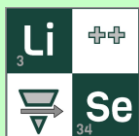
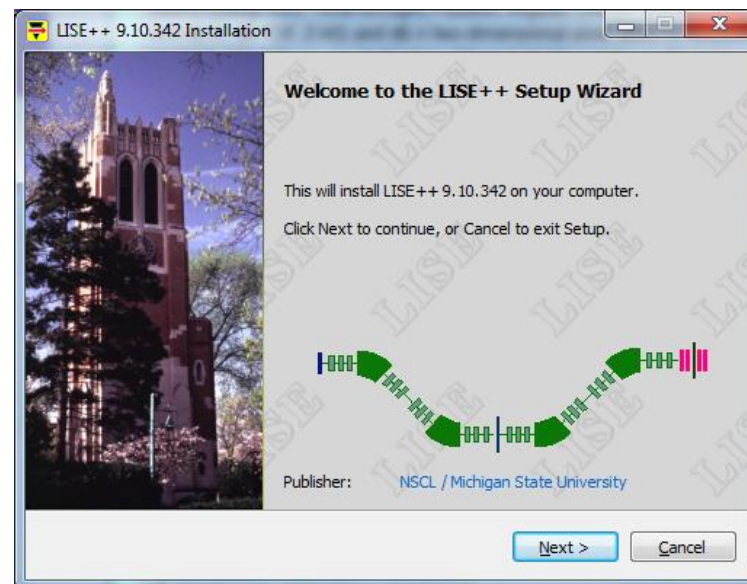


Predictions of Isotope Production Yields

by *Oleg B. Tarasov* (NSCL/MSU)



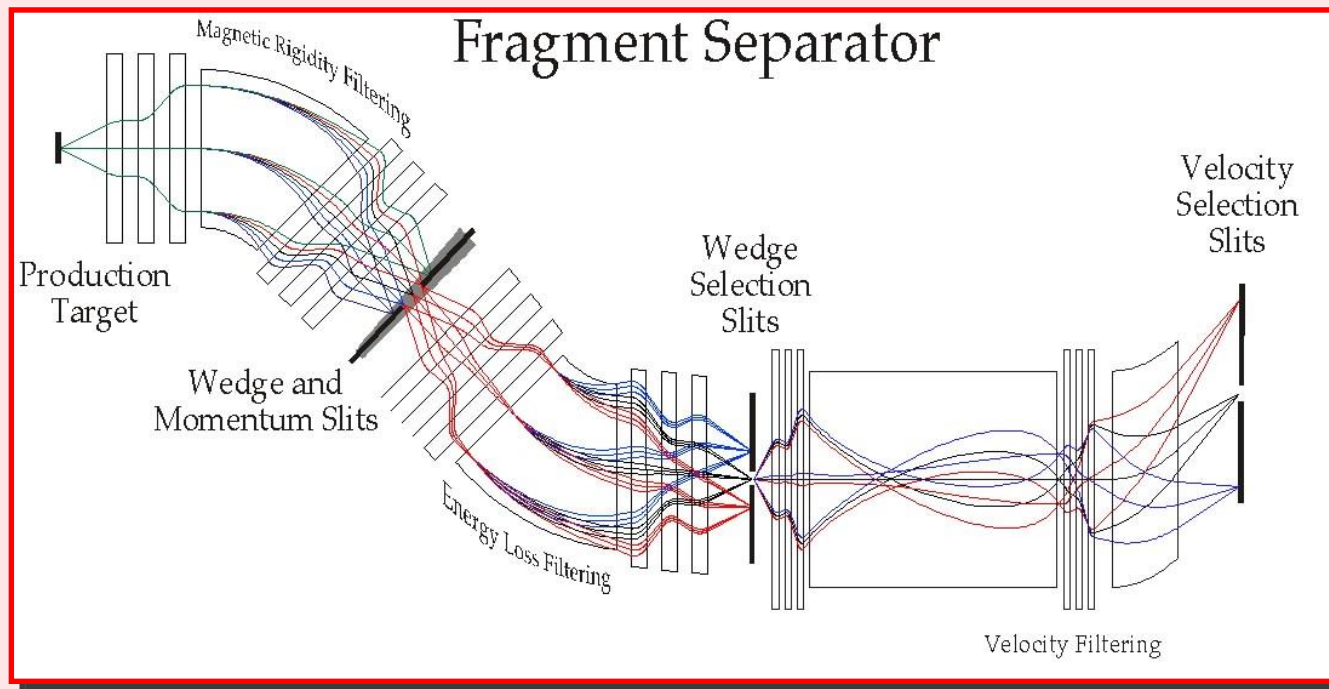
- Introduction to LISE++ code
- FRIB rates
- “Direct” production: ⁴⁴Ti example
- Commensal operation:
Helium-Jet Ion-Guide System



LISE++ : EXOTIC BEAM PRODUCTION WITH FRAGMENT SEPARATORS

- ❑ The LISE++ program is designed
 - to predict intensities and purities for the planning of future experiments with in-flight separators
 - is also essential for radioactive beam tuning where its results can be quickly compared to on-line data.

In-Flight isotope production: Basic principle of operation



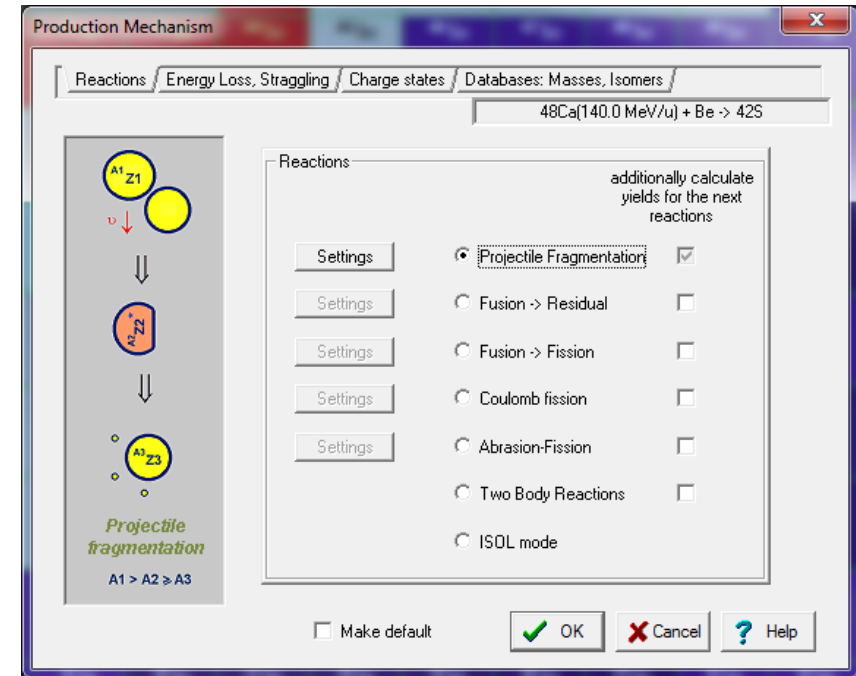
1. Production

2. Separation

3. Registration,
Identification

Table
Reactions and production models implemented in LISE++

Reaction	Production cross-section model	Ref.
Projectile fragmentation	EPAX 2.15, 3.1 LISE++ abrasion-ablation	[17] [27]
Fusion-residues	LisFus model PACE4 (manually)	[27] [28]
Fusion-fission	LISE++ package	[29]
Coulomb fission	LISE++ package	[30]
Abrasion-fission	LISE++ 3EER model	[31]
Two body kinematics	EPAX 2.15 (temporary)	



References:

- [17] K. Summerer, B. Blank, Phys. Rev. C 61 (2000) 034607; K. Summerer, Phys. Rev. C 86 (2012) 014601
- [27] O. Tarasov, D. Bazin, Nucl. Instr. and Meth. B 204 (2003) 74.
- [28] A. Gavron, Phys. Rev. C 21 (1980) 230.
- [29] O.B. Tarasov, A.C.C. Villari, , Nucl. Instr. and Meth. B 266 (2008) 4670-4673.
- [30] O.B. Tarasov, Eur. Phys. J. A 25 (2005) 751; Tech. Rep. MSUCL1299, NSCL, Michigan State University, 2005.
- [31] O.B. Tarasov, Tech. Rep. MSUCL1300, NSCL, Michigan State University, 2005.

Electromagnetic separation devices in LISE⁺⁺

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]
Gas-filled separator	Magnetic (B[T])	\vec{F}_B	Magnetic rigidity
Solenoid	Magnetic (B[T])	\vec{F}_B	Focusing (combination A, q, v)
Electrostatic dipole	Electric (E [kV/m])	$\vec{F}_E = q\vec{E}$	Electric rigidity $E\rho = \frac{mv^2}{q}$ [J/C]
RF kicker	Electric (E [kV/m])	\vec{F}_E	Time
RF buncher	Electric (E [kV/m])	\vec{F}_E	Bunching
Wien-filter <i>E-cross-B filter</i>	Magnetic (B[T]) Electric (E [kV/m])	$\vec{F} = \vec{F}_B + \vec{F}_E$	Velocity

- “Wedge” selection
- Decay time 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.

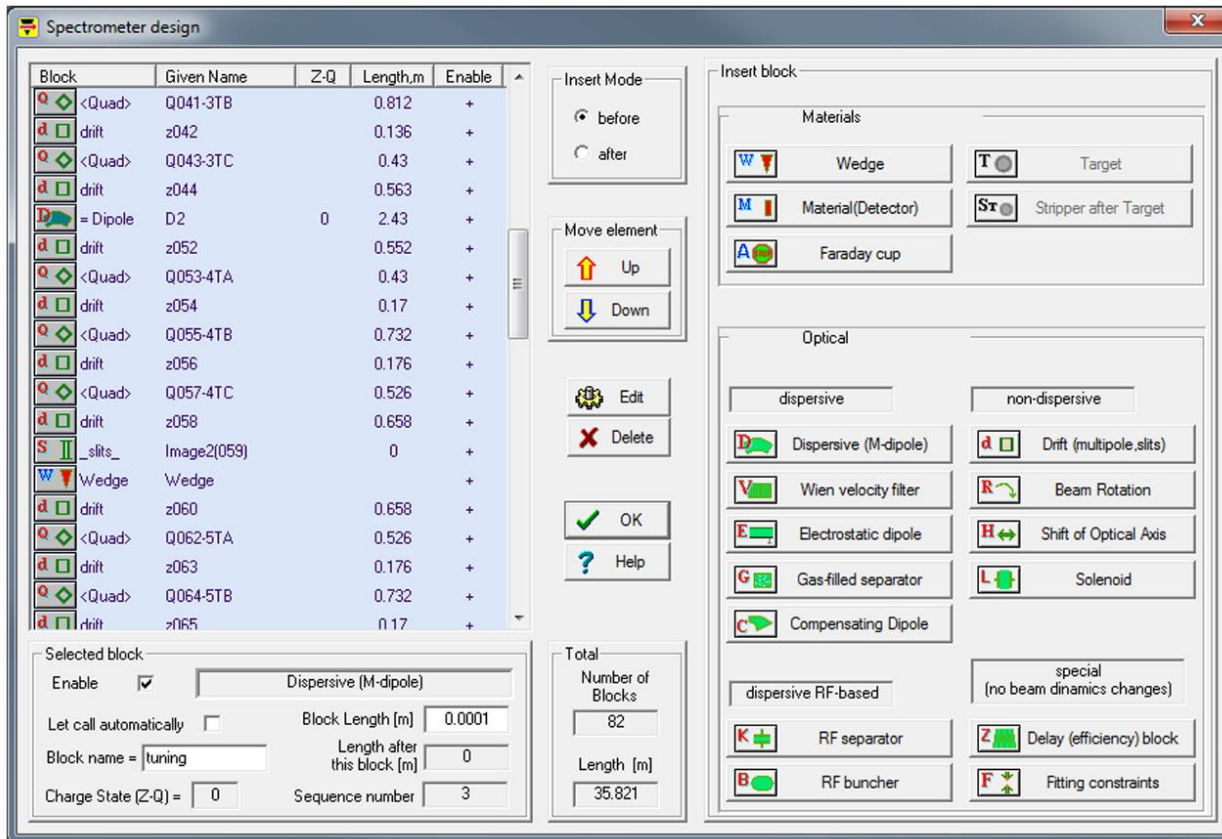
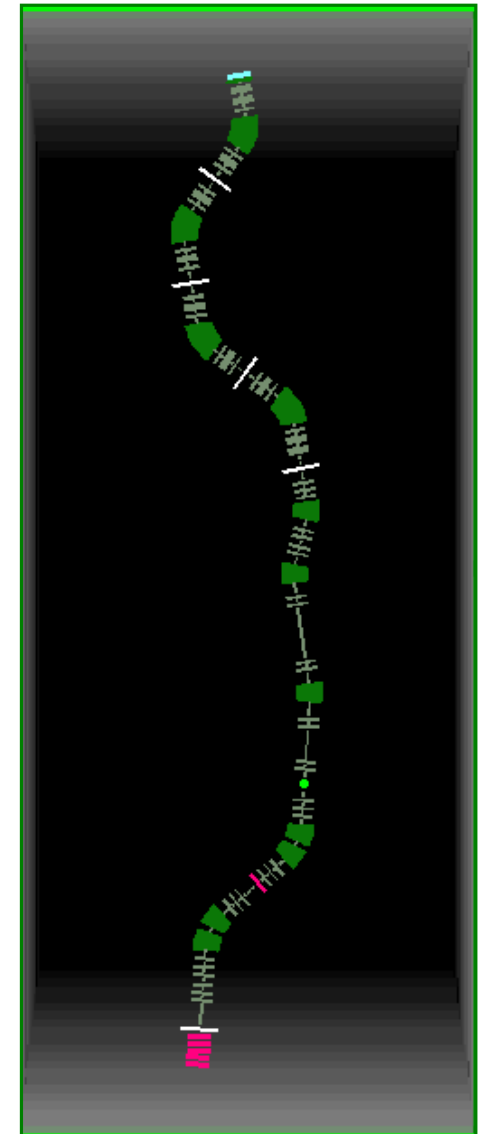


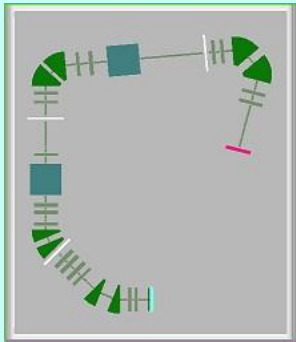
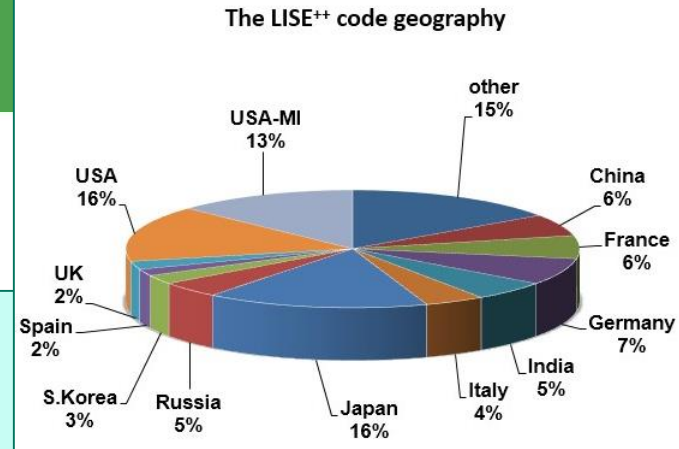
Fig. 1. Updated view of the "Spectrometer Design" dialog window.



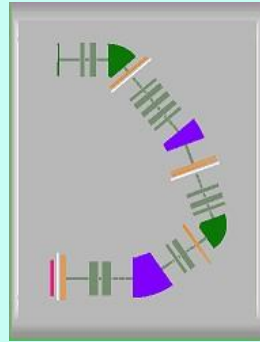
Configuration: A1900_S800BL (2nd order) 164 blocks

Application

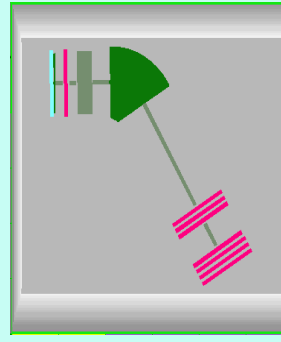
Includes *extended* configurations of separators at NSCL/MSU, RIKEN, GANIL, GSI, FLNR/JINR, TAMU, TRIUMF, ANL and others.



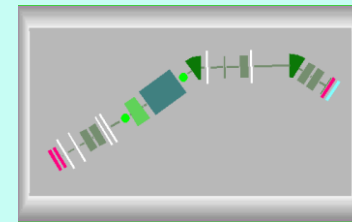
SECAR, *MSU*



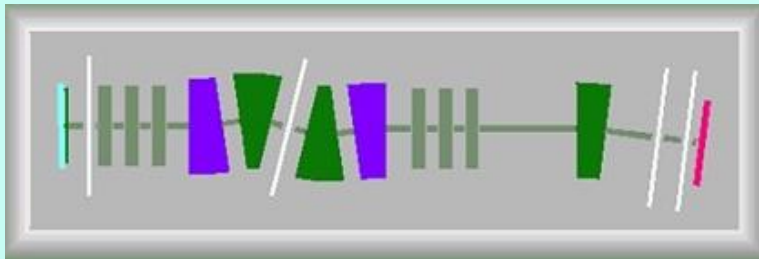
DRAGON, *Canada*



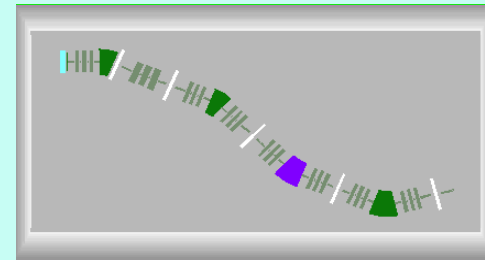
PRISMA, *Italy*



MARS,
TAMU



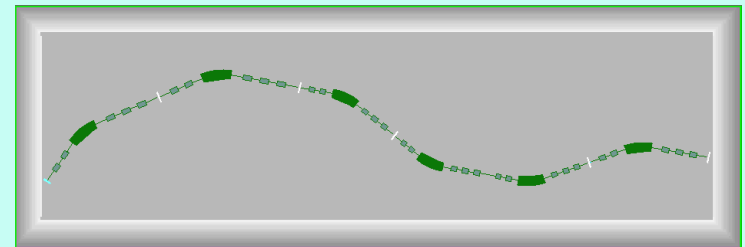
SHELS, *Russia*



S³, *France*



BigRIPS+ZeroDegree, *Japan*



SuperFRS_HEB, *Germany*

- The code is distributed free with the LISE⁺⁺ user license
- Official site : lise.nsl.msui.edu
- Current version 9.10.343, 15-Aug-2016

- Version 10 will be released soon
- Current operating system : MS Windows
- Currently porting to new framework : cross platform & parallel computing

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 optics),
- «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.

LISE++ [G:\M\lpp]

File Options Experiment Settings Physics Models Calculations Utilities 1D-Plot 2D-Plot Databases Help

Projectile: $^{82}\text{Se}^{34+}$ (sec 783)
 Fragment: $^{140}\text{MeV/u}$ 100 pNA
 Target: ^{19}F 1.5 cm x 2
 Stripper

Physics Models: tuning, z015, Q017-1TA, z018, Q019-1TB, z020, Q021-1TC, z022, D1, z030, Q031-2TA, z032, Q033-2TB, z034

dE-TKE
 ^{40}Ar (50.0 MeV/u) + Ta (100 μm); Settings on ^{36}Ar ; Config: DWDMMMMMM
 dp/p=4.05%; Wedges: Al (100 μm); Brho(Tm): 1.8555, 1.7893
 1st TKE detector: Material 3 ** dE: Material 3 - Si (350 μm)

Physical calculator window:
 Element: Ar, Z: 18, Q: 18, Ion mass = 35.9577 amu
 Energy: 12.0116 MeV/u, Energy: 11.9975 AMeV
 Brho: 1.0000 Tm, TKE: 431.91 MeV
 Erho: 47.7496 MJ/C, Velocity: 4.76846 cm/ns
 P: 5396.26 MeV/c, Beta: 0.1590566
 p_{impst}: 0.299792 GeV/c, Gamma: 1.012895

Radiation residue calculator

Mode to implant: 2. List of isotopes to implant from file
 File: "238U_Coulomb-Fission.radist" N of isotopes = 490

Select detector to obtain the list of isotopes stopped in: FP_PPAC0 N of isotopes = 0

Total Irradiation Rate: Rate = 7.563e+07 pps

Irradiation (Implantation): IT: Irradiation Time [sec] = 1, N of DI @ time (IT) = 553

Radiation Residues as Function of time (DT): DT: Decay Time after irradiation [sec] = 1e7, N of DI @ time (FT) = 138, Total Yield @ time (FT) = 7.57e+7

Buttons: Calculate, Options, 1D: Residues as function of time, 1D: Activity as function of time, 2D: Final Residues (@ TF), Quit, Link

Elapsed time is 00:00:36.74 or 36.74 sec

New utility from 08/01/16
 "Radiation Residue Calculator"
 is important tool regarding to isotope harvesting

http://lise.nsl.msu.edu/9_10/RadiationResidue.pdf

Site: <https://groups.nsl.mscl.msu.edu/frib/rates/fribrates.html>

100% | | | <https://groups.nsl.mscl.msu.edu/frib/rates/fribrates.html>

Enter values for A and Z

A	<input type="text" value="44"/>	
Z	<input type="text" value="22"/>	
N	22	
$T_{1/2}$	$1.890e+9$	sec
<input type="button" value="Calculate Yield"/>		

Beam

AZ	58Ni	
Energy	275.3	MeV/u

Fragment

Energy	223.9	MeV/u
$B_p(Q=Z)$	4.560	Tm
Fast beam rate	$1.46e+10$	pps
Stopped beam rate	$1.17e+8$	pps
Reaccelerated beam rate	$3.28e+7$	pps



- A). The LISE++ code (v.9.2.68) has been used for transmission calculations.
- B). The rates are estimated based on the EPAX 2.15^[1] cross section parameterization for fragmentation and the LISE++ 3EER model^[2,3] for in-flight fission.
- C). Reaccelerated and stopped beam rates above 1E+9 are very uncertain. The use of solid catchers may yield higher rates in some cases.
- D). Estimated rates may change as the various assumptions are tested and refined.

[1] - K. Sümmerer and B. Blank, *Phys. Rev. C* 61 (2000) 034607.
 [2] - O.B. Tarasov and D. Bazin, *NIM B* 266 (2008) 4657-466.
 [3] - O. B. Tarasov, "LISE++ development: Abrasion-Fission", *Tech.Rep. MSUCL1300, NSCL, Michigan State University 2005.*

For further information regarding these calculations, please refer to the [readme file](#) (PDF - 420 kB).

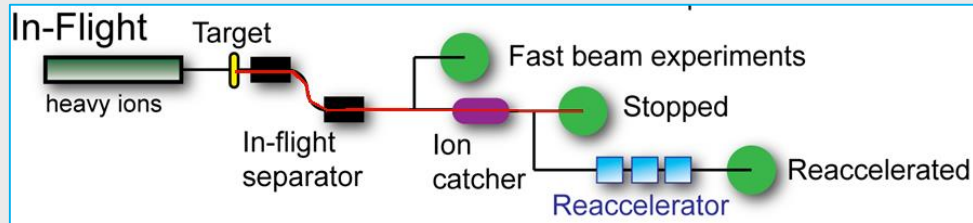
Applet created by Dennis Wey.

Please contact [Oleg Tarasov](#) with any questions or comments concerning to yields or this site.

settings

Table 1. Priority isotopes for harvesting at FRIB. These isotopes were identified at a Working Group meeting in Santa Fe, NM September 30 – October 1, 2010.

Isotope	Half-life	Application
^{32}Si	160 y	Tracer; geology and botany
^{44}Ti	60 y	Medicine, astrophysics, nuclear structure
^{48}V	16 d	Stockpile Stewardship
^{67}Cu	2.6 d	Medicine
^{85}Kr	10.0 d	Astrophysics, stockpile stewardship
Eu*		Stockpile Stewardship
^{211}Rn	14.6 h	Medicine
^{225}Ra	14.9d	Medicine, Electric Dipole Moment
^{225}Ac	10.0 d	Medicine



Projectile $^{58}\text{Ni}^{28+}$
140 MeV/u 1 pA
Fragment $^{44}\text{Ti}^{22+}$

T Target ^9Be
584.291 $\mu\text{g}/\text{cm}^2$

Str Stripper

D D1 **Brho**
2.9668 Tm

S II I1_slits **slits**
-100 H +100

D D2 **Brho**
2.9668 Tm

S II I2_slits **slits**
-150 H +150

W I2_wedge **AI**
100 $\mu\text{g}/\text{cm}^2$

D D3 **Brho**
2.8676 Tm

D D4 **Brho**
2.8676 Tm

M I FP_PPAC0 **AI**
2 $\mu\text{g}/\text{cm}^2$

M I FP_PPAC1 **AI**
2 $\mu\text{g}/\text{cm}^2$

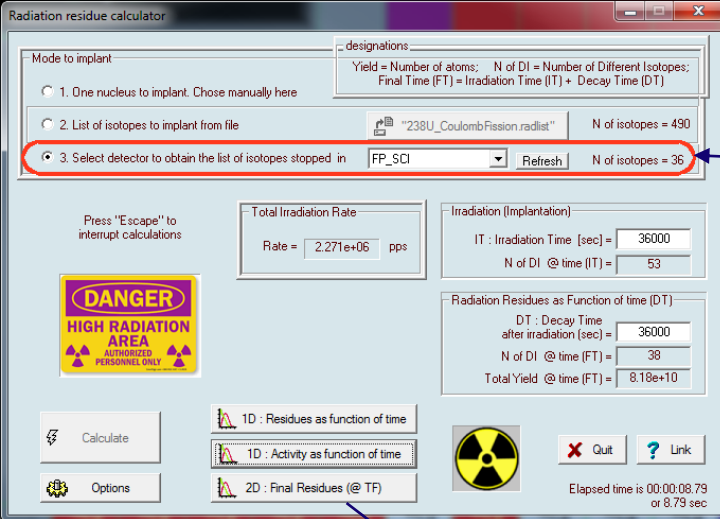
S II FP_slits **slits**
-8 H +8
-25 V +25

M I FP_PIN **Si**
513 $\mu\text{g}/\text{cm}^2$

M I FP_SCI **C9H10**
100 nm

Use the wedge for purity

⁴⁴Ti's case : Residues



Isotopes selected by the Fragment-Separator are implanted in FP_SCI detector

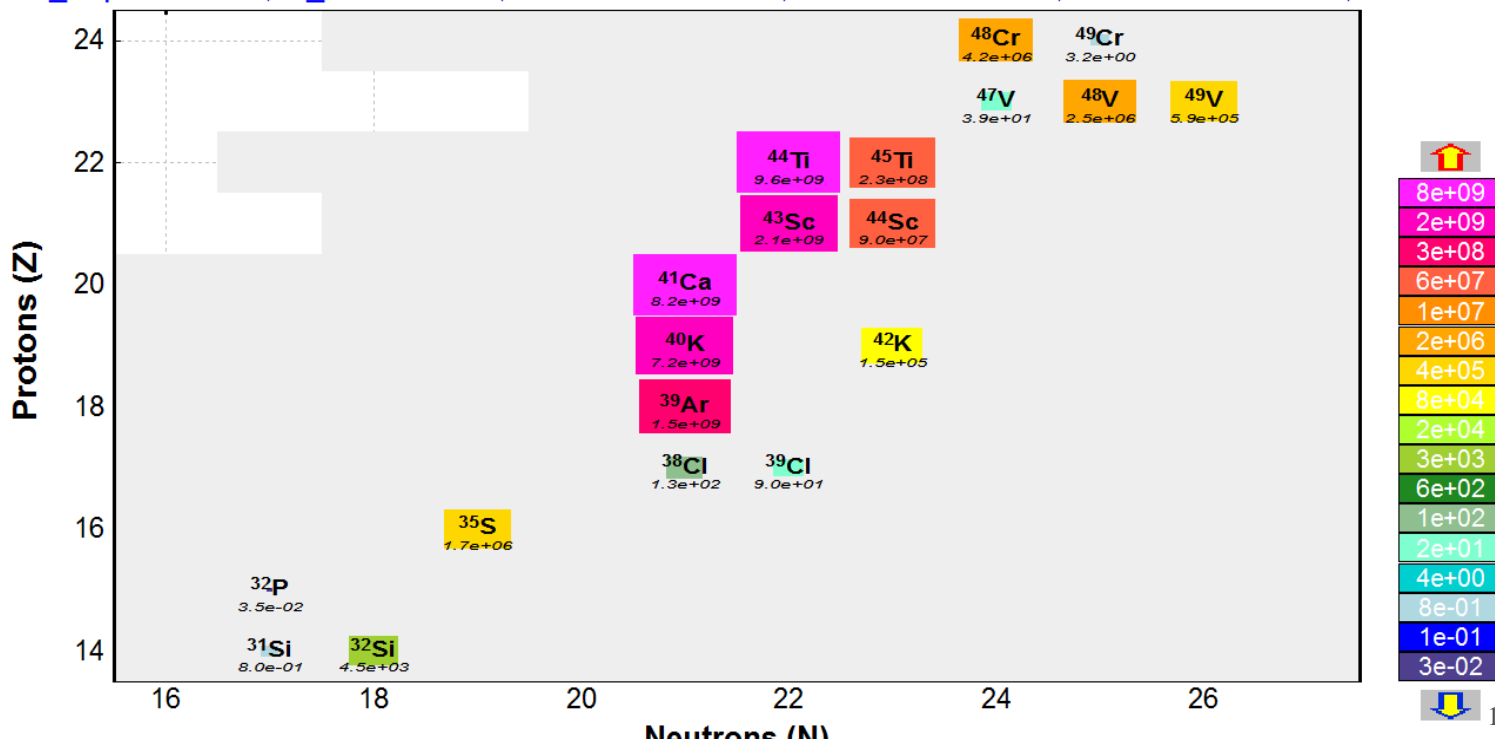
http://lise.nsl.msu.edu/9_10/radiation/44Ti%20from%2058Ni.lpp

10 hours of irradiation, 10 hours of decay :
⁴⁴Ti's number of atoms is highest!

Radioactive decay residues

Implantation detector : "FP_SCI" (36 different isotopes)

Irradiation Time (IT) = 3.60e+04 sec; Decay Time (DT) = 3.60e+04 sec; Plot only Radioactive
N_Implant=1000, N_Resid=1000, Abs.Error=1.0e-09, Rel.Error=1.0e-03, Threshold=1.0e-08, Model="OI"

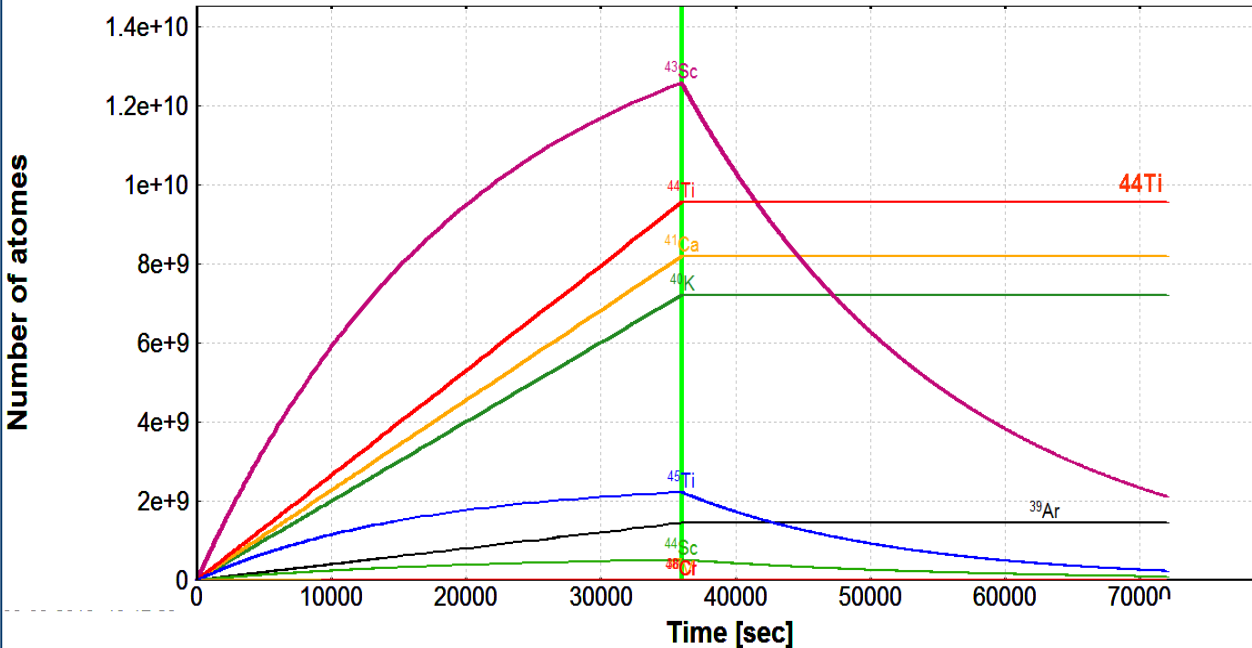


Evolution of Radiation Residue Yield

Implantation detector : "FP_SCI" (36 different isotopes)

Irradiation Time (IT) = 3.60×10^4 sec; Decay Time (DT) = 3.60×10^4 sec; Plot only Radioactive

$N_{\text{Implant}}=1000$, $N_{\text{Resid}}=1000$, Abs.Error= 1.0×10^{-9} , Rel.Error= 1.0×10^{-3} , Threshold= 1.0×10^{-8} , Model=

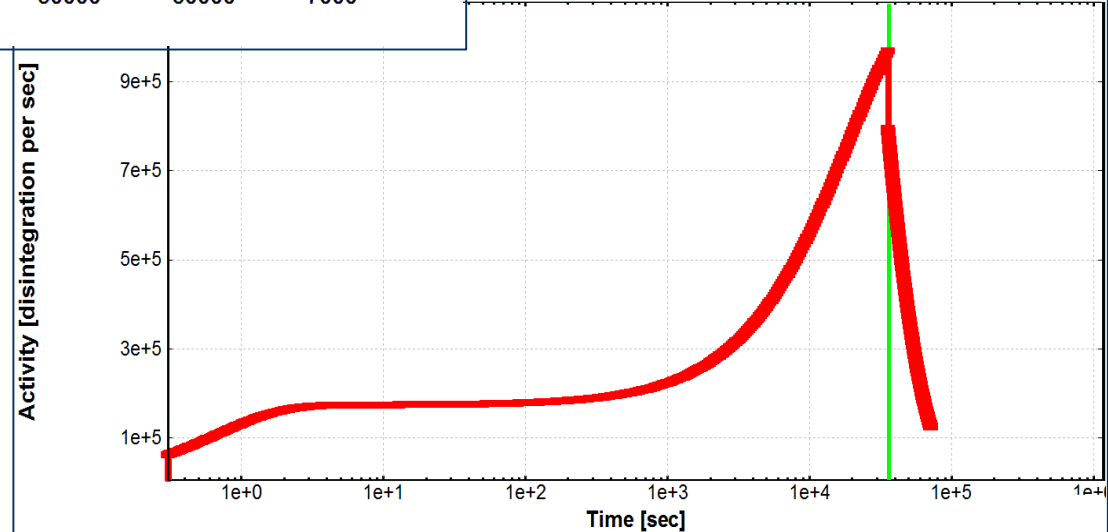


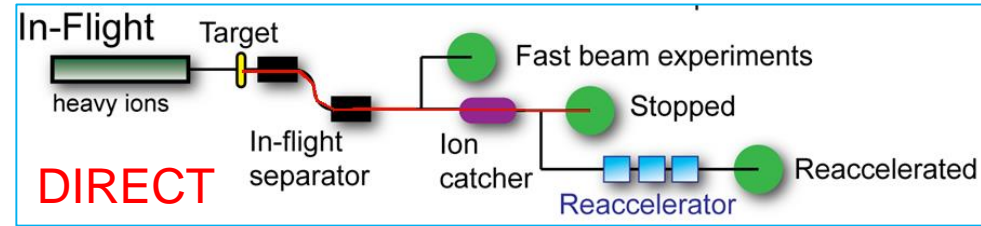
Activity

detector : "FP_SCI" (36 different isotopes)

sec; Decay Time (DT) = 3.60×10^4 sec; Plot only Radioactive

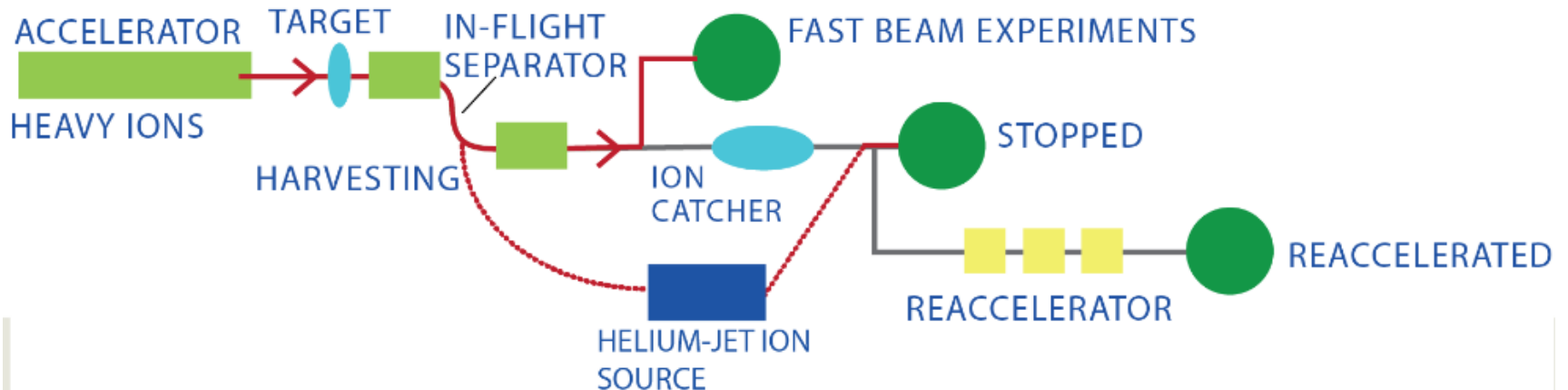
Abs.Error= 1.0×10^{-9} , Rel.Error= 1.0×10^{-3} , Threshold= 1.0×10^{-8} , Model="OD





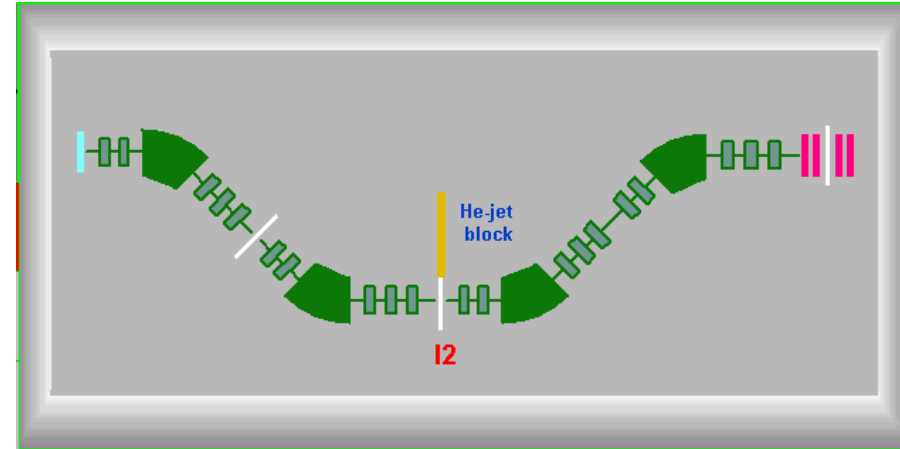
Commensal operation:

- Rare isotopes produced off-axis of the fragment separator are caught in a high-pressure cell filled with a helium-aerosol mixture
- Harvested isotopes are transported to the helium-jet ion source
- Rare isotopes are accelerated, purified and delivered to experimental stations



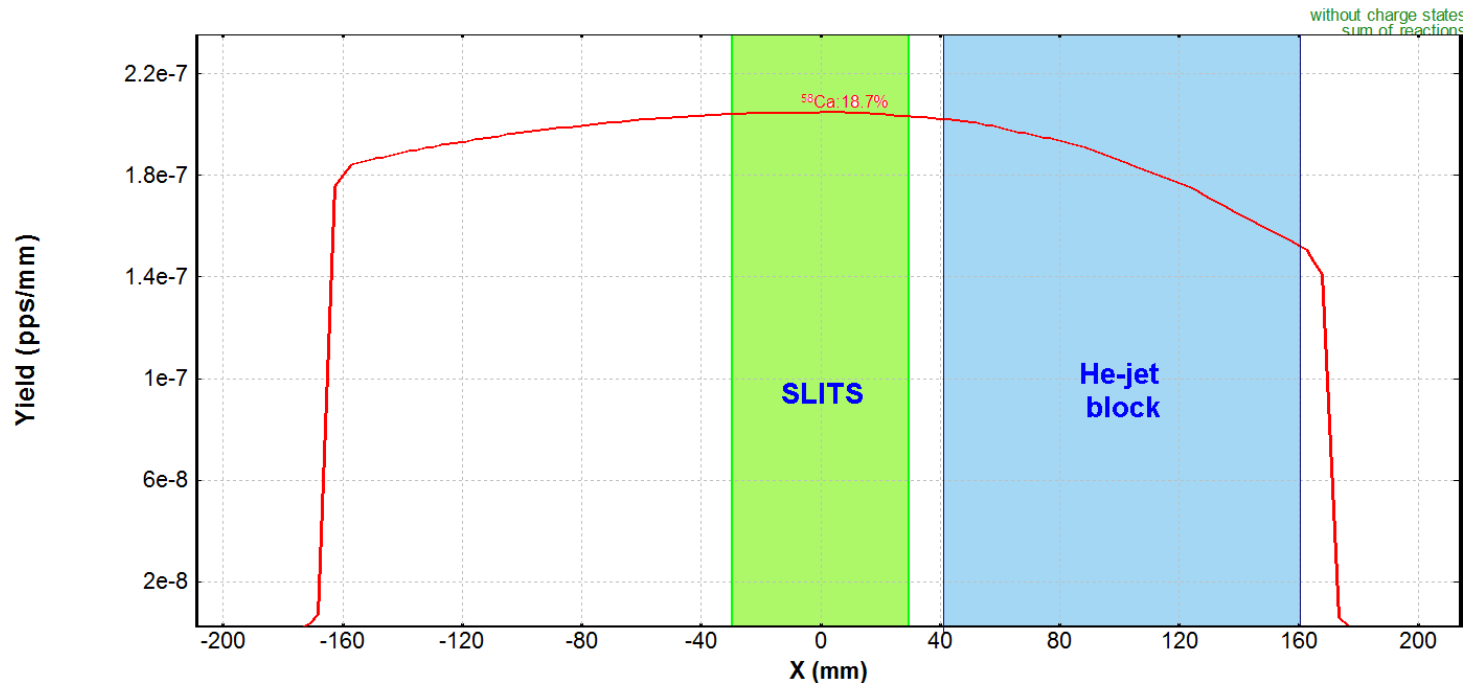
Assume the production ^{58}Ca from using the ^{82}Se beam with the A1900 fragment separator, and the He-jet block located at 40-160 mm (I2 position)

http://lise.nsl.msui.edu/9_10/radiation/82Se_58Ca.lpp



I2_slits-Xspace: output before slits

^{82}Se (140 MeV/u) + Be (500 mg/cm²); Settings on ^{58}Ca ; Config: DSDSWDDMMSSMM
 dp/p=1.00% ; Wedges: 0; Brho(Tm): 4.4920, 4.4920, 4.4920, 4.4920



Steps to create the “He-jet” configuration from previous case:

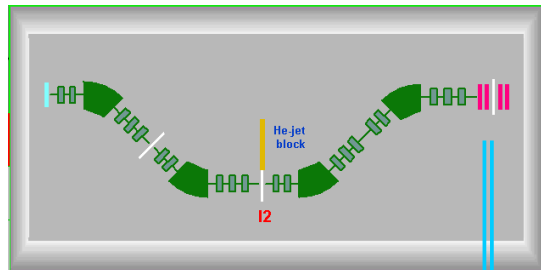
1. Set Width of I2 slits equal to the He-jet block width (+/- 60 mm)
2. Behind the I2 slits insert a thick material enough to stop all products
3. After this material set the Faraday cup
4. Insert the shift block dX=100 mm in front of the I2 slits, assuming the central axis is passing through the center of He-jet block

http://lise.nsl.mscl.msu.edu/9_10/radiation/82Se_58Ca_He-jet.lpp

P	Projectile	82 Se ³⁴⁺
		140 MeV/u 100 pA
F	Fragment	58 Ca ²⁰⁺
T	Target	⁹ Be 500 mg/cm ²
St	Stripper	
D	D1	Brho 4.4920 Tm
S	I1_slits	slits -100 B +100
D	D2	Brho 4.4920 Tm
H	Shift 1	d X = +100.0 mm
S	I2_slits	slits -ε0 B +ε0
M	He-jet block	Fe 10 mm
A	FaradayCup 1	<input checked="" type="checkbox"/> enable

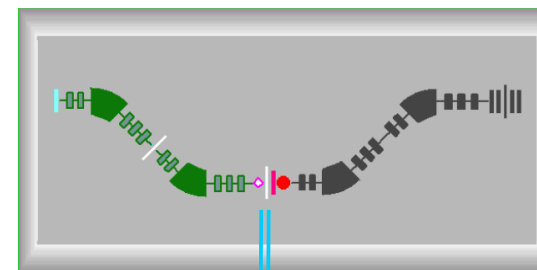
47Ti	48Ti	49Ti	50Ti	51Ti	52Ti	53Ti	54Ti	55Ti	56Ti
------	------	------	------	------	------	------	------	------	------

82Se 58Ca.lpp

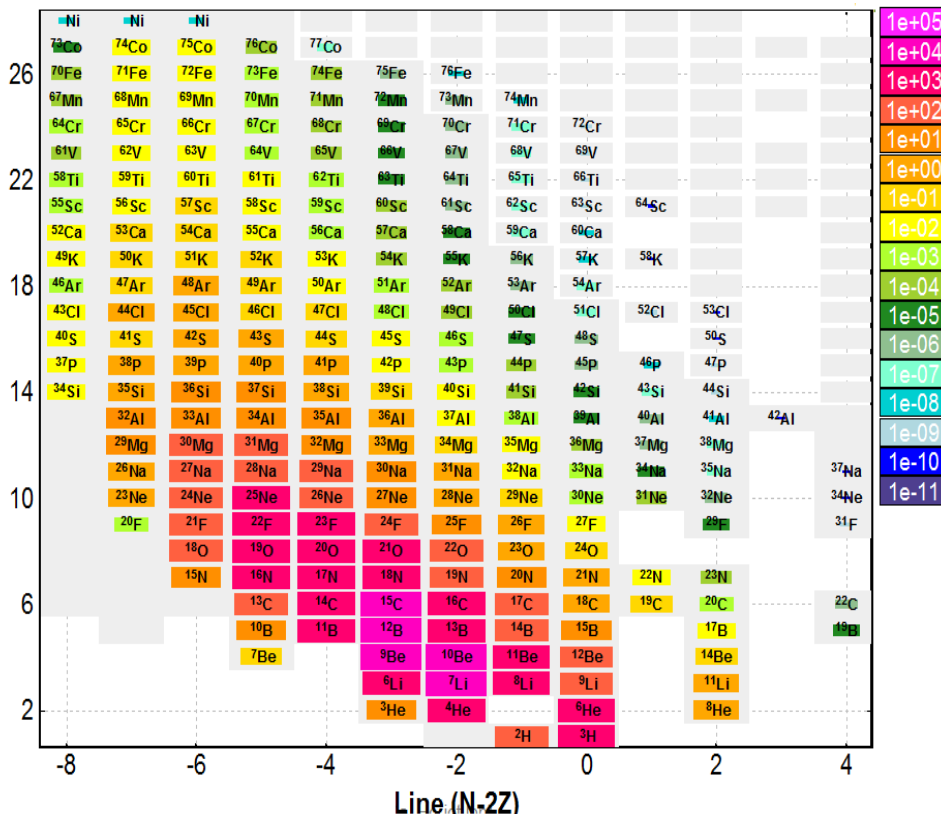
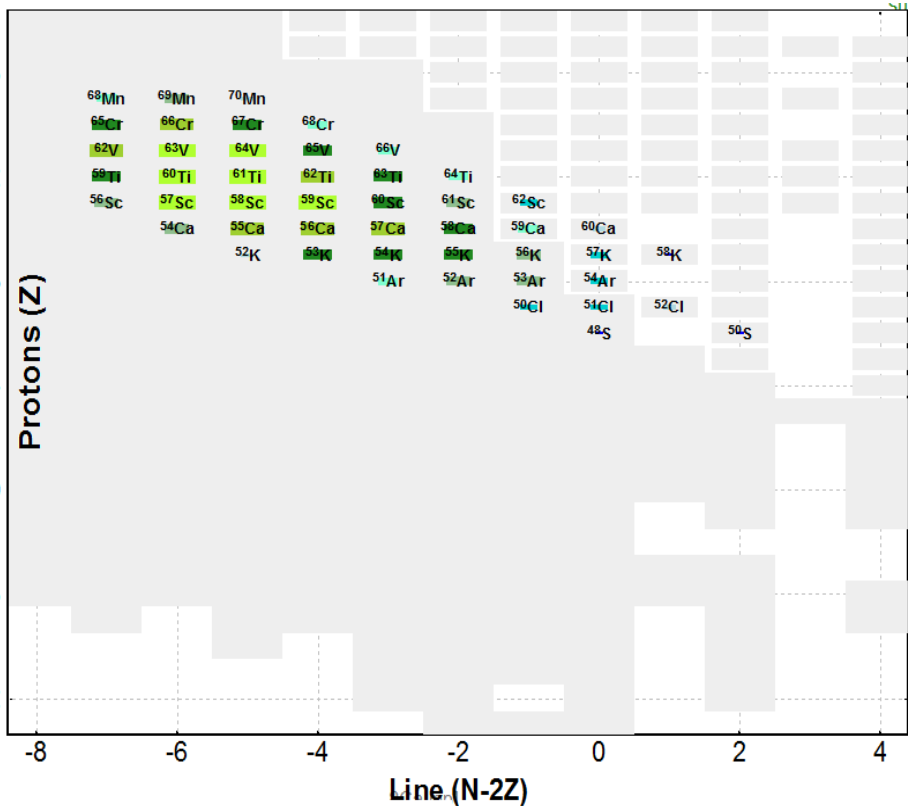


Rate 0.02 pps

82Se 58Ca He-jet.lpp



Rate 1.6e5 pps



1. Calculate all products with new 82Se_58Ca_He-jet.lpp file
2. Call the Radiation Residue Calculator
3. Set the Irradiation and Detector (Transportation) times (for example* 1 & 10 hours)
4. Chose “He-jet block” as detector
5. Click the “Calculation” button

Option	Value	Description	Default value
N_Implant	500	number of points : Irradiation	100
N_Decay	500	number of points : DECAY	100
AbsError	1.000e-15	absolute error tolerance	1e-11
RelError	1.000e-04	relative error tolerance	1e-03
Y_thrshld	1.000e-14	Minimum yield value	1e-10

Maximum number of iterations (50000) has been reached for N_implantation=100 for two last implantation steps

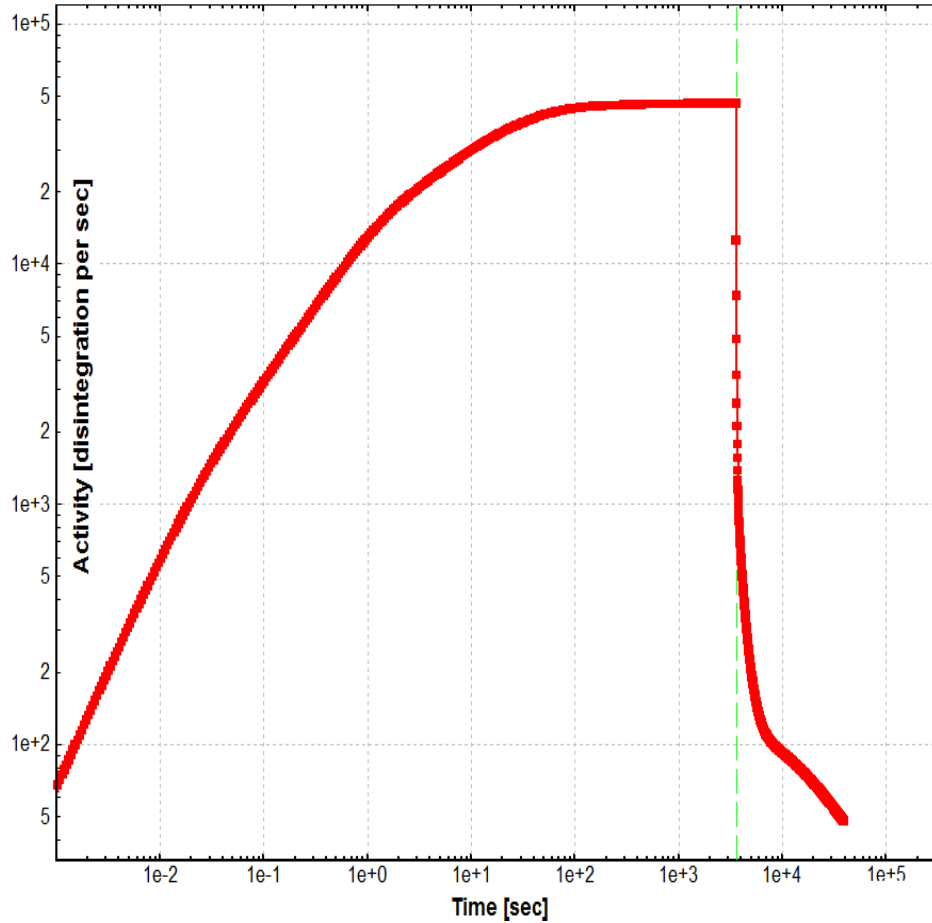
* It is a JUST EXAMPLE!

Activity

Implantation detector : "He-jet block" (161 different isotopes)

Irradiation Time (IT) = 3.60e+03 sec; Decay Time (DT) = 3.60e+04 sec; Plot All isotopes

N_Implant=500, N_Resid=500, Abs.Error=1.0e-11, Rel.Error=1.0e-03, Threshold=1.0e-10, Mode="ODE"

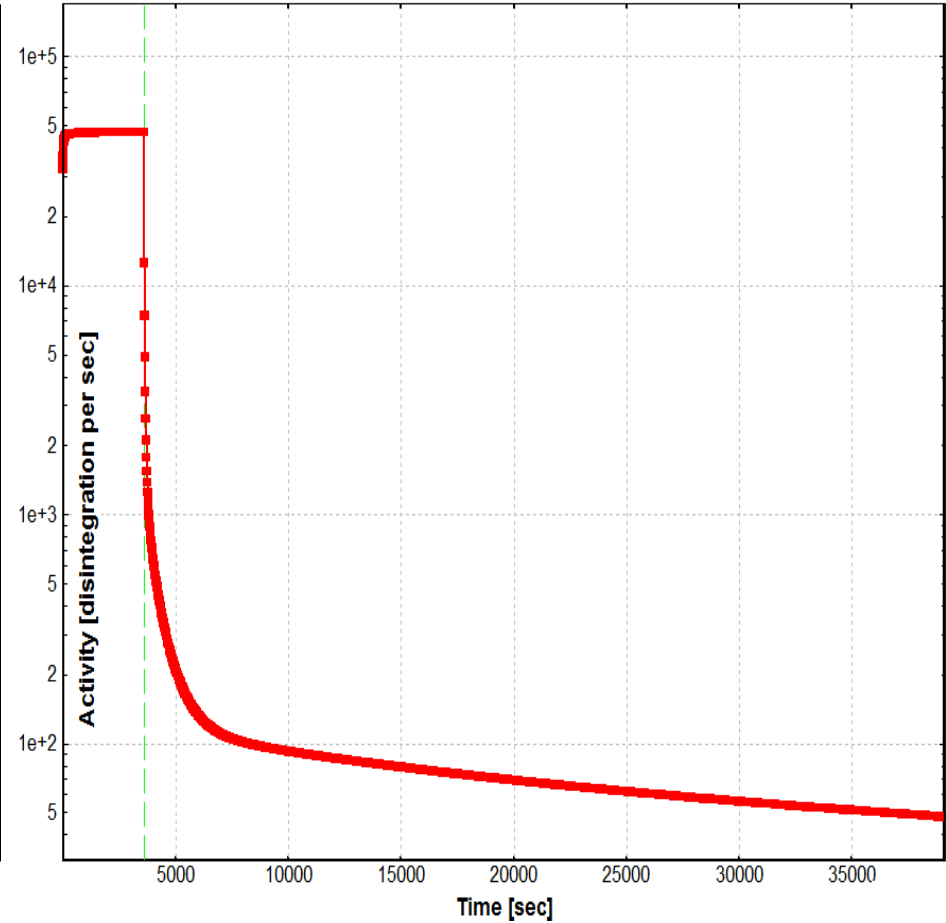


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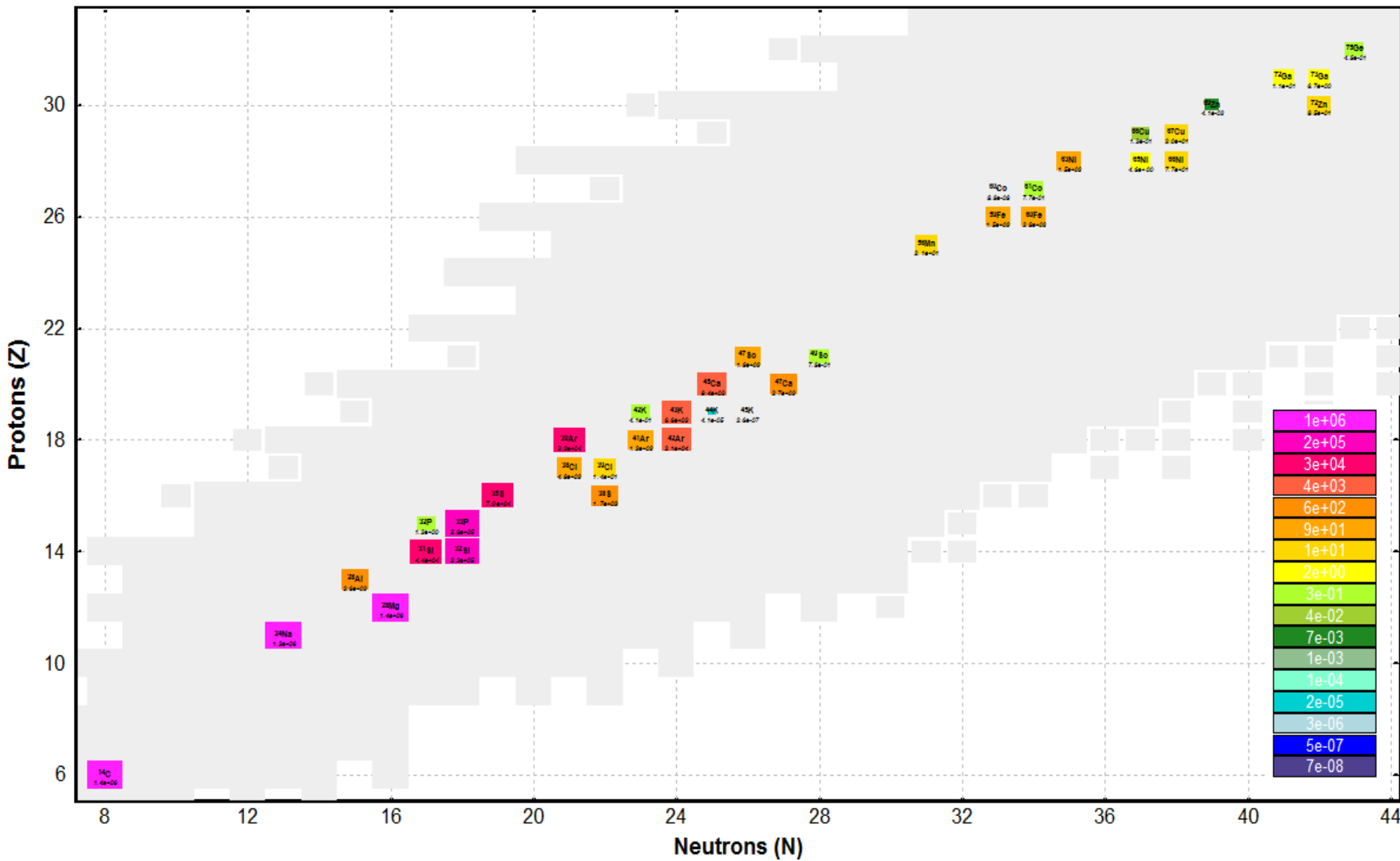
Only radioactive residues

Radioactive decay residues

Implantation detector : "He-jet block" (161 different isotopes)

Irradiation Time (IT) = 3.60e+03 sec; Decay Time (DT) = 3.60e+04 sec; Plot only Radioactive

N_Implant=500, N_Resid=500, Abs.Error=1.0e-11, Rel.Error=1.0e-03, Threshold=1.0e-10, Model="ODE"



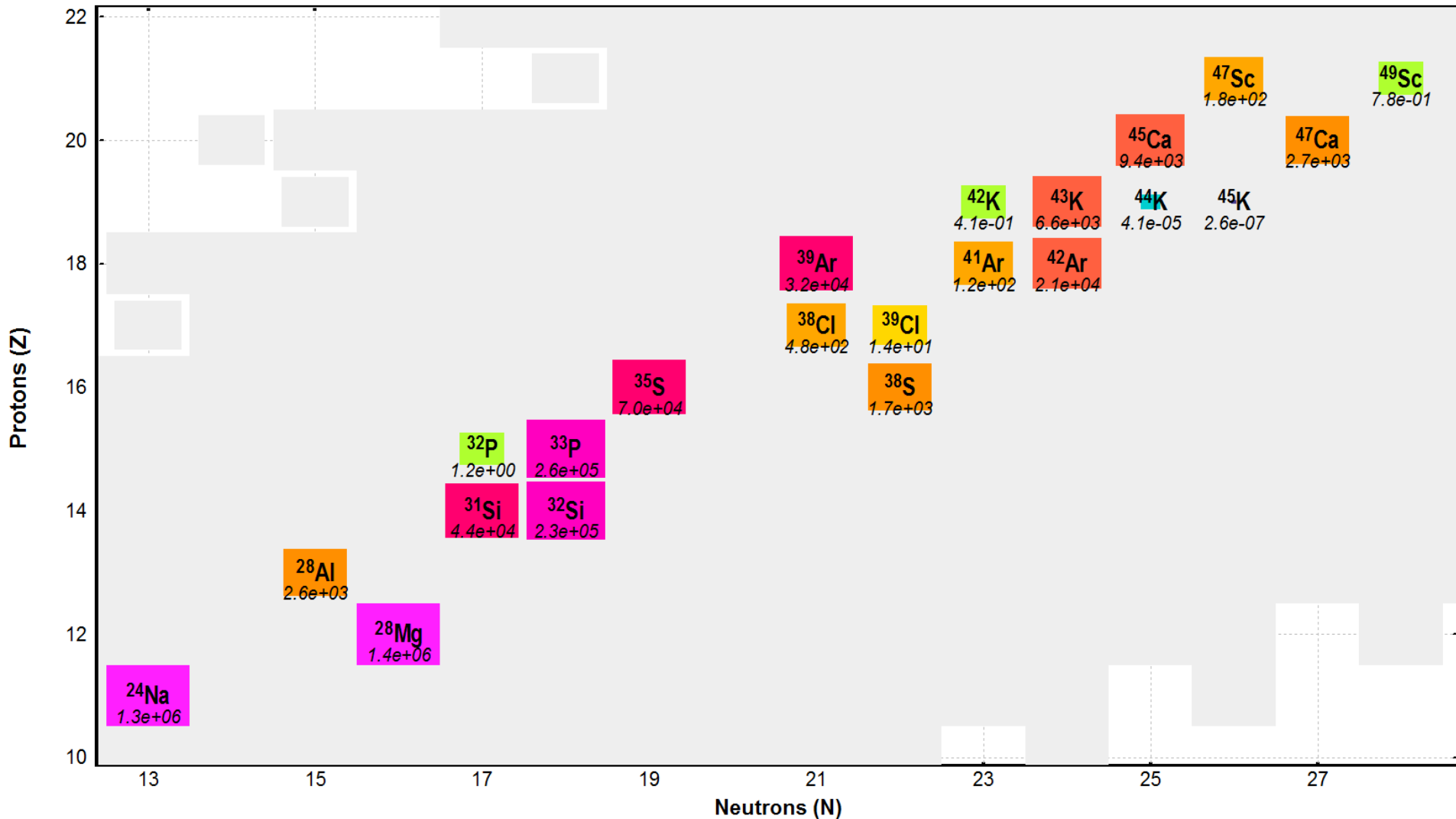
Only radioactive residues

Radioactive decay residues

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Irradiation Time (IT) = 3.60e+03 sec; Decay Time (DT) = 3.60e+04 sec; Plot only Radioactive

N_Implant=500, N_Resid=500, Abs.Error=1.0e-11, Rel.Error=1.0e-03, Threshold=1.0e-10, Model="ODE"



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- 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.