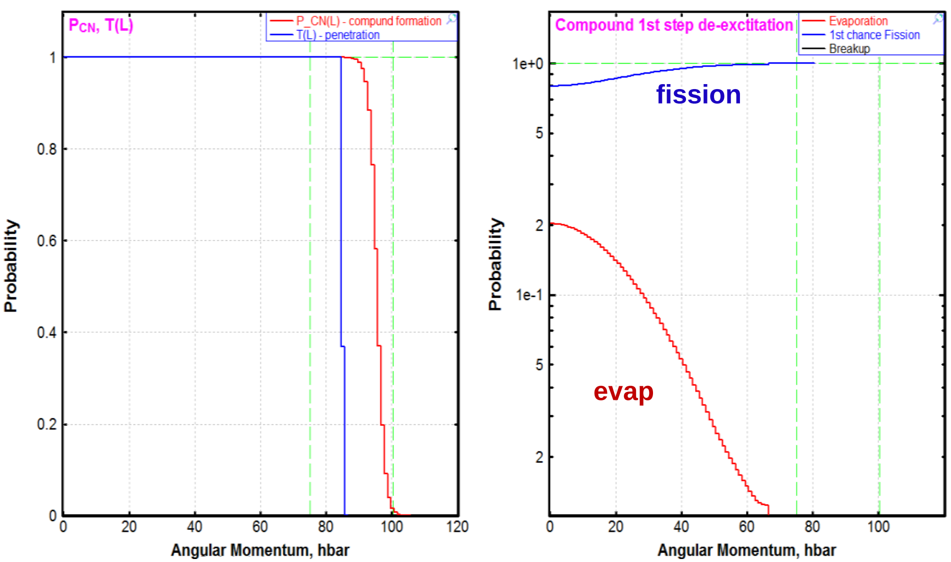
Barfac=2.10 Corrections [Odd-Even: "yes" Shell: "yes"]
Fission barriers vanish at L=67 (BarFit) & at L=74 (FisRot)

Transmission for a barrier & CN formation probabilities as f(L)



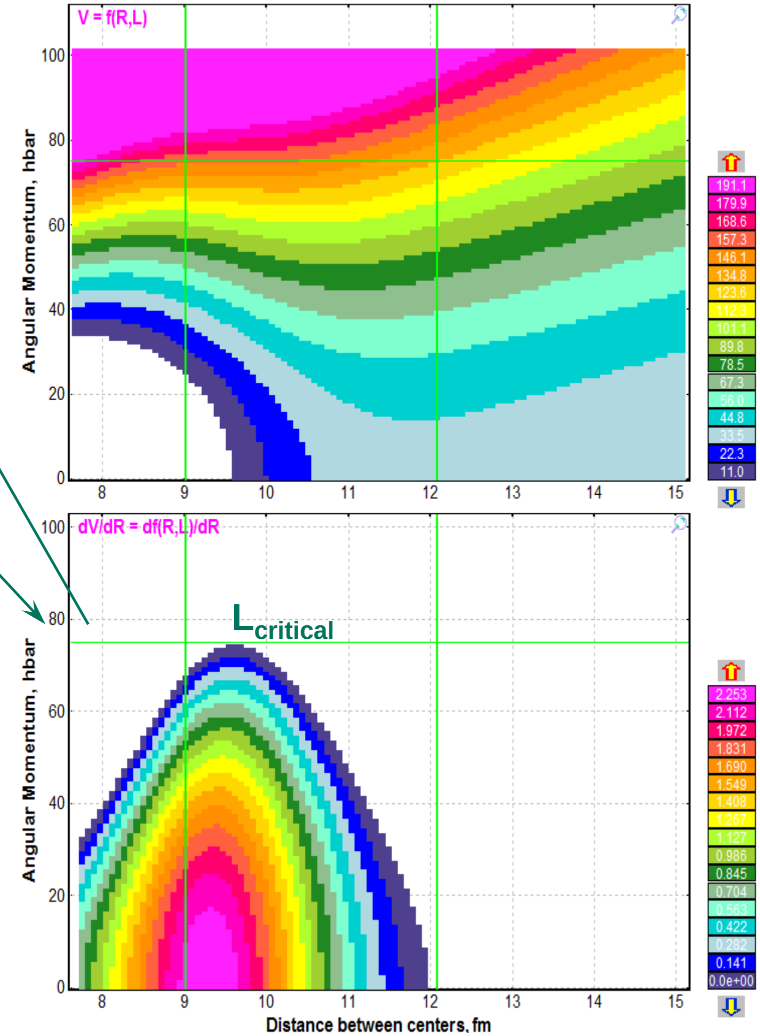
Probabilities as f (L)

^{238}U(24.0 MeV/u) + ^{9}Be -> ^{247}Cm* (E_{CM}=208.3 MeV); h_omega=5.0
L_{crit}=75; L_{max}^{Graz}=99.9; L_{max}^{LISE}=100.3; Nuclear potential: WoodSaxon
Vertical lines correspond to $L_{critical}$ & $L_{maximum}$

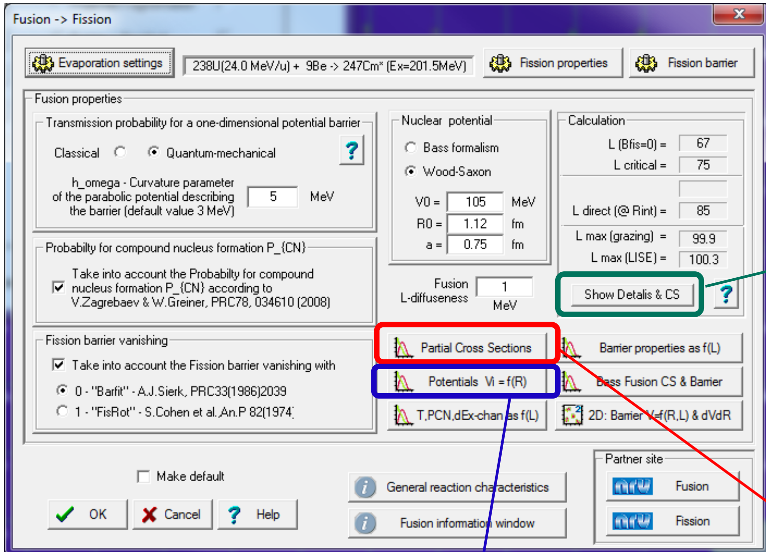


2D Potential plots as f(R,L) & df(R,L)/dR

^{238}U(24.0 MeV/u) + ^{9}Be -> ^{247}Cm* (E_{CM}=208.3 MeV)
L_{crit}=75; L_{max}^{Graz}=99.9; L_{max}^{LISE}=100.3; Nuclear potential: WoodSaxon; WS params: 105.0,1.12,0.75
Vertical lines correspond to (C_p + C_t) and $R_{interaction}$, Horizontal line to $L_{critical}$



Potential energy and Partial cross sections

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Cross sections (mb)

 Partial (LISE++)
Interaction                 3.690e+03
Compound                    1.656e+03
Quasi-Fission               1.539e-07
Fast Fission                4.156e+02
Deep Inelastic              5.356e+02
Direct+QE                   1.083e+03

 Compound 1st step de-excitation channels (LISE++)
Fusion-Residue              8.992e+01
Fusion-Fission              1.566e+03
Fusion-Breakup              0.000e+00

 Cross section used in calculations (beginning of target)
Fusion-Fission              2.167e+03
Use this factor for rates   0.723
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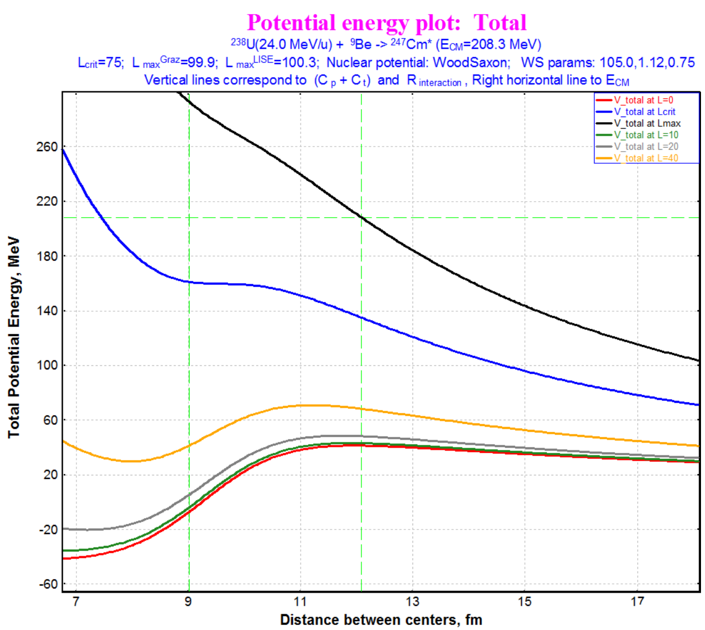
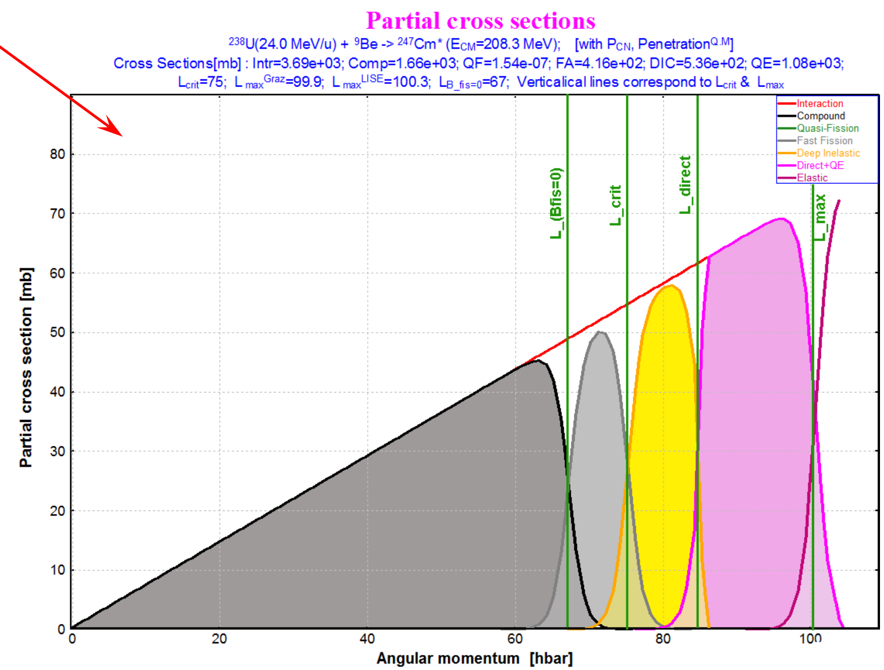
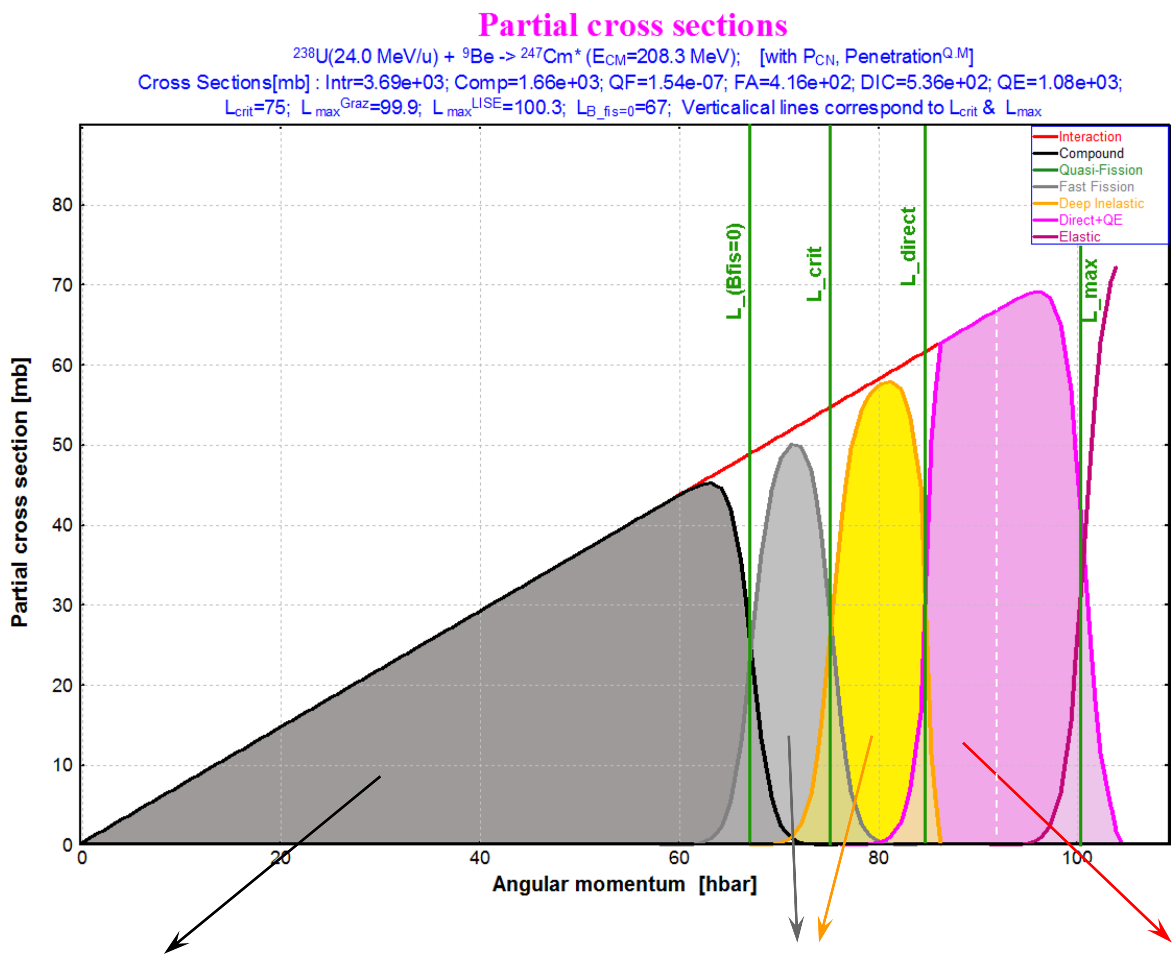




Output channels in the e547 experiment : ^{238}U (24 MeV/u)

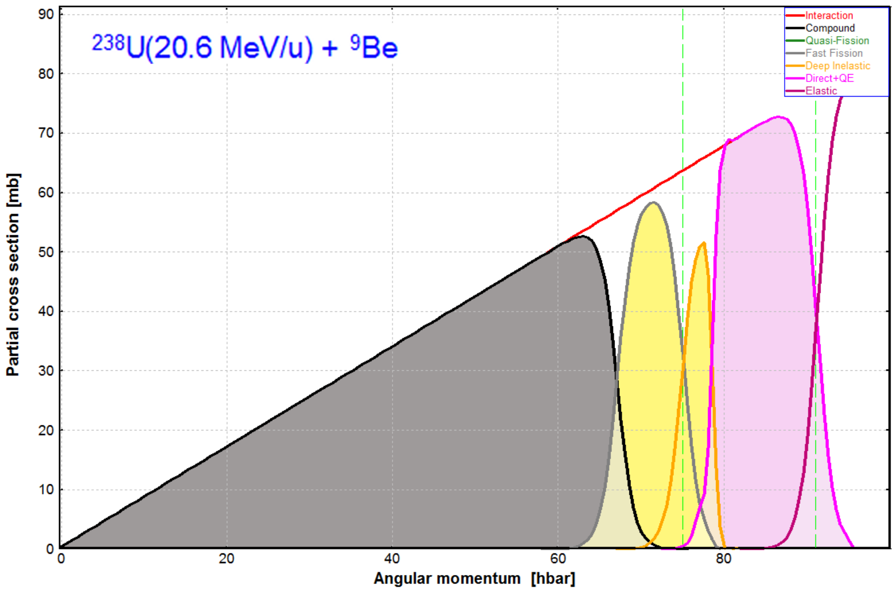


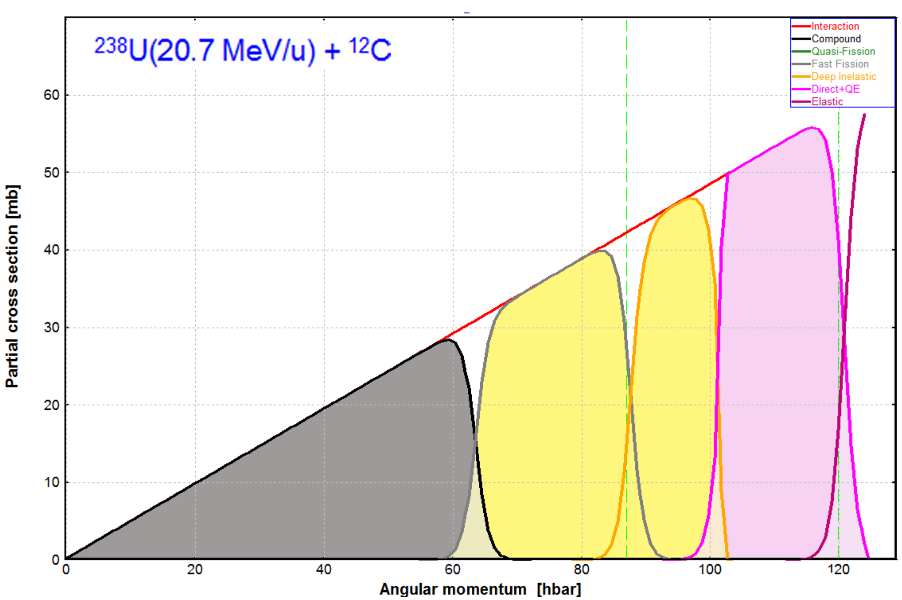
Compound fission ~100%
Fissile Z = 96
High Excitation Energy

Sequential fission after DIC
Fissile Z < 92
High Excitation Energy

Partially go to fission
Fissile Z~92
Low Excitation Energy

e547 experiment : Be vs. C targets

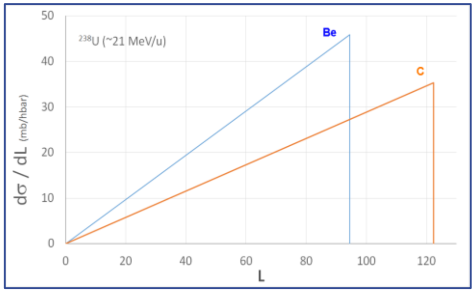




average for 17-24 MeV/u range

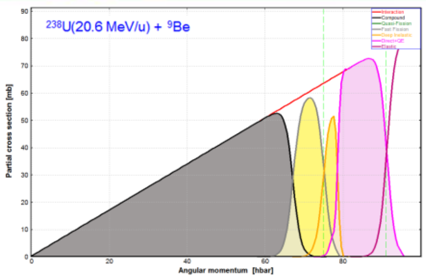
Fission Barrier Vanishing	Reactions	Targets: Be	Targets: C
Sierk	DIC+FA	19%	42%
	Fusion-Fission	56%	29%
	QE	25%	29%
Cohen	DIC+FA	8%	29%
	Fusion-Fission	66%	41%
	QE	25%	29%

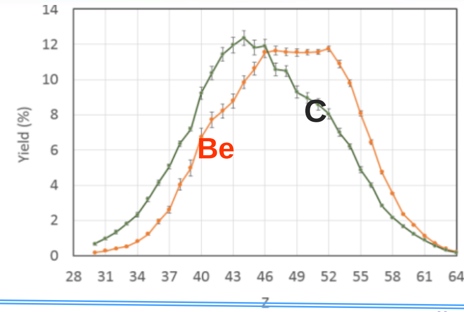
Momentum (hbar)	Be	C
L (Bfis=0)	67	63
L critical	75	87
L direct @ Rint	79 (12)	101 (38)
L max (grazing)	90.5	118.9
L max (LISE)	91.0	119.5



Carbon target.. 50% split… Why?
This is due to difference of moments of inertia between C+U and Be+U just above where fission barrier go to zero

e547 experiment: results interpretation





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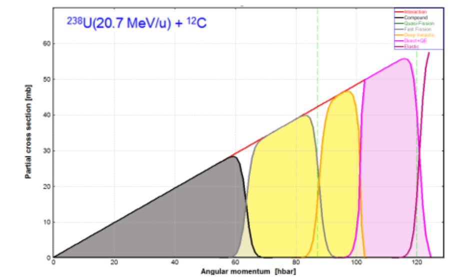
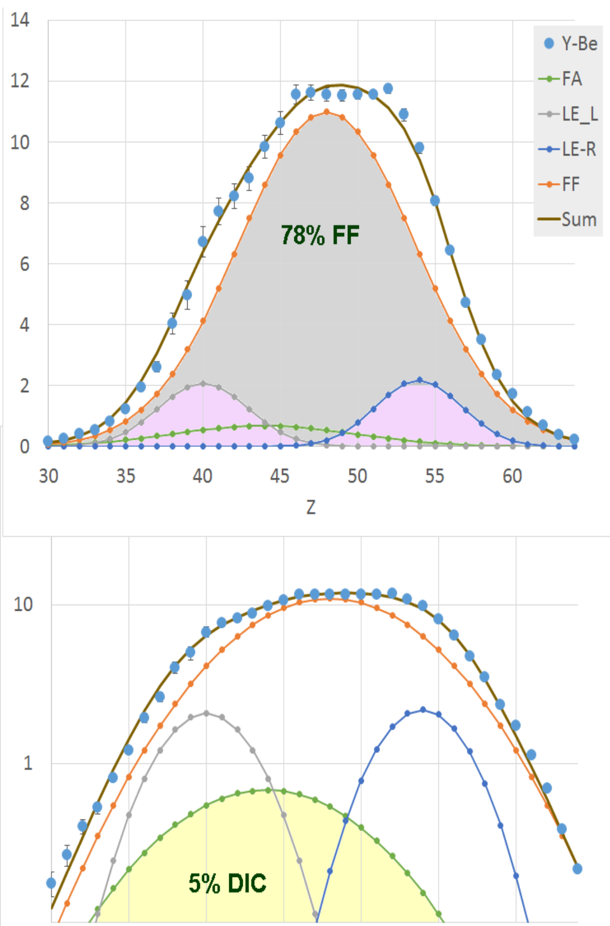
QE-channel partially goes to Low-excitation fission

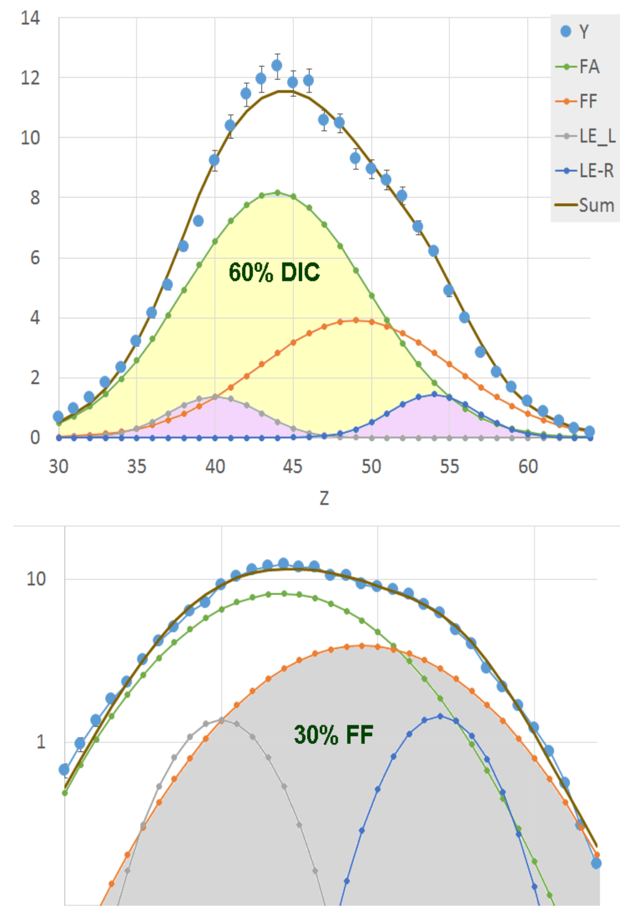


Preliminary!!!

Be-target



C-target

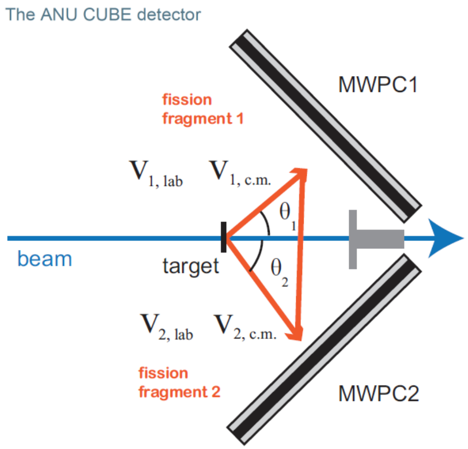


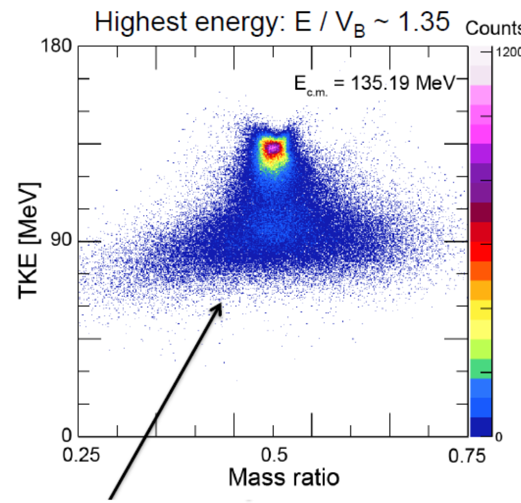
- Three main channels with earlier discussed parameters were used in fitting
- Reaction positions and widths were used the same in both case during fitting process except FF positions (48 and 49)
- From fitting results it follows, that Fusion-fission dominates in the case of Be-target, and sequential fission in the case of C-target
- New LISE^{++} partial cross section analysis fairly describes experimental results
- Significant distinction in elemental distributions of fragments produced with two different light target is explained by larger DIC component with C-target due to fission barrier vanishing
- Fusion-Fission mechanism is responsible in both cases for High-Z isotope production (Z>60)

Experimental study of barrier distributions for $^{58}Ni+^{60}Ni$

http://aip2014.org.au/cms/uploads/presentation/elizabeth_williams.pdf

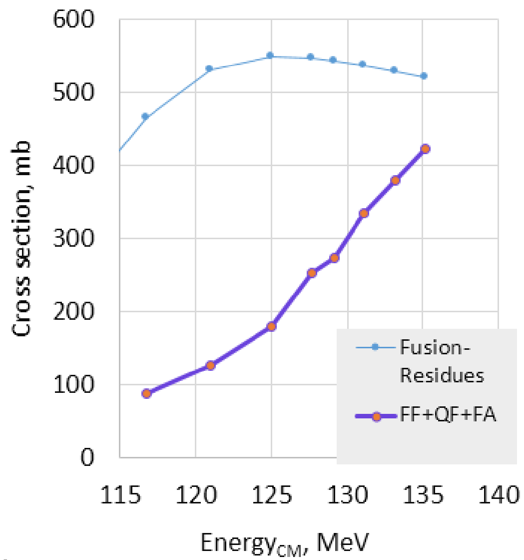
Dr. Elizabeth Williams
Department of Nuclear Physics
The Australian National University, Canberra, ACT, Australia
AIP Congress, Canberra, ACT
9 December 2014



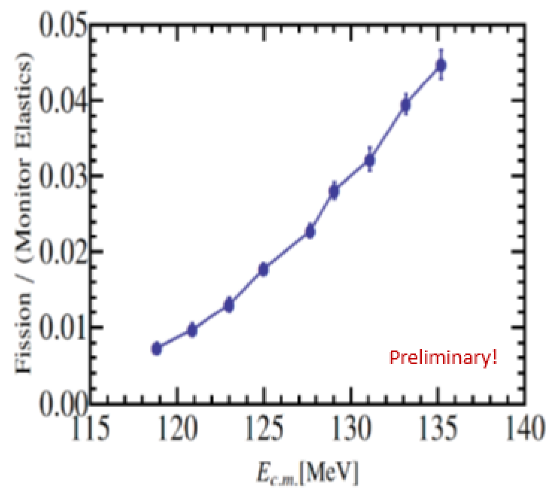


Deep inelastic + Fusion-fission
- Fusion-fission onset at $E_{c.m.}$ ~ 125 MeV

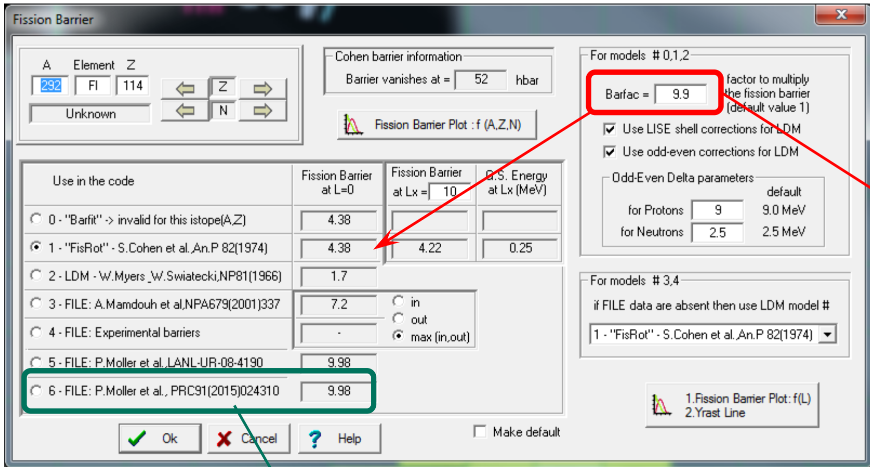
LISE++



E.W.'s presentation @ AIP

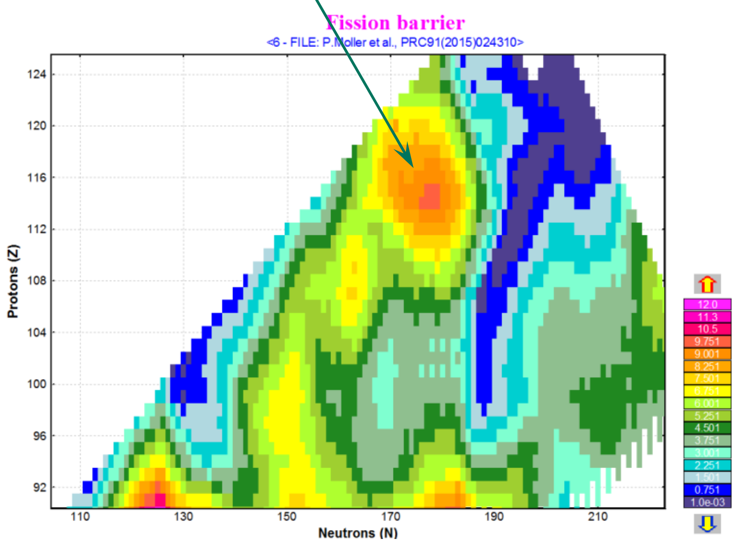


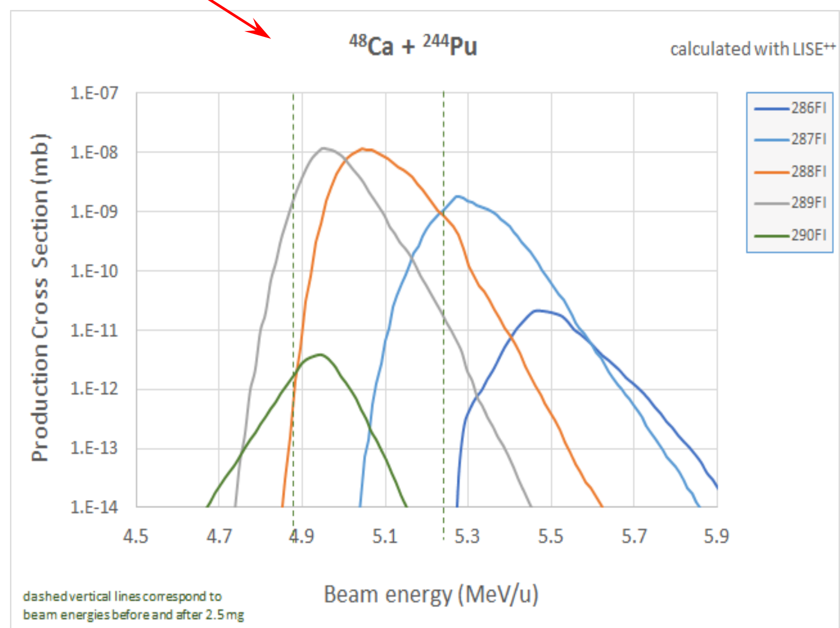
Using LISE^{++} in the SHE region : fission barriers



Barrier factor to describe experimental data or sophisticated calculations

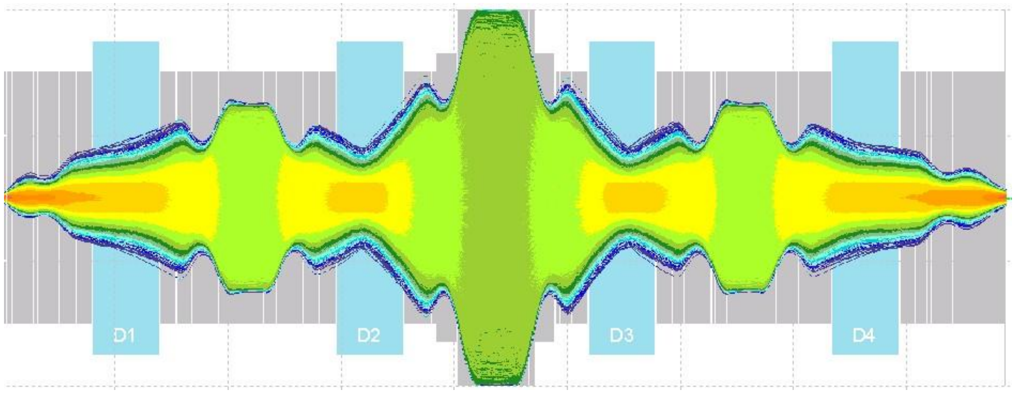
It looks like a very high value (with AME2012 use)
There is possibility to load user mass excess table





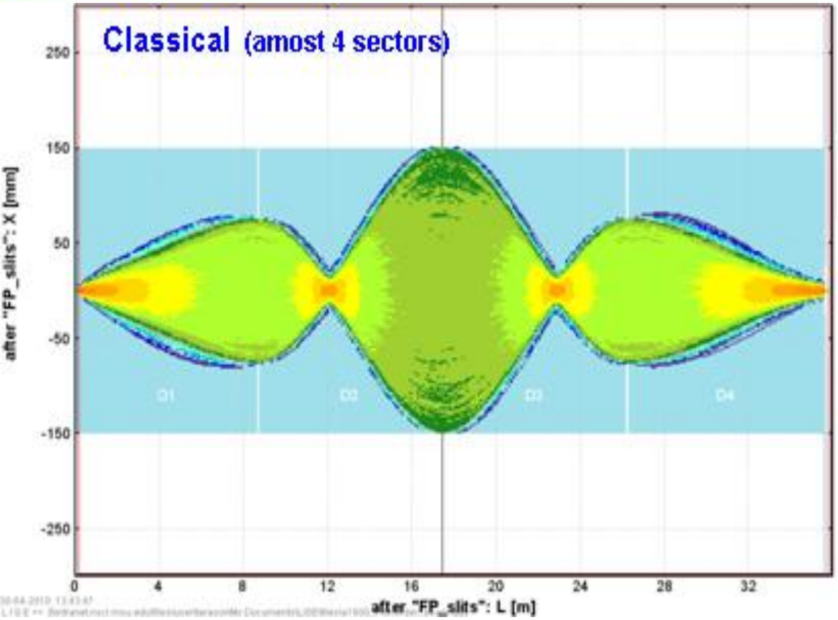
Progress in Beam Ion Optics

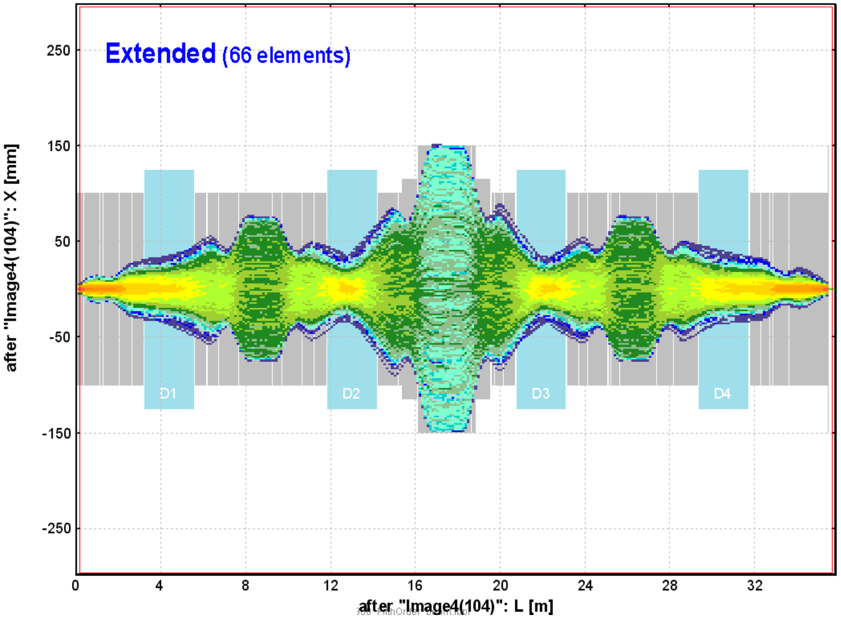
- Large progress in ion-beam optics with the introduction of elemental blocks that enable a new type of configuration, labeled “extended (or elemental)” in addition to the classic “sector” configuration.
- Optical matrices can now be calculated within LISE^{++} (up to second order), directly input by the user, or linked to COSY maps (up to fifth order).
- This enables a detailed analysis of the transmission, useful for fragment separator design, and is a powerful tool to calculate angular acceptances, and display ion-beam optics characteristics.



- Quadrupole & sextupole fields superposition
- Effective multipole length
- Magnetic field vs. current calibration B(I)
- In-house second order matrix calculation
- Import of TRANSPORT files
- Optimization of quad fields (in progress)

Extended (elemental) vs classic (sector) configurations



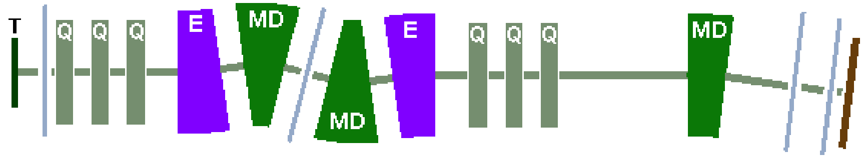


- **Classical (segmented) configuration:** dispersive block contains quads, drifts, dipole and other optical components
  - Fast transmission calculations
  - Optical matrices can be input by user or linked to COSY maps
  - Simple and compact description of optical system
  - Effective with analytical calculations for experiment planning

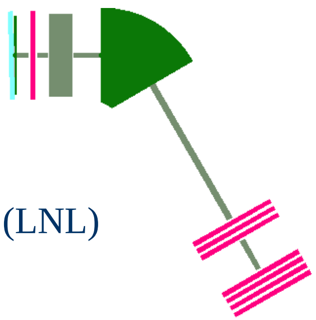
- **Extended (elemental) configuration:** like in the TRANSPORT code all elements are separated, and their matrices can be **calculated** by the LISE^{++} code including 2nd order
  - Allows detailed analysis of transmission
  - Optical matrices can be input by user, linked to COSY maps or calculated in the LISE^{++} code, and used in segmented configurations
  - Tools to obtain angular acceptances,
  - Tools for displaying ion-beam opt
  - Very useful with Monte Carlo calculations including fragment separator design

New Extended configurations in low-energy domain

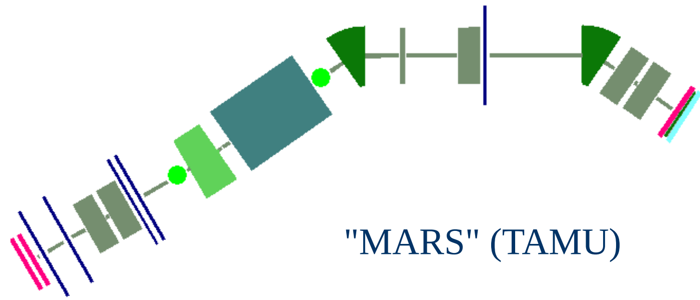
Available in the LISE++ package



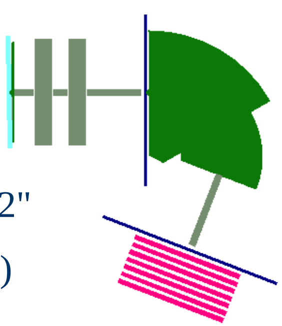
"SHELS" (FLNR/JINR)



"PRISMA" (LNL)



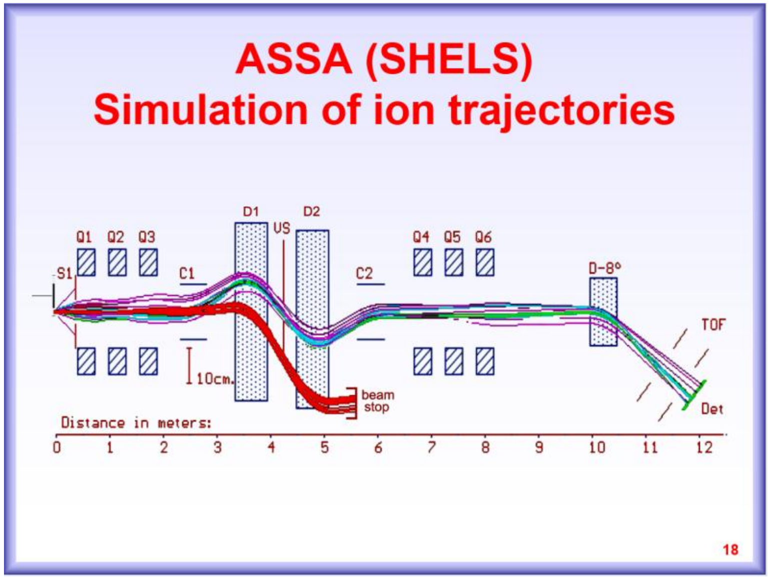
"MARS" (TAMU)



"MSP144+Q2"
(FLNR/JINR)

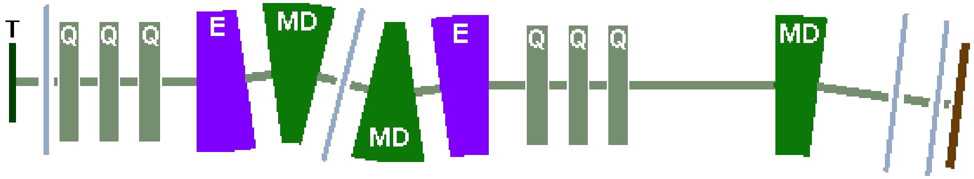
“LISE” (GANIL)*

** developed by GANIL team*



"SHELS" separator
http://www-win.gsi.de/tasca14/program/contributions_TASCA14/TASCA14_contribution_Popeko.pdf

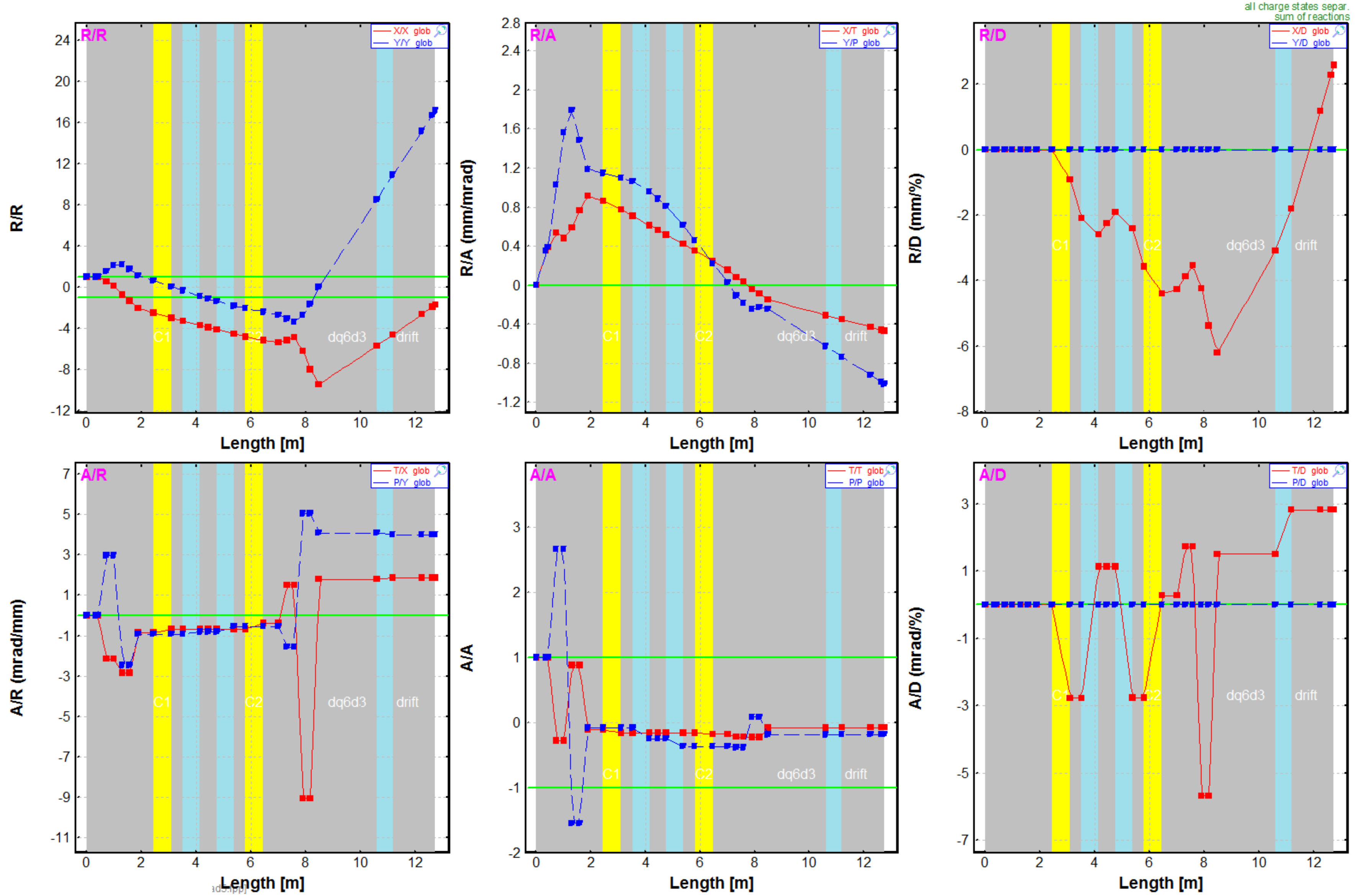
Based on experimental settings of ^{50}Ti(4.7 MeV/u) + ^{208}PbS



“SHELS” : 1st order matrix elements

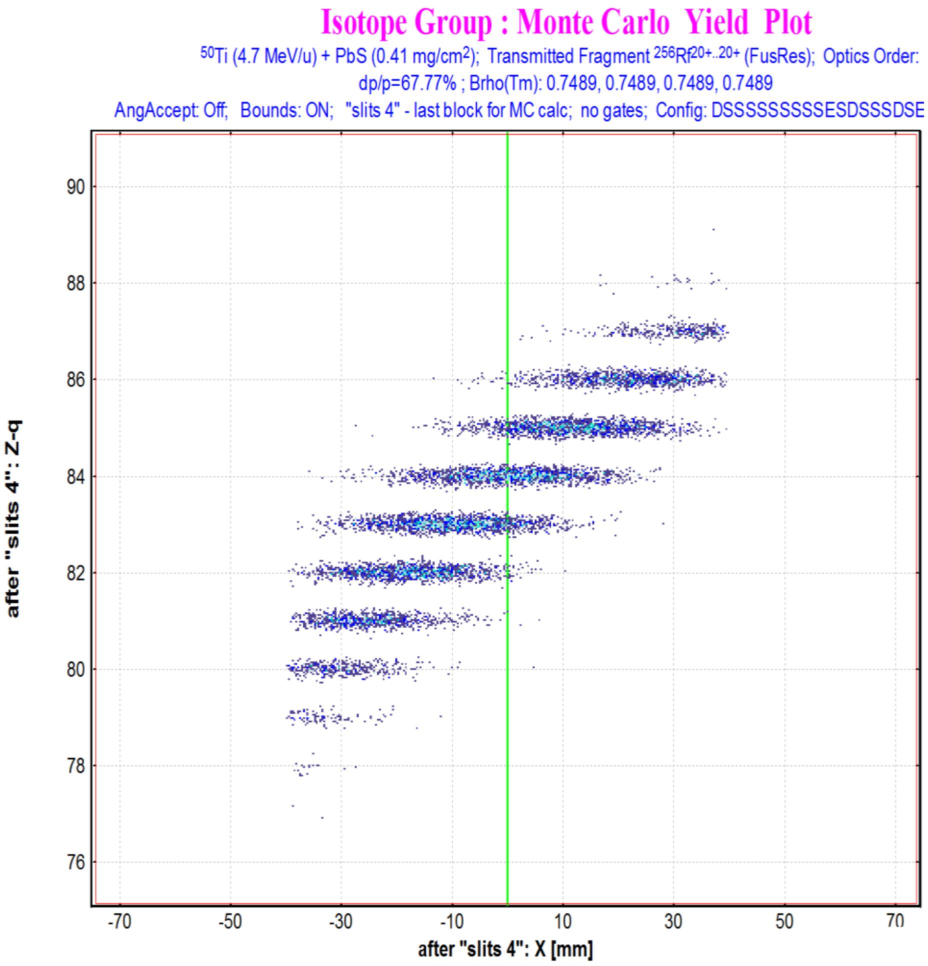
First order matrix elements

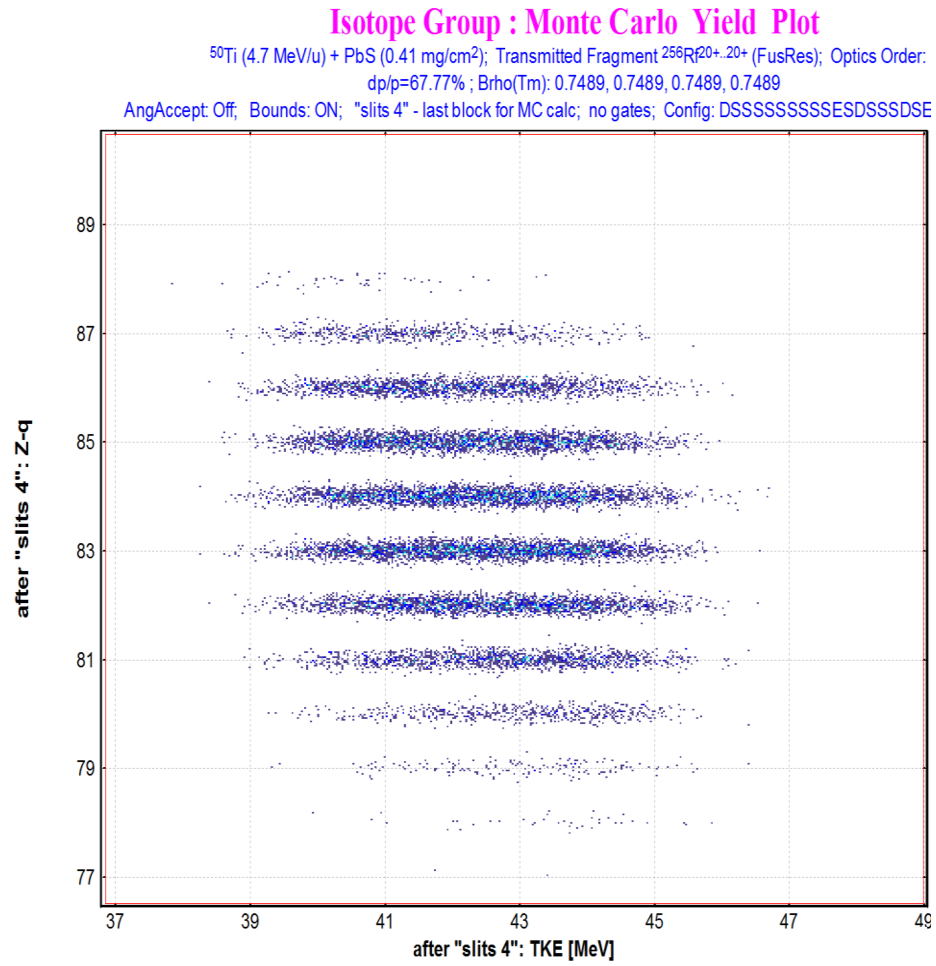
^{50}Ti (4.7 MeV/u) + PbS (0.41 mg/cm^2); Settings on $^{256}Rf^{20+..20+}$; Config: DSSSSSSSSESDSSSDSESSSSSSS...
dp/p=67.77% ; Brho(Tm): 0.7489, 0.7489, 0.7489, 0.7489



"SHELS" : spatial distributions @ slits 4

^{256}Rf charge states



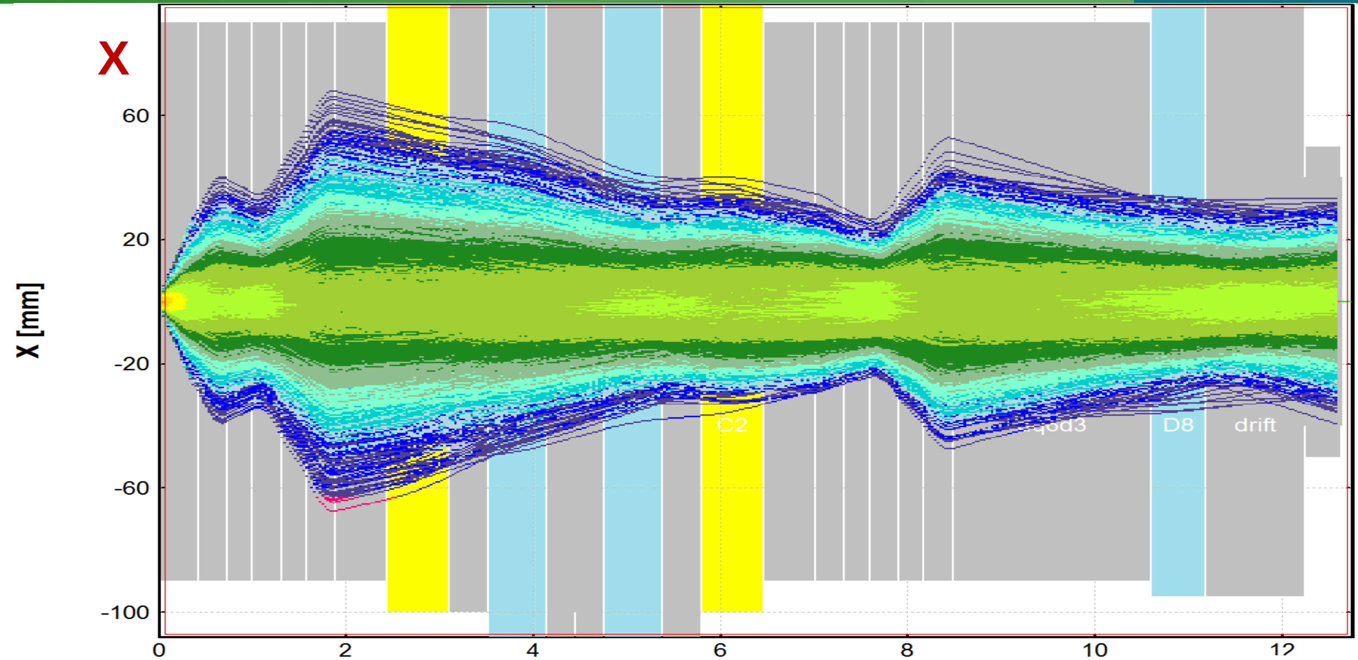


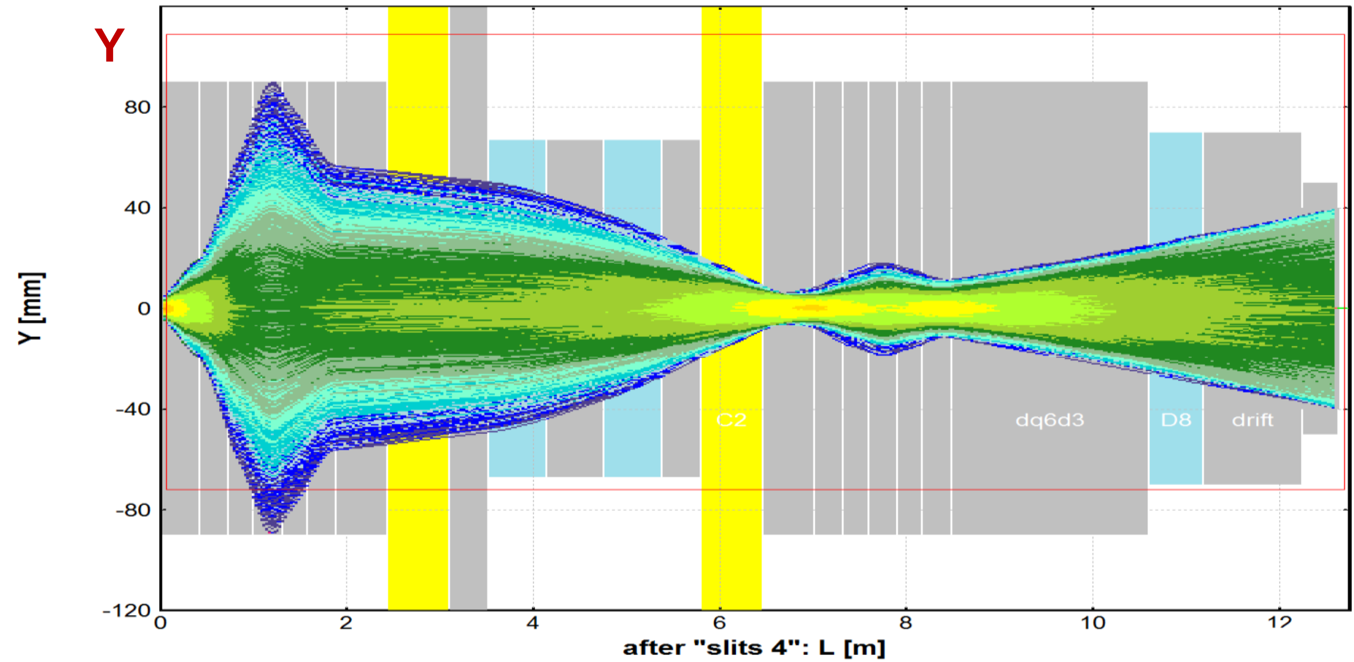
"SHELS" separator: envelopes of fragment of interest

MICHIGAN STATE UNIVERSITY
LISE++

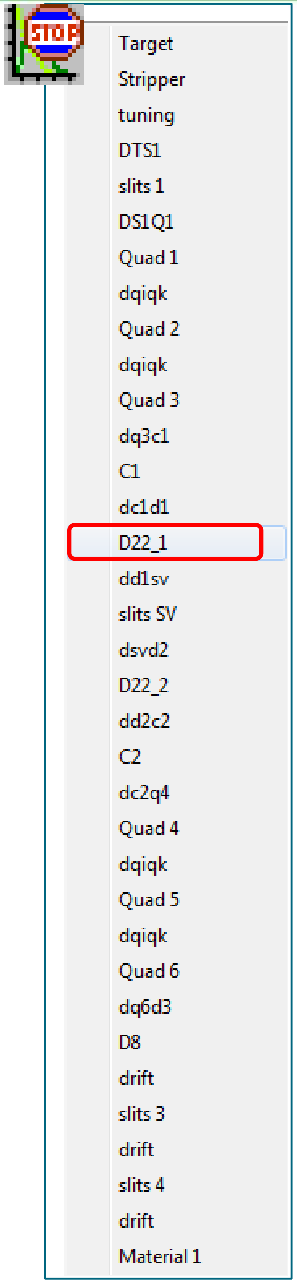
$^{256}Rf^{20+}$

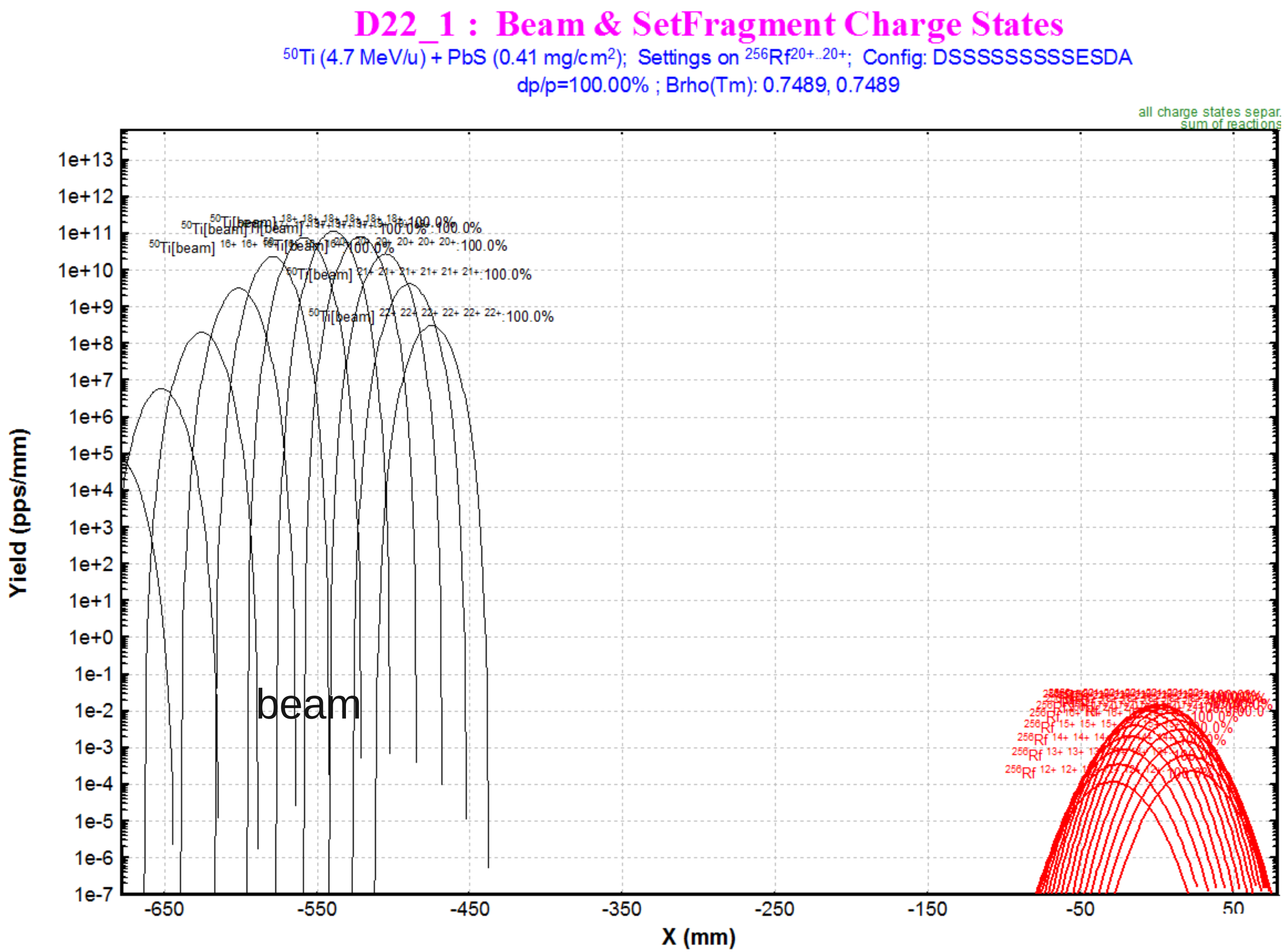
transmission
(without charge state coefficient)
86.6%





"SHELS" Beam suppression : after D22_1



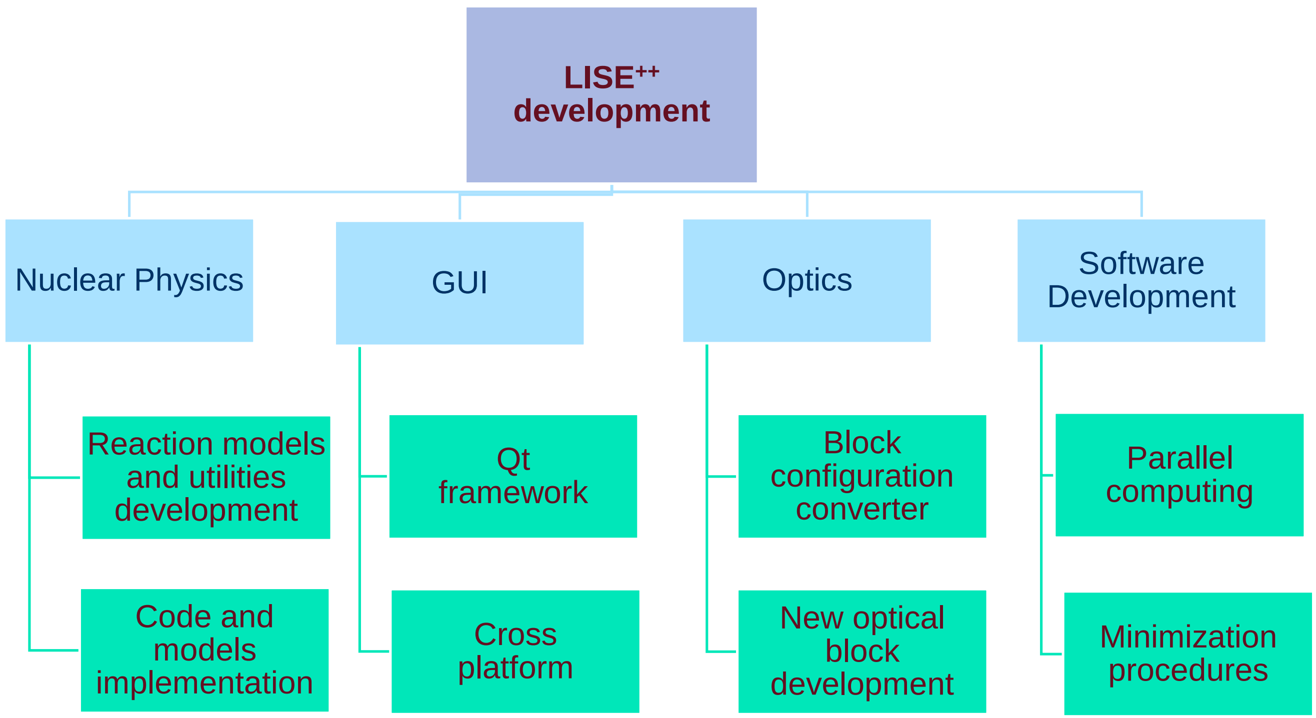


LISE^{++} future : Porting

M.Kuchera presentation at the CHEP 2015 conference

The LISE^{++} program will be transported to a modern Qt graphics framework. Benefits include providing a 64-bit application, cross-platform compatibility, and the ability to take advantage of computational advances.

Future plans include improved numerical optimization methods in areas such as ion optics. Lastly, integration with control systems are planned.



LISE^{++} future development

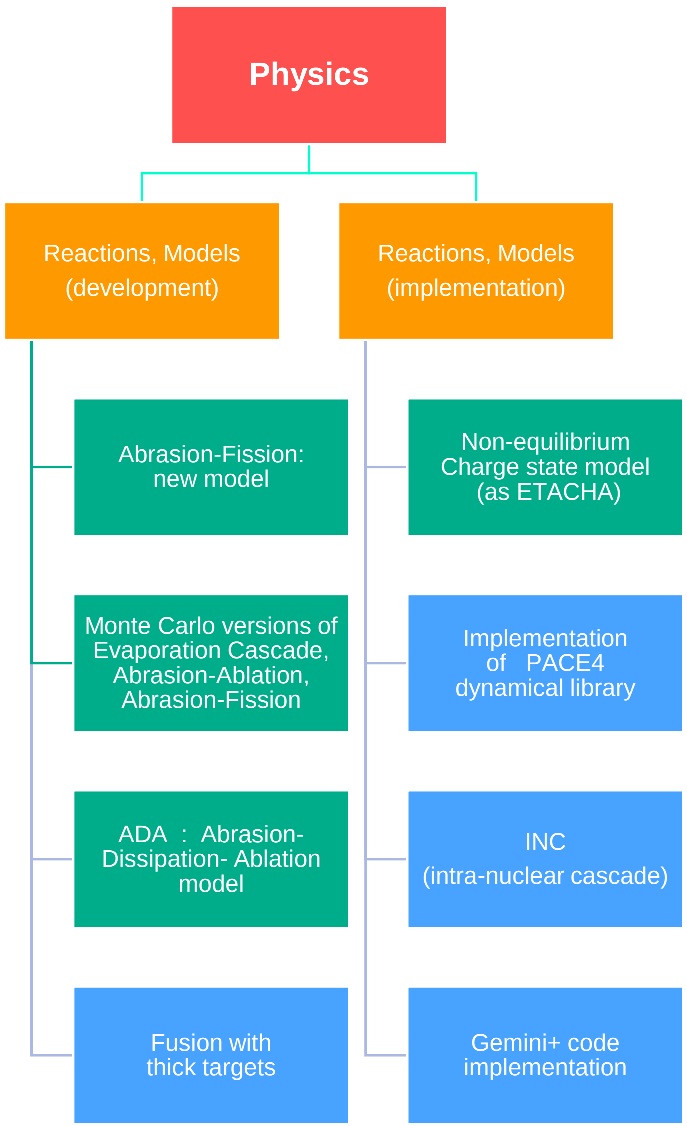
Nearest

- Radioactivity residues utility
  - residues in detector
  - harvesting
  - production in slits, detectors

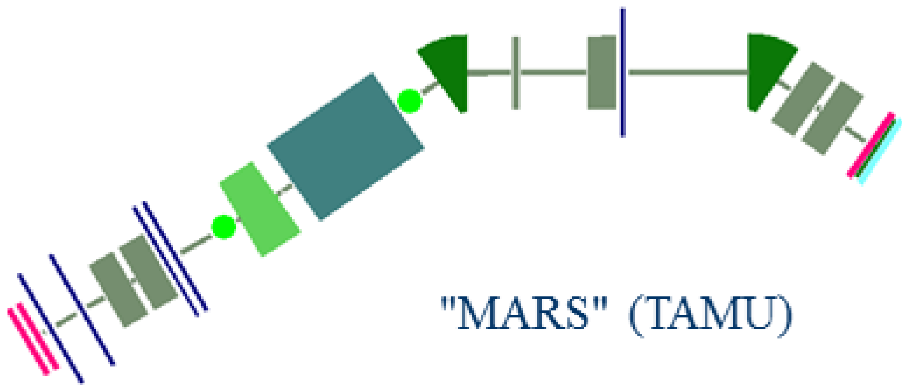
we already have
- half-life and decay database,
- shell (graphics),
- secondary beams in detector,
- reaction mechanism for production in slits and so on

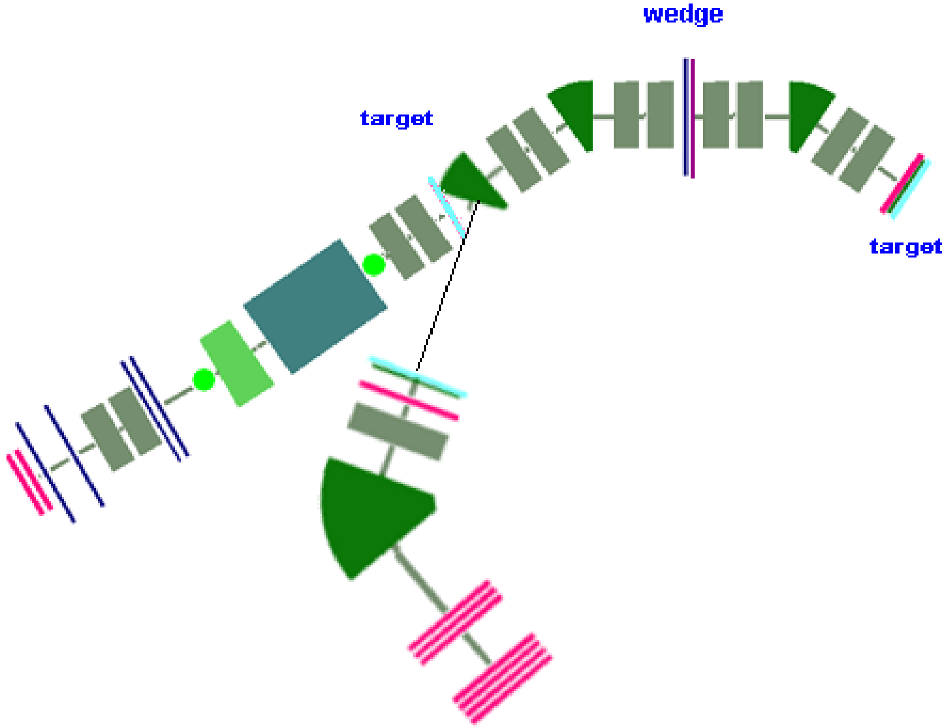
- Finish export/import ↔ TRANSPORT
- Quad field values minimization
- Gas-filled optical blocks in MC mode(???)
  (optical blocks including dispersive, and step by step spatial analysis in the material passing procedure already exist in the code)

Nuclear Physics models development during the porting process



MARS as a switch yard





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Dr.G.Knyazheva (FLNR/Dubna),

for fruitful discussions.

Thank you for your attention!

Good luck to the Spartans with the Blue Devils in the Final Four!

Authors, Grants

Exotic Beam Production with Fragment Separators

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GANIL E547 experiment

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