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Rare isotopes production with next-generation in-flight separators

August 2019

Workshop on Physics of Exotic Nuclei
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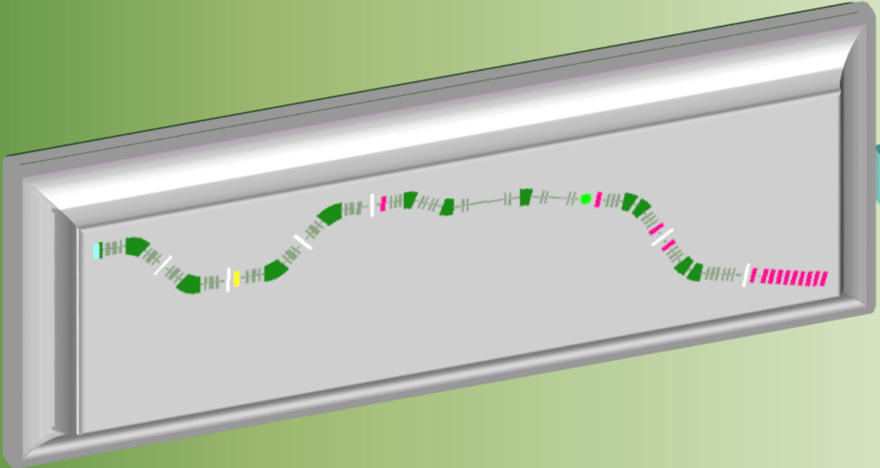
LISE++



LISE++

1. Introduction in RIB production
2. Optimum energy for intense RIBs
3. Fragment production rate factors
4. DERICA yields
5. High-Z beams at low and intermediate energies
6. Production of super neutron-rich isotopes
7. New generation facility requirements
8. Summary

NSCL

Rare isotopes production with next-generation in-flight separators

Why? Where? How?

Investigations into physics of exotic nuclei in laboratories worldwide	Marek Lewitowicz
Long-term scientific program of RIB research at JINR	Leonid Grigorenko
Fragment-separators for high-intensity primary beams	Haik Simon

Some aspects of RIB production with 100 MeV/u beams

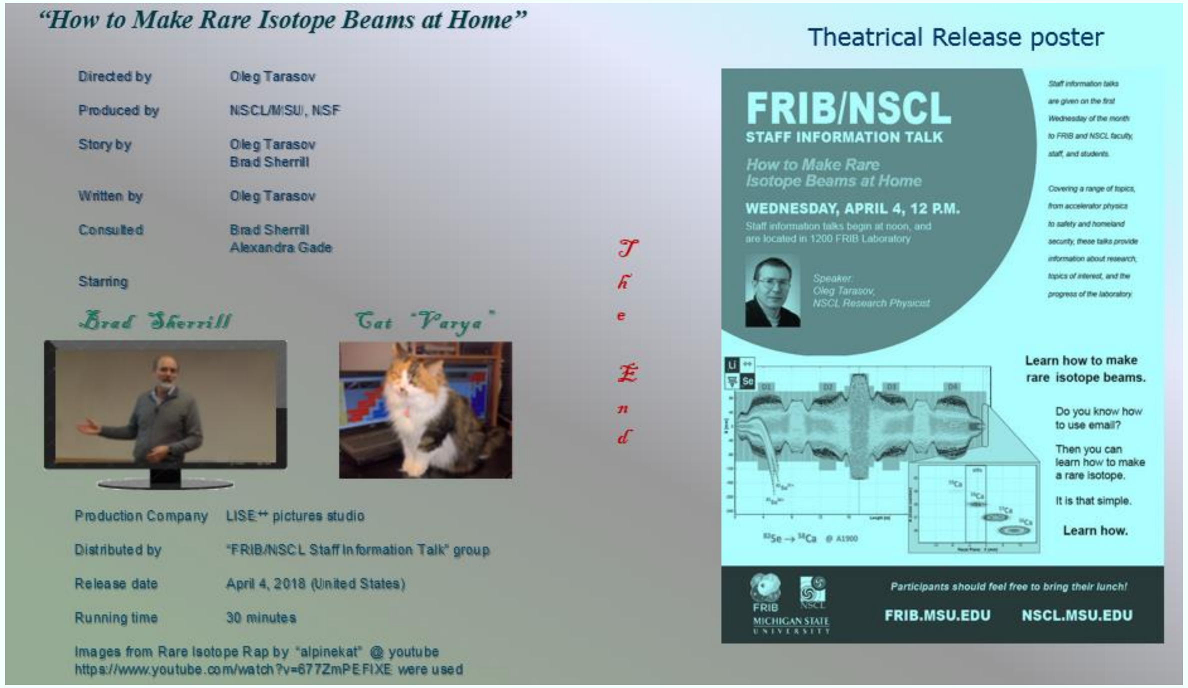
LISE^{++} package
Excel
LISE for Excel

"Production of Fast Rare Ion Beams"

Lectures at the Euroschool on Exotic Beams including examples of how to use the LISE^{++} code

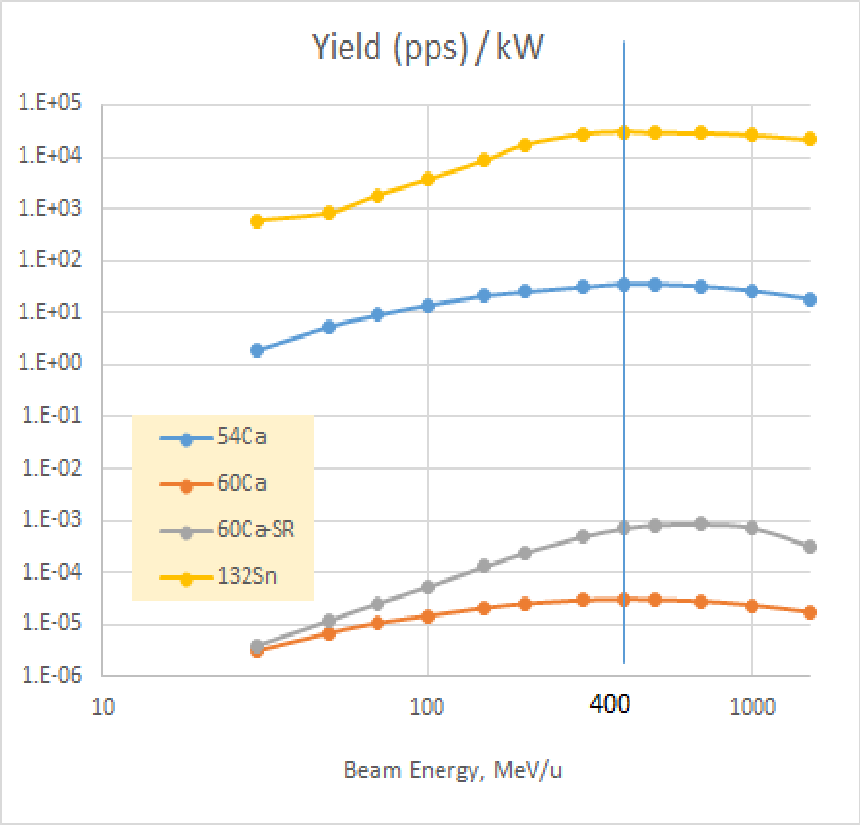
- Introduction to production of Fast Rare Ion Beams
- Production Area
- Separation
- Identification
- Production of new isotopes
- LISE^{++} : Utilities
- Radioactive beam physicist task

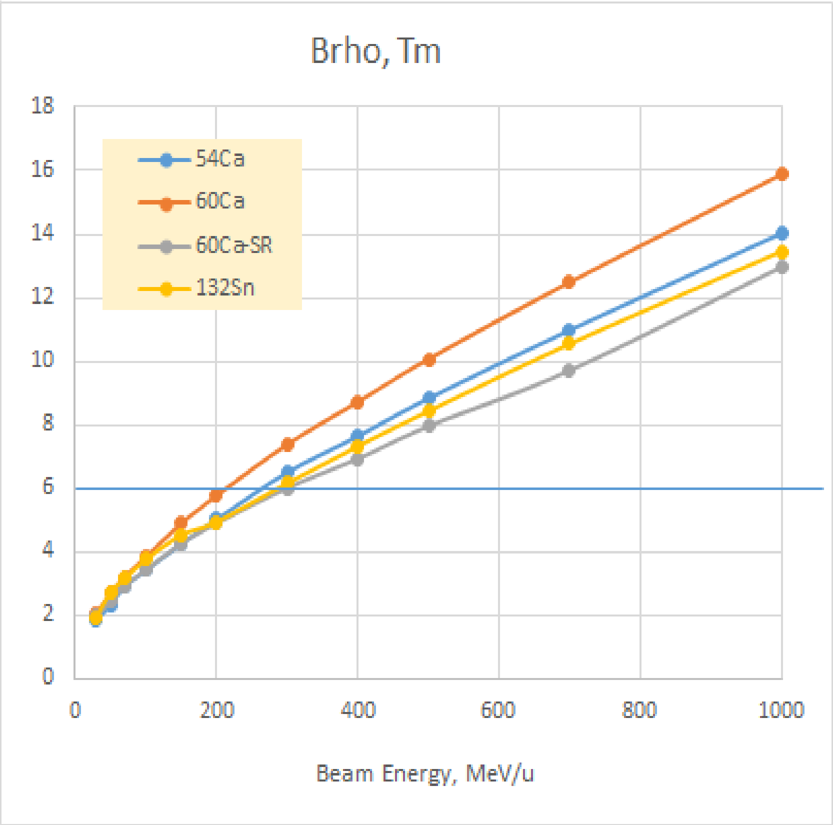
"How to Make Rare Isotope Beams at Home"

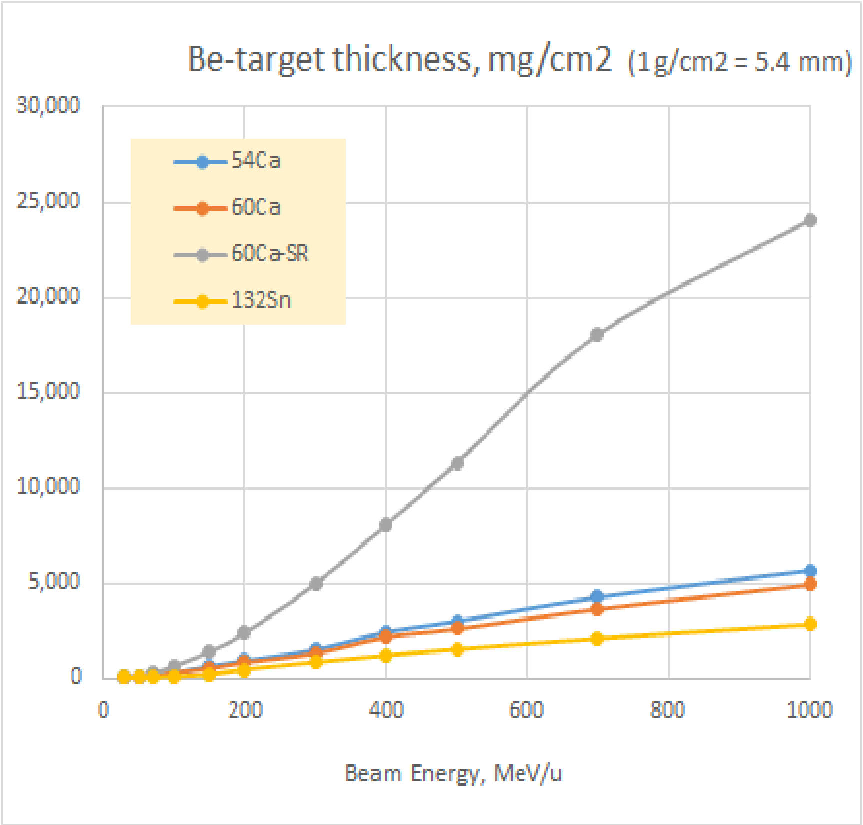


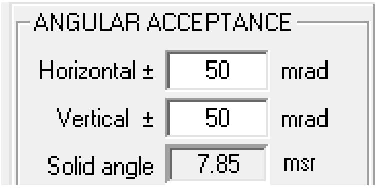
Optimum energy for intense RIBs

Functions of energy : Projectile Fragmentation & Abrasion-Fission



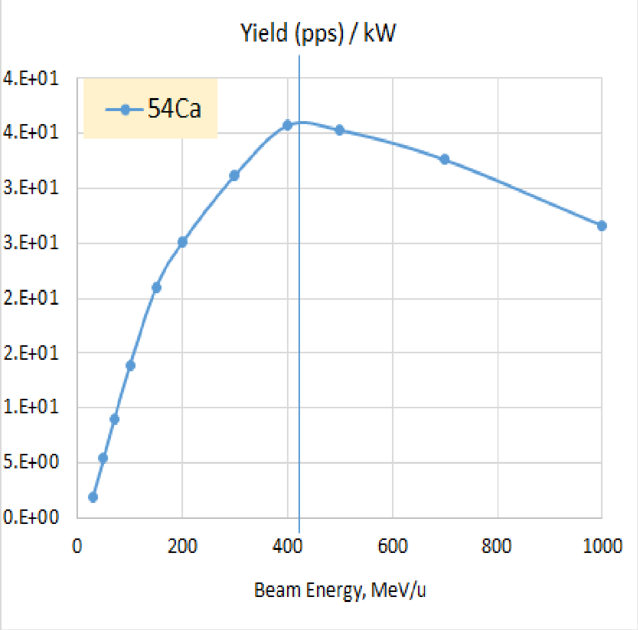


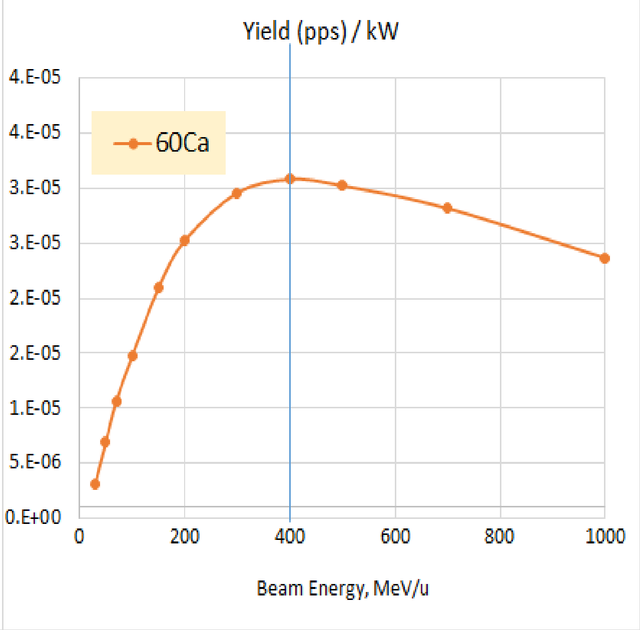


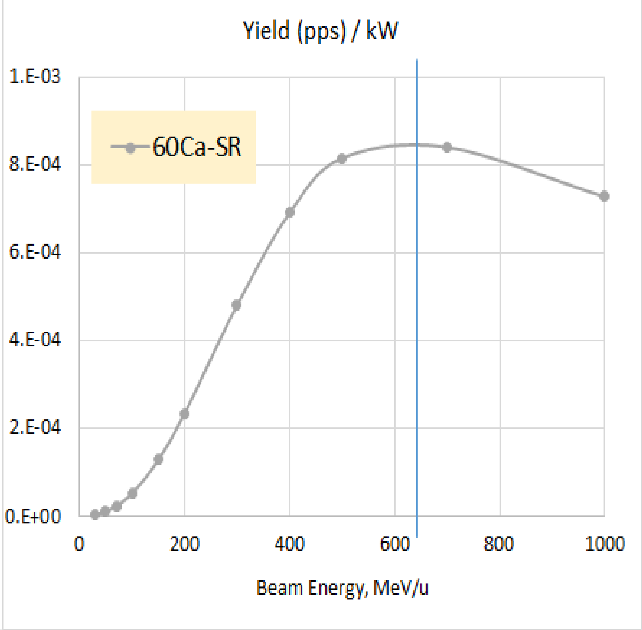


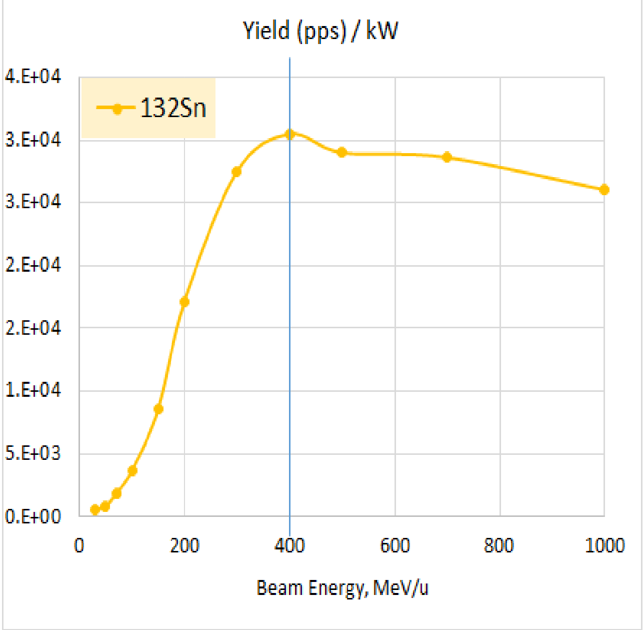
EPAX2
Convolution

Functions of energy : Projectile Fragmentation & Abrasion-Fission (linear scale)



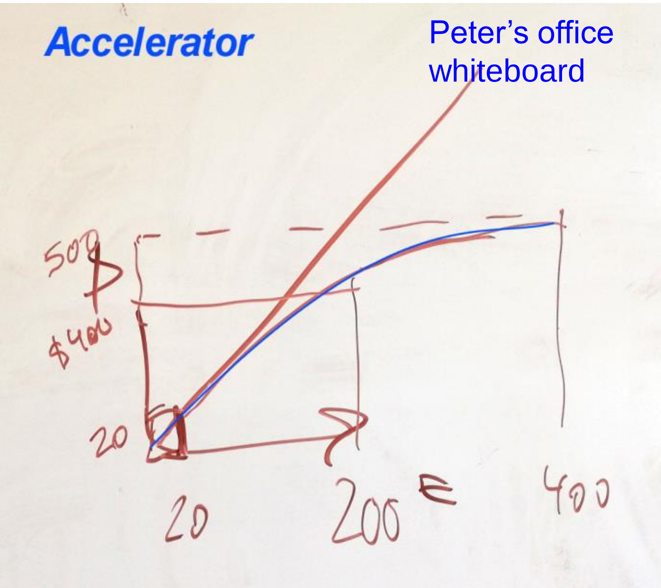


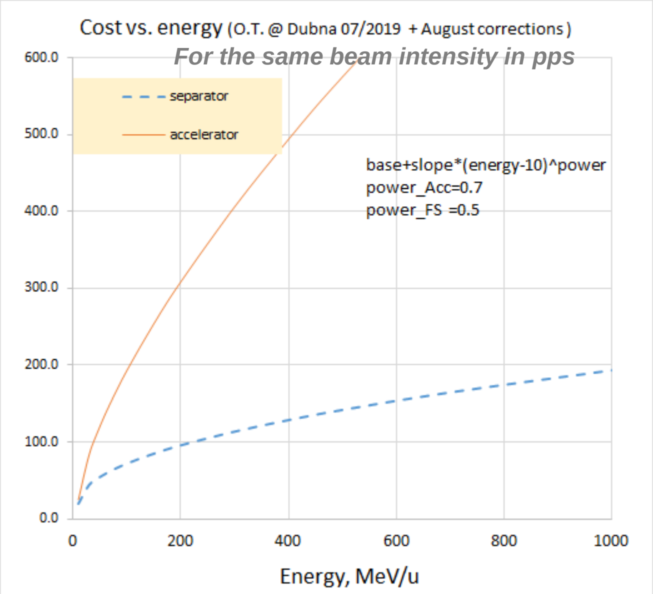




US cost+ labor

Normalization
I=1e14 @ 240 MeV/u (76Ge)

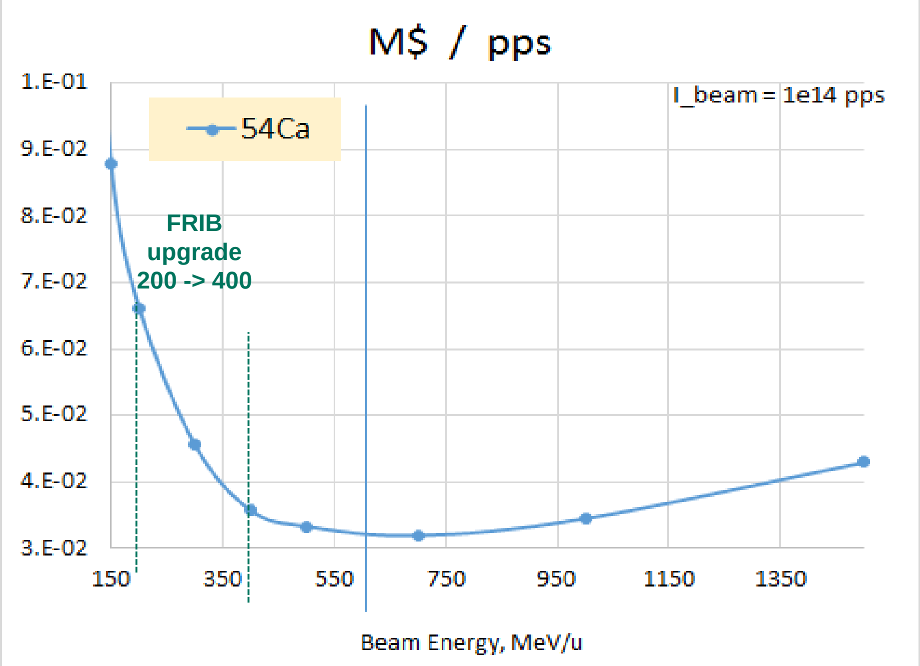


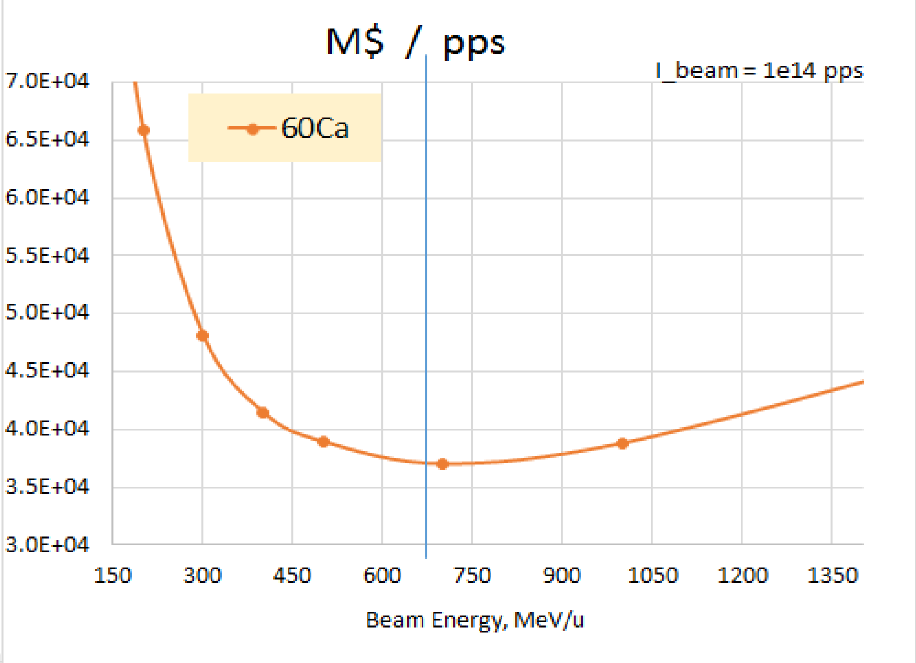


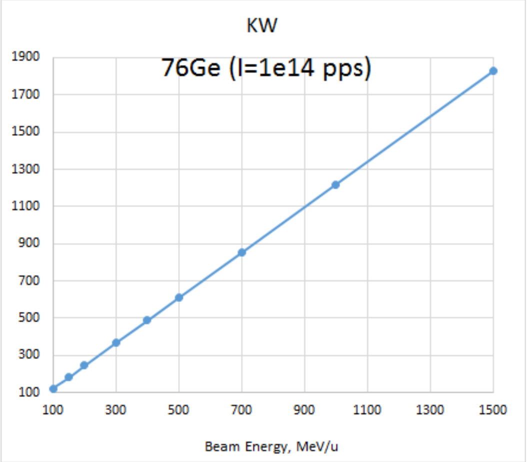
Yield / $

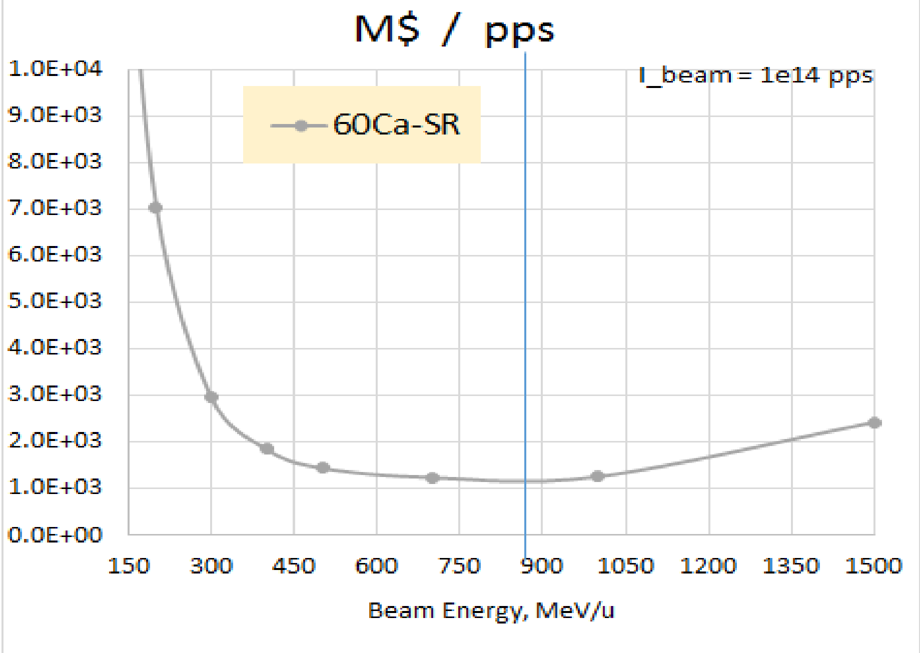
Where is more optimal?

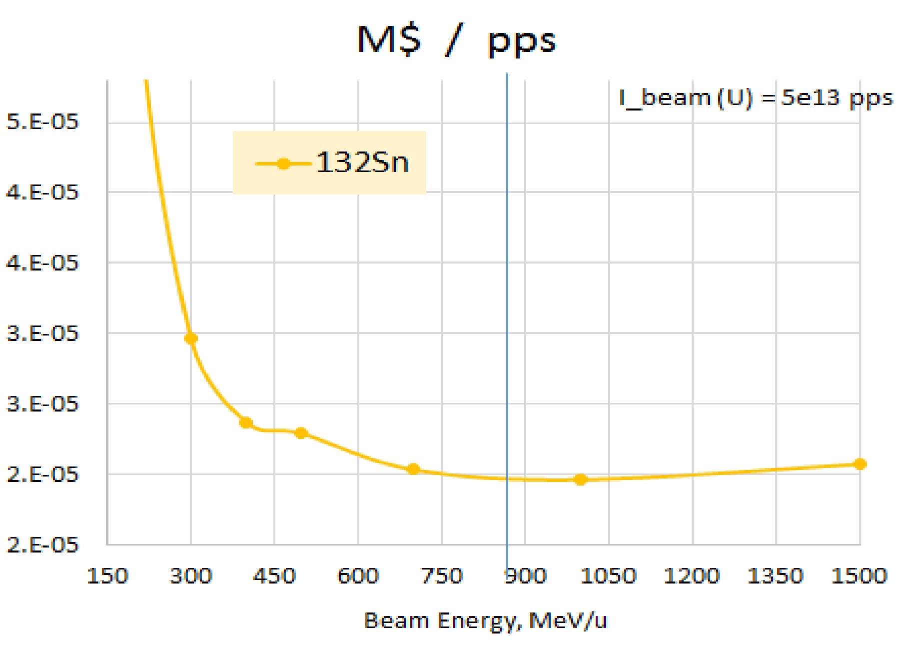
Rare Isotope Beam cost as a function of energy

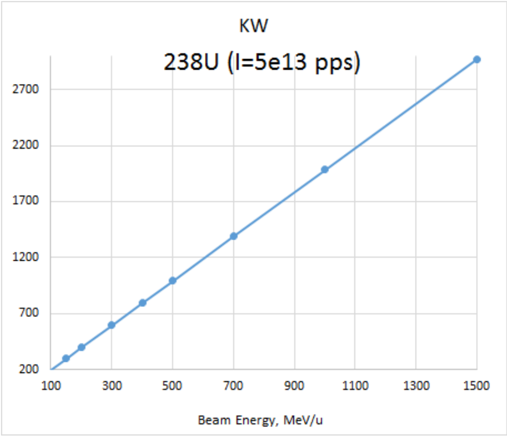












+ Reaction target thickness factor
might be taken into account

Fragment production rate factors

Fragment production rate

N(A, Z)	number of events for a given fragment was extracted separately	
dσ /dp	differential cross-sections	↔
d_t	**target thickness**	↑↑
I	**beam intensity**	
Δt	duration of measurement,	
R_{LIVE}	live time ratio (as well pile-ups)	
c	**the transmission efficiency through a fragment separator** (ang. & mom)	↑*
Δp	denotes the momentum opening	
N_A	is the Avogadro number and	
M_t	the atomic mass number	
c_{loss}	loss due to reactions of primary beam and fragment of interest in material	↓↓
c_{second}	gain due to production of fragments of interest in secondary reactions	↑
c_{charge}	charge state factor	↑

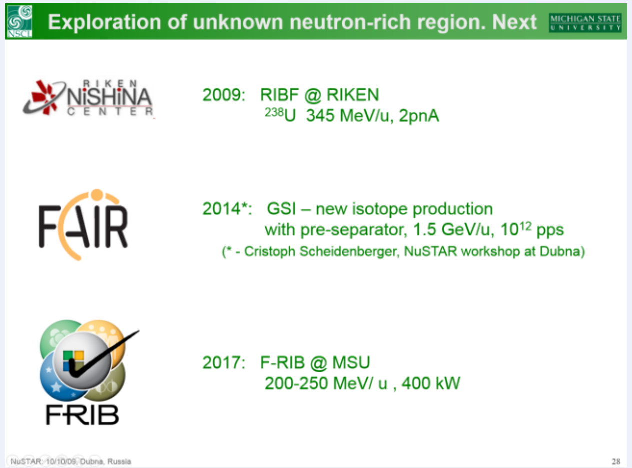
Dependence from beam energy

* Fixed thickness target

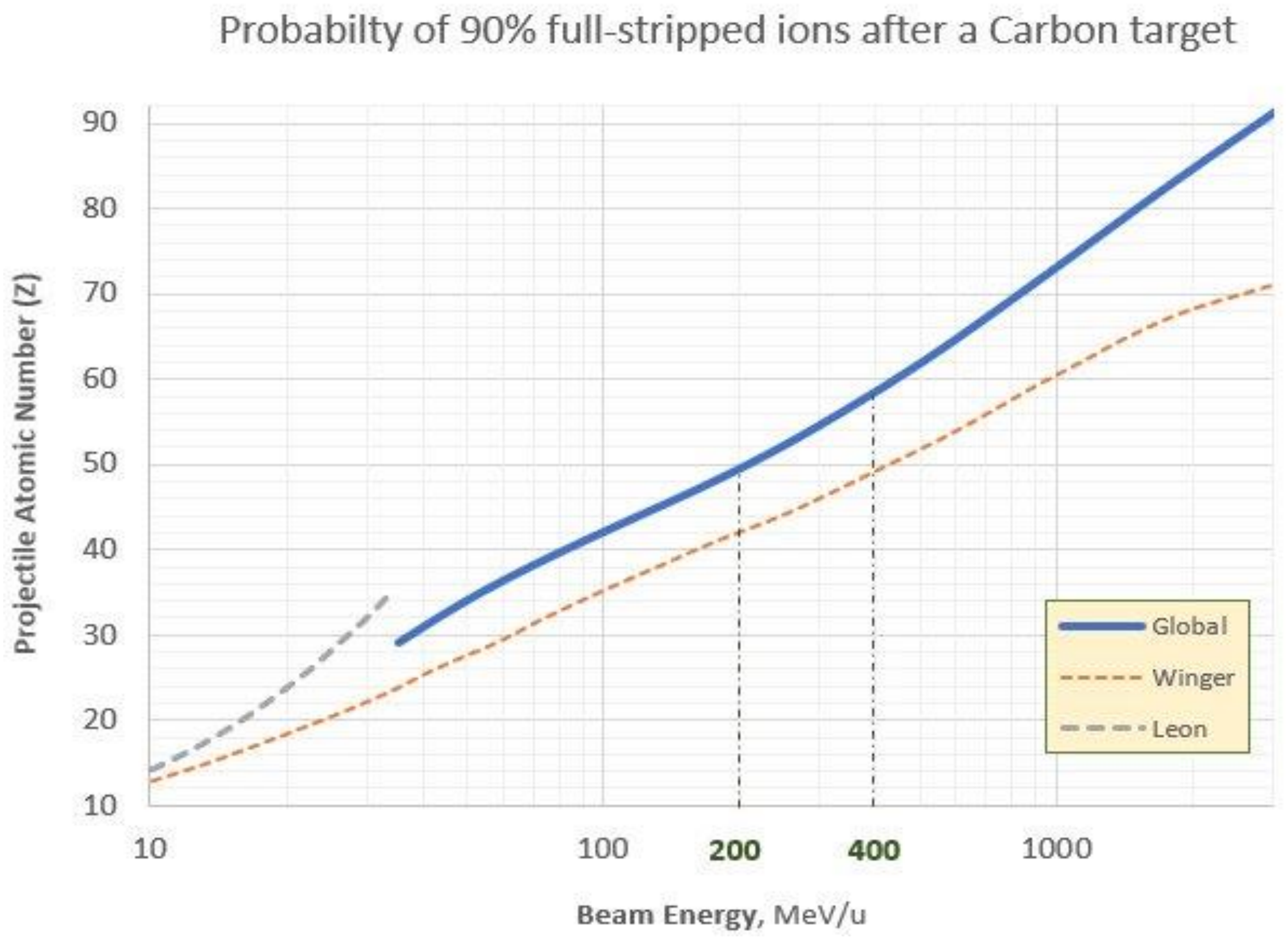
$$N(A,Z) = (d\sigma/dp)\ \Delta p\ \Delta t\ \ M_t\ /\ N_A\ \ d_t\ I\ c\ R_{LIVE}\ \ C_{second}\ C_{loss}\ C_{charge}$$

From the presentation @ NuSTAR meeting (10/10/09, Dubna, Russia)

138Sn	F-RIB	RIBF	FAIR	factors F-RIB	factors RIBF	factors FAIR
Energy, MeV/u	200-250	350	1500			
Thickness, g/cm2	0.34	1.3	7.4	1	4	22
Cross section, mb	6.00E-09	6.00E-09	6.00E-09	1	1	1
Primary beam intensity, pps	5.00E+13	1.30E+10	3.00E+11	3846	1	23
Secondary reactions coefficient	3.06	9.29	54.71	1	3	18
Loss due to reactions in material	0.9	0.7	0.12	7	6	1
Anglular and momentum acceptances	0.7	0.5	0.8	1.4	1	1.6
Charge states	0.5	0.72	1	1	1.4	2.0



Charge state factor



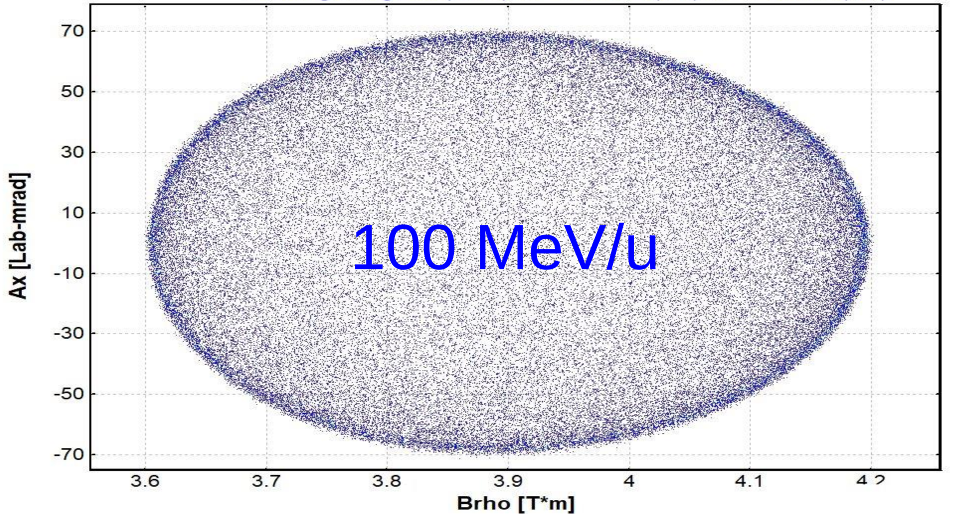
- 'Reasonably pure' 100 MeV/u RIB can be obtained up to Z=40
- High-Z experiments will be discussed later

Fission fragment kinematics as function of energy

http://lise.nscl.msu.edu/paper/2019/FissionVelocity%20v4.pdf

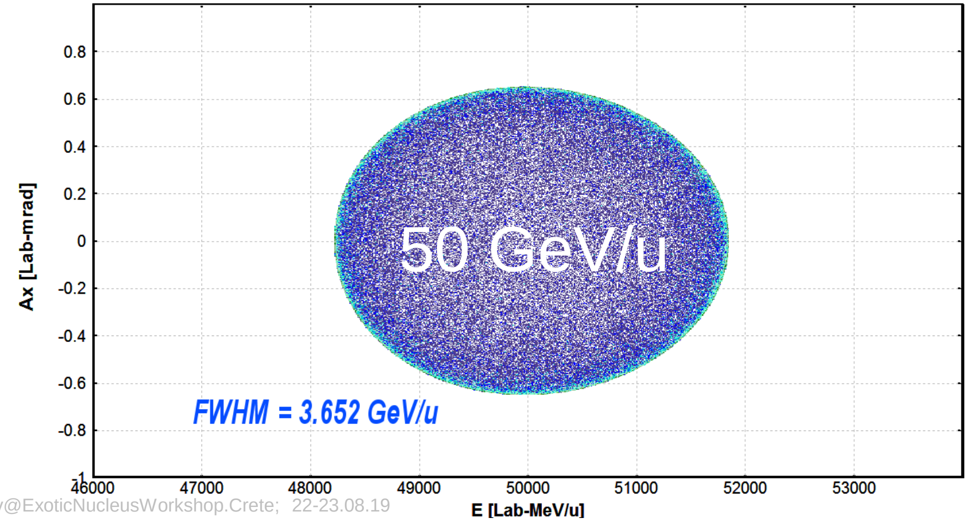
^{132}Sn fragment kinematics (expected final)

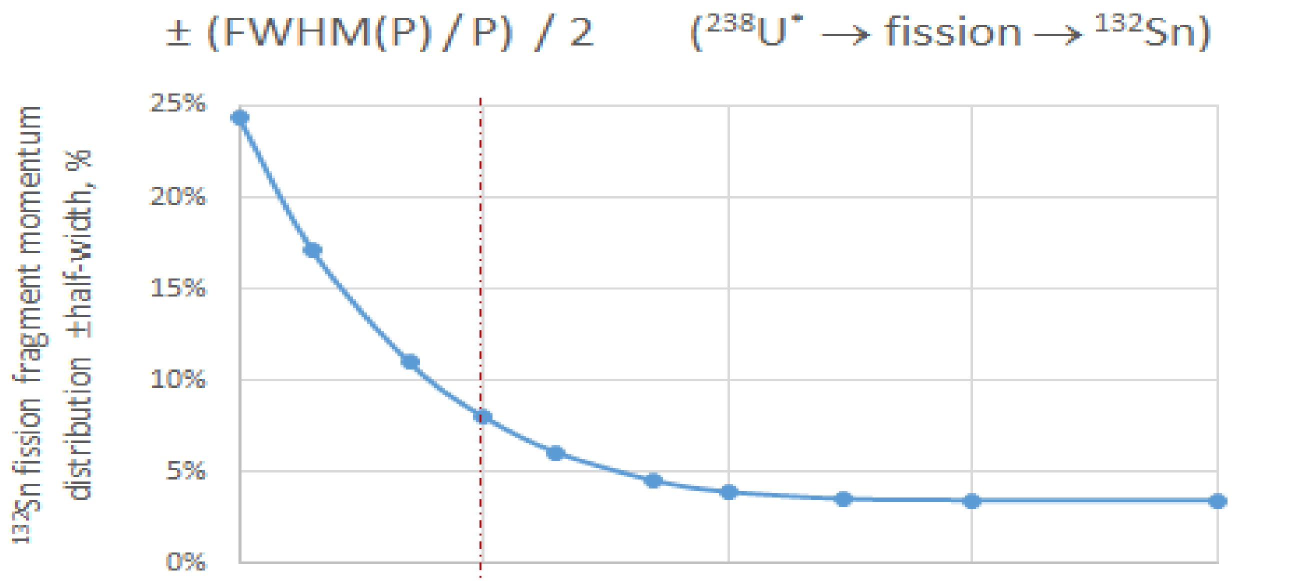
^{238}U => ^{132}Sn(^{137}Sn*) + ^{99}Mo(^{101}Mo*) (Projectile Energy : 100.00 MeV/u)
Q reaction: 160.12 MeV (Excitations 30.0=>26.5+24.5); Ang.Distr.(CM): Isotrop
Rectangle Ang.Acc.(mrad): H = +-3000.0(0.5); V = +-3000.0(0.5)

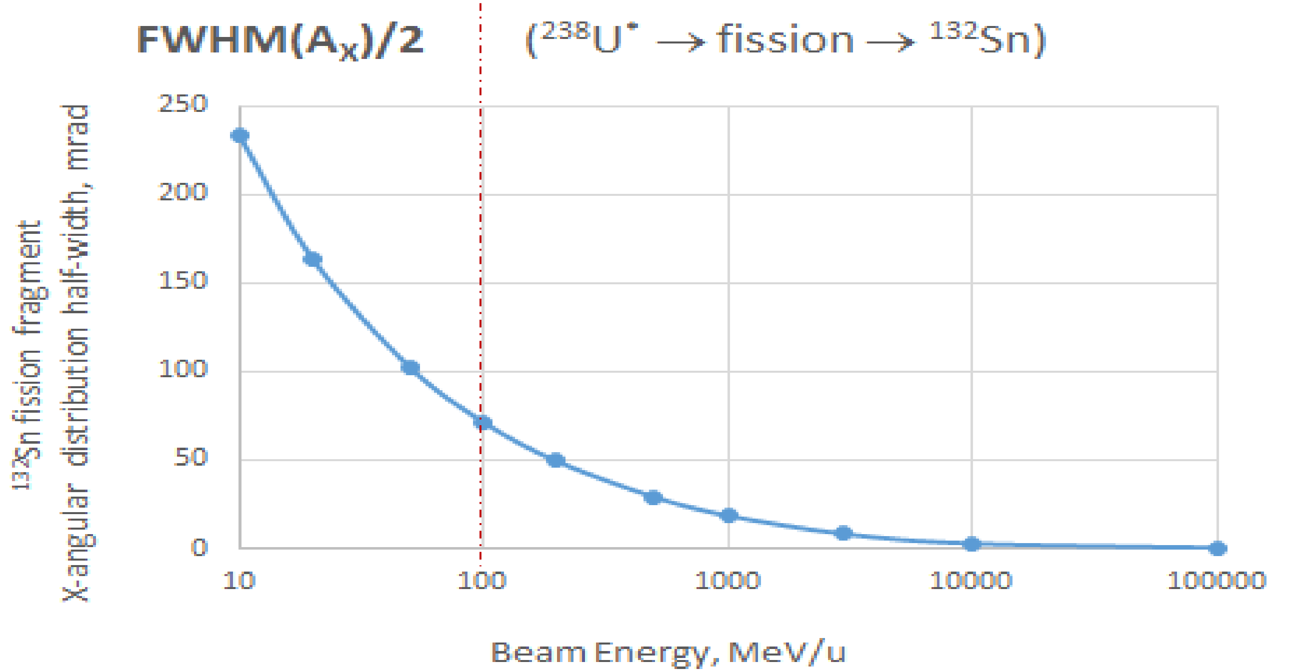


^{132}Sn* fragment kinematics(excited)

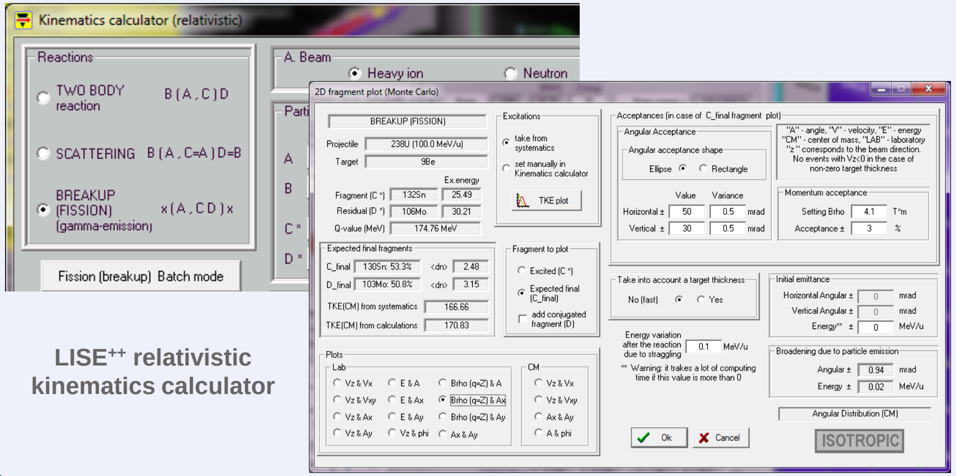
^{238}U => ^{132}Sn* + ^{106}Mo* (Projectile Energy : 50000.00 MeV/u)
Q reaction: 174.76 MeV (Excitations 0.0=>10.5+15.2); Ang.Distr.(CM): Isotropic



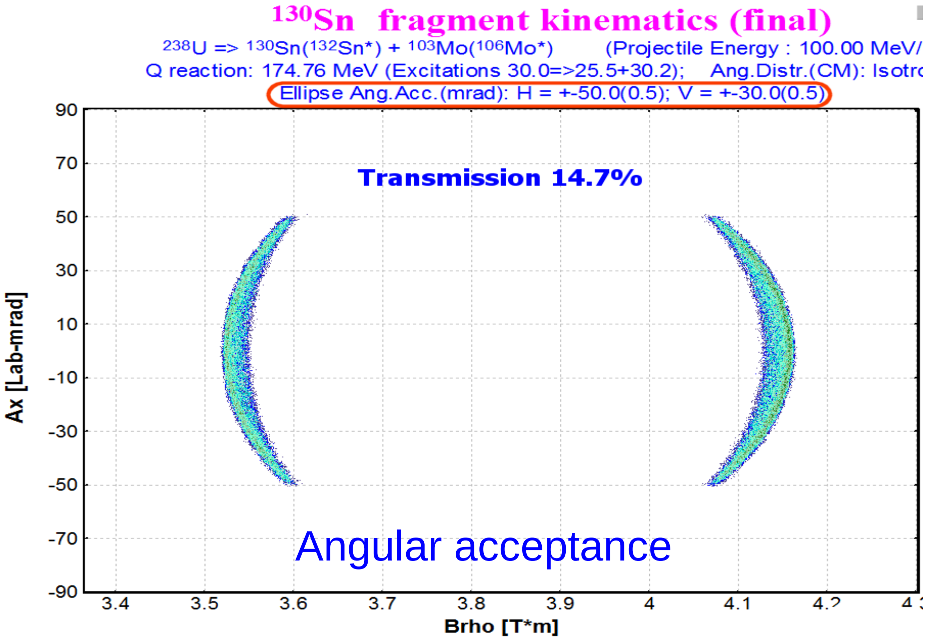




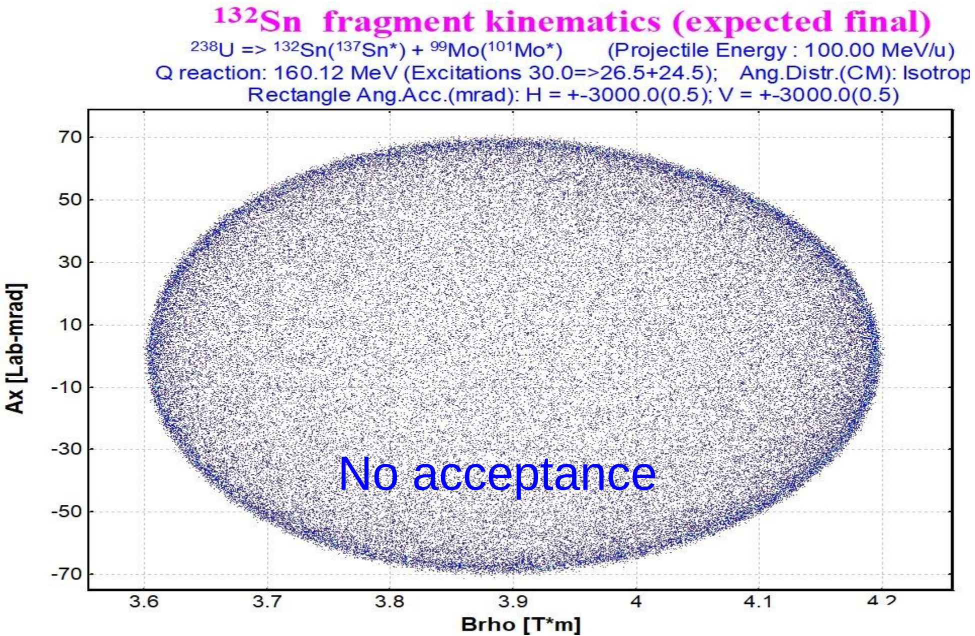
Fission fragment transmission: DERICA case

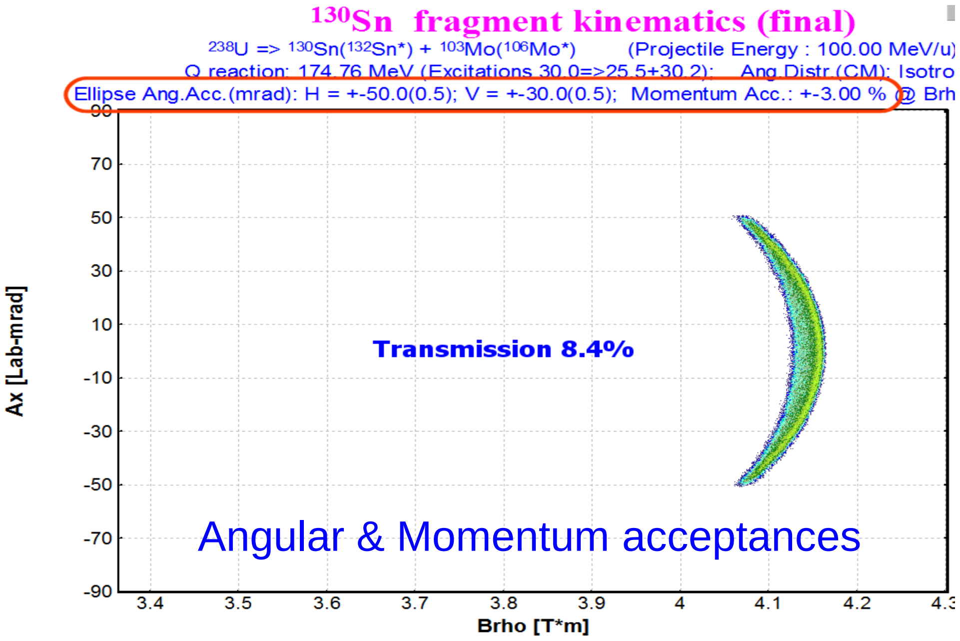


LISE++ relativistic kinematics calculator

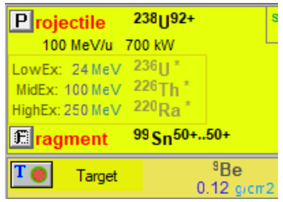


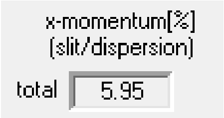
- Without charge state factor
- Angular acceptance dominates in the case of thin target
- Less 10% transmission

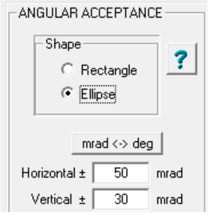


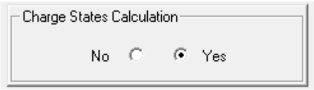


Fission fragment yield and transmission at DERICA

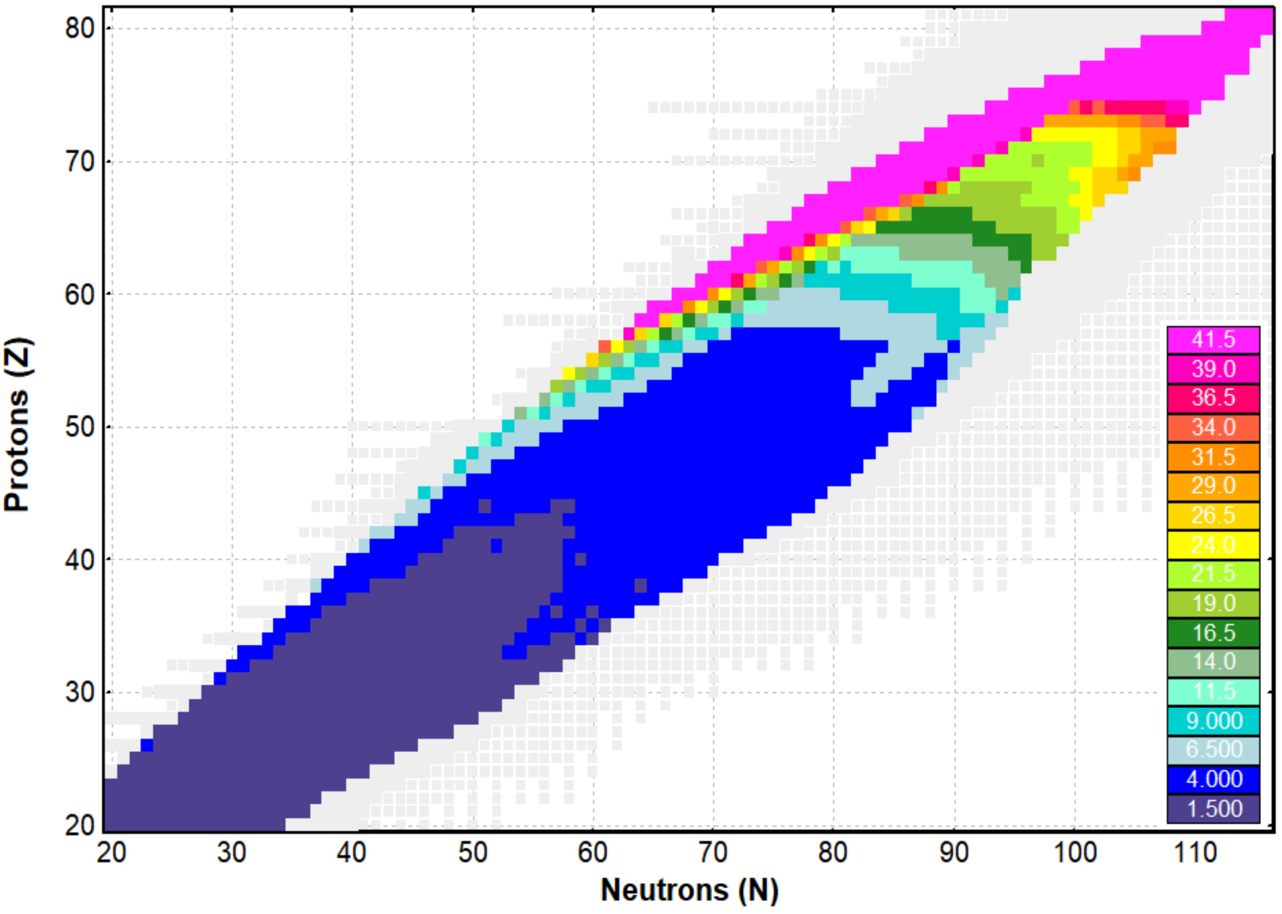




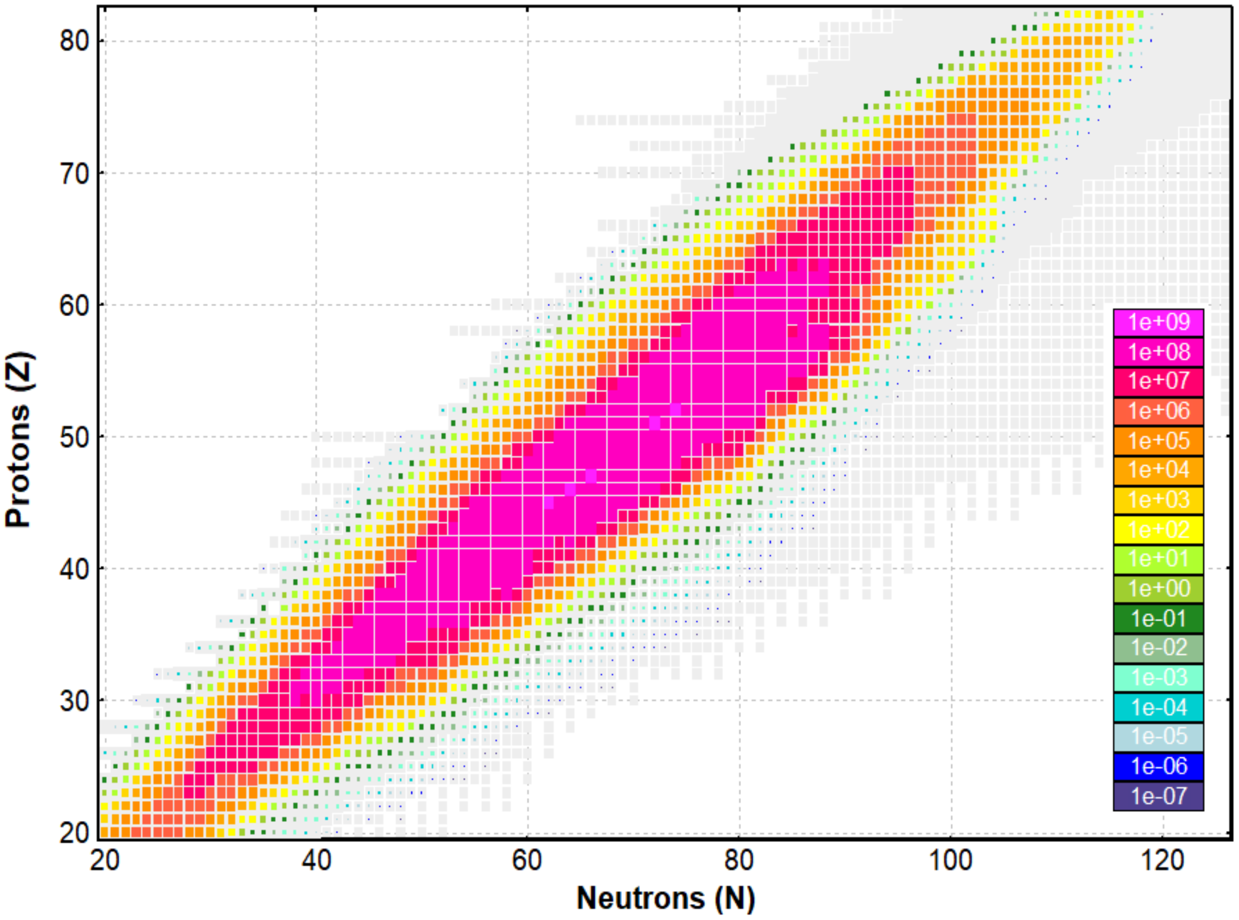




Transmission



Yield (pps)



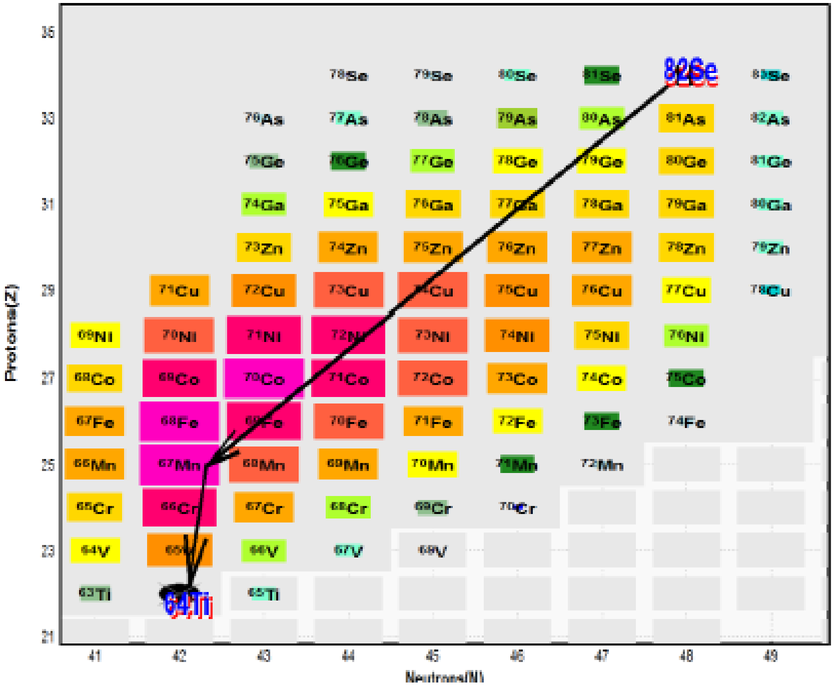
Secondary reactions

LISE++ :	O.Tarasov and D.Bazin, NIMB 266 (2008) 4657
LISE Sec.Reactions:	D.Bazin O.Tarasov et. al., NIM A482 (2002) 307

LISE++ calculates the addition to each product nucleus by considering the contributions from ALL of the intermediate nuclear reaction steps.
The effect is expected to be largest for the most exotic products.

Parent nuclei: multistep production probability

^{82}Se (140.0 MeV/u) + Be (443.61 mg/cm^2) -> ^{64}Ti

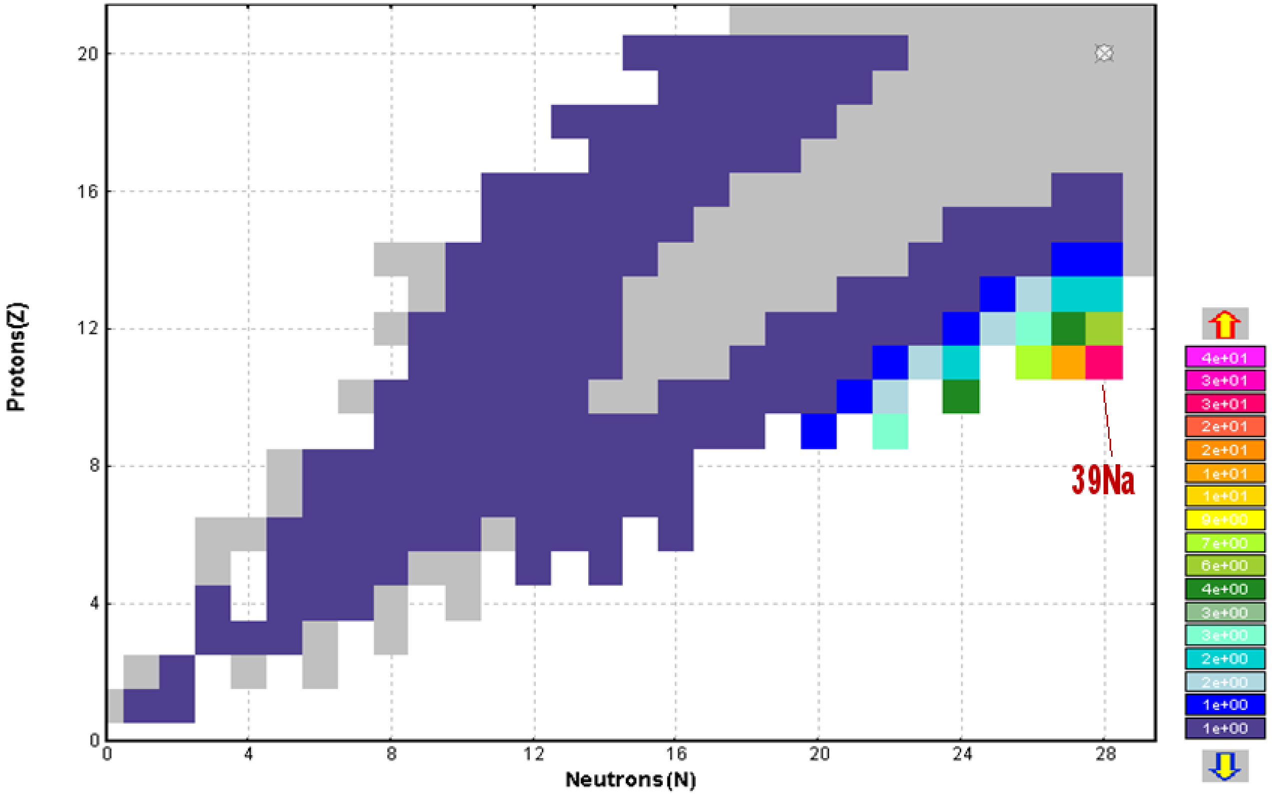


Secondary reactions coefficients for transmission calculations

Coefficients for fragments with NONZERO primary production cross section

^{48}Ca (140.0 MeV/u) + Li (1507.1 mg/cm^2) -> ^{1}H (NPsec=512)

Total number of SR coefficients = 270; Number with nonzero primary cross sections = 269

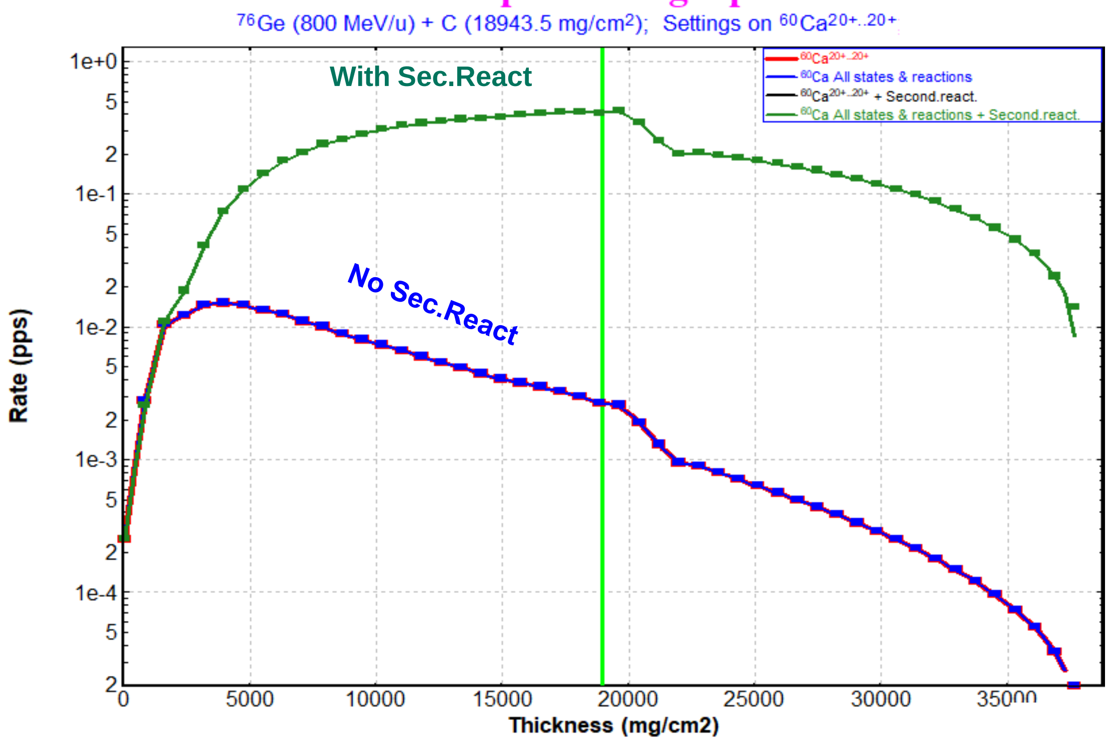


Still there is not a publication to prove large experimental impact of secondary reactions

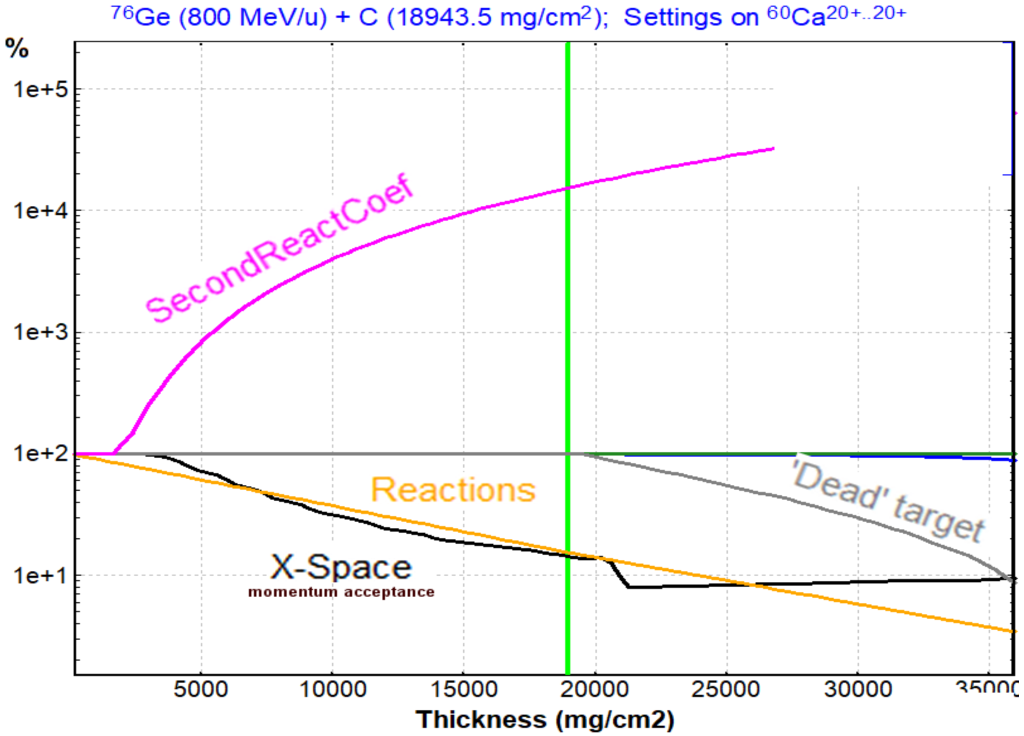
^{60}Ca RIKEN experiment :
^{62}Sc – good candidate (charge-exchange reaction)?

Secondary reactions factor : $^{76}Ge \rightarrow {}^{60}Ca$

Optimal target plot

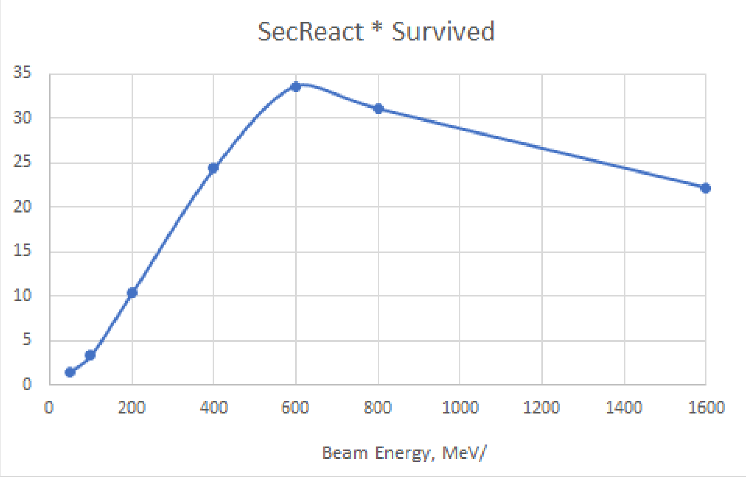


Transmission for optimal target plot



“dead” target : beam stops in a target

MeV/u	mg/cm2			
Energy	C-target thickness	Secondary Reactions	Survived in Target	SR* Survived
50	101	1.5	0.99	1.5
100	460	3.5	0.95	3.3
200	1994	12.5	0.83	10.3
400	6560	46.4	0.53	24.4
600	13000	120.7	0.28	33.7
800	19006	202.6	0.15	31.1
1600	30510	452.5	0.05	22.2



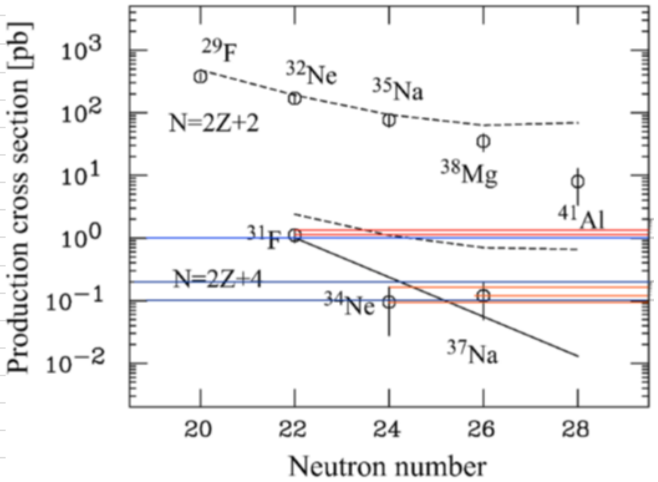
- Target thickness has been optimized for Secondary reactions
- Losses due to reactions in wedges were not taken into account
- Fragment-separator settings correspond to DERICA FRS

Secondary reactions : results with use of low-energy data

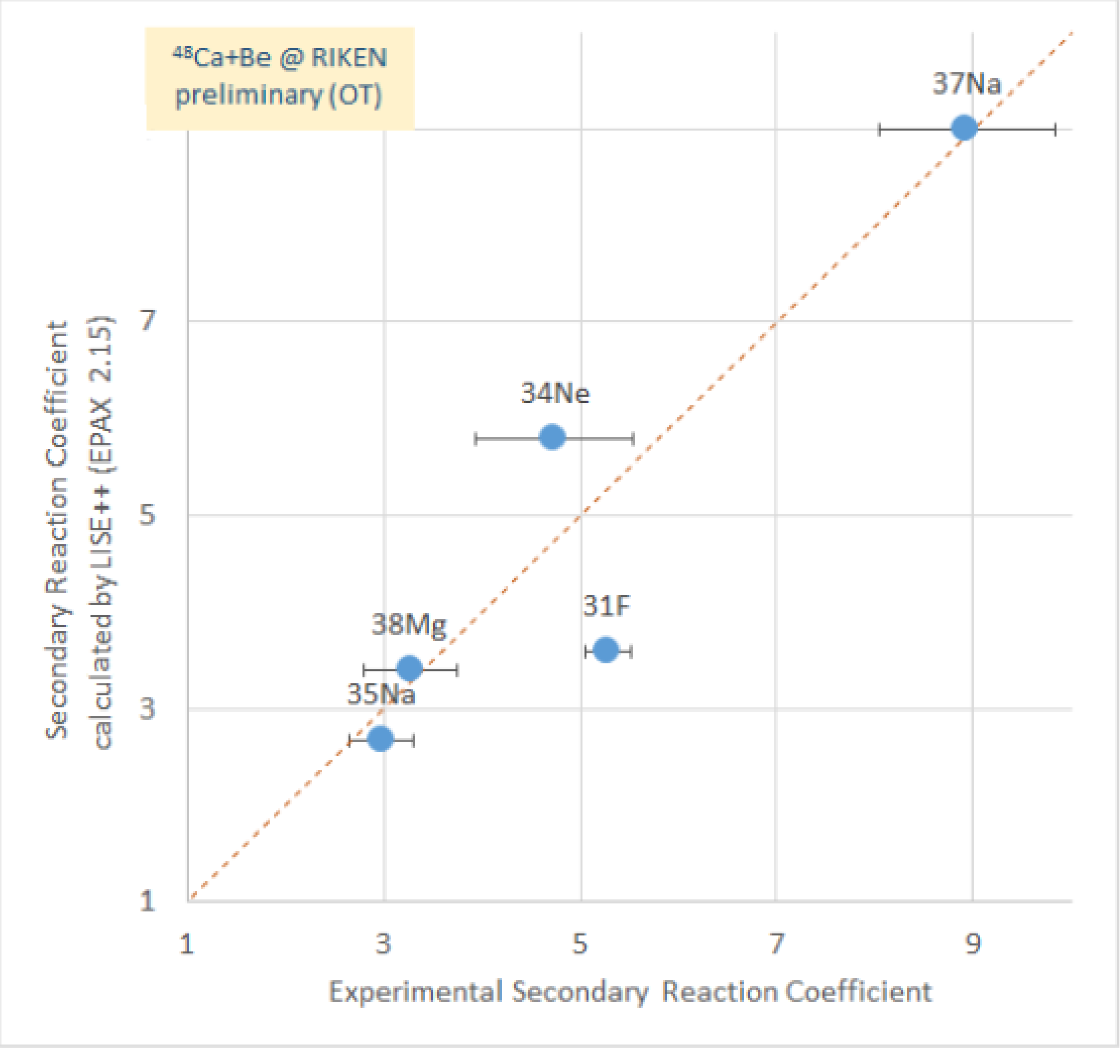
	Cross section, pb								
	Measu-rement BigRIPS, 12/2014	error	LISE++ Calculation EPAX 2.15 (no 2ndary reactions)	RIPS ** 64 MeV/u Ta target	error (+)	RIPS ** 64 MeV/u Be target	ratio BigRIPS/RIPS Be target	ratio error	LISE++ secondary reaction coefficient EPAX 2.15
^{31}F	2.53	0.07	1.16	1.006	0.01	0.48	5.3	0.2	3.6
^{34}Ne	0.21	0.02	0.53	0.093	0.013	0.04	4.7	0.8	5.8
^{37}Na	0.46	0.02	0.34	0.101	0.009	0.05	9.6	0.9	9.0
^{38}Mg	54.5	0.545	30.5	35	5	16.67	3.3	0.5	3.4
^{35}Na	127.5	1.275	45.8	90	10	42.86	3.0	0.3	2.7

** RIPS 64 AMeV:
M. Notani et al., Phys. Lett. B542 (2002) 49

EPAX 2.15 Ratio CS(Ta)/CS(Be)= 2.1



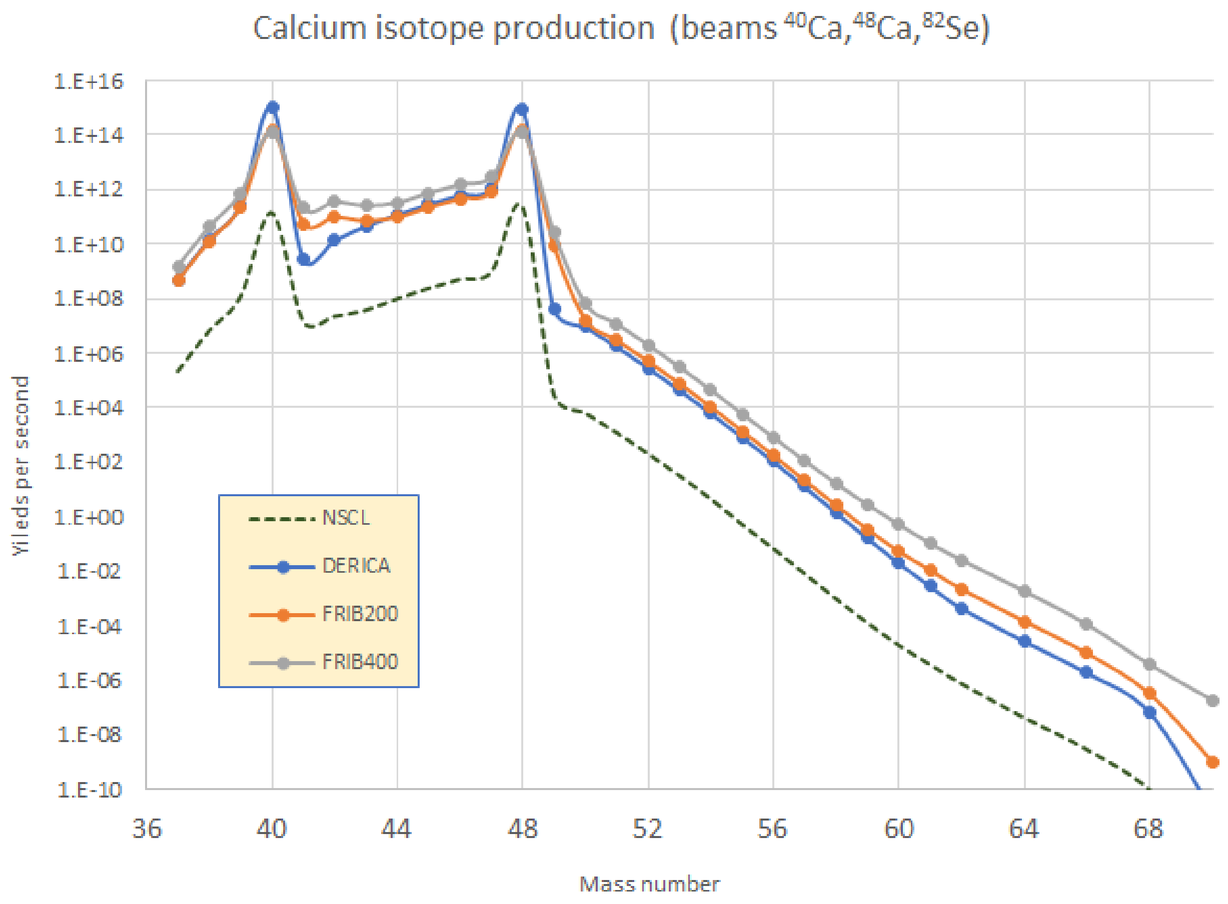
Analysis from 01/19/2015
+ ^{38}Mg & ^{35}Na points from @ 10/16/2016

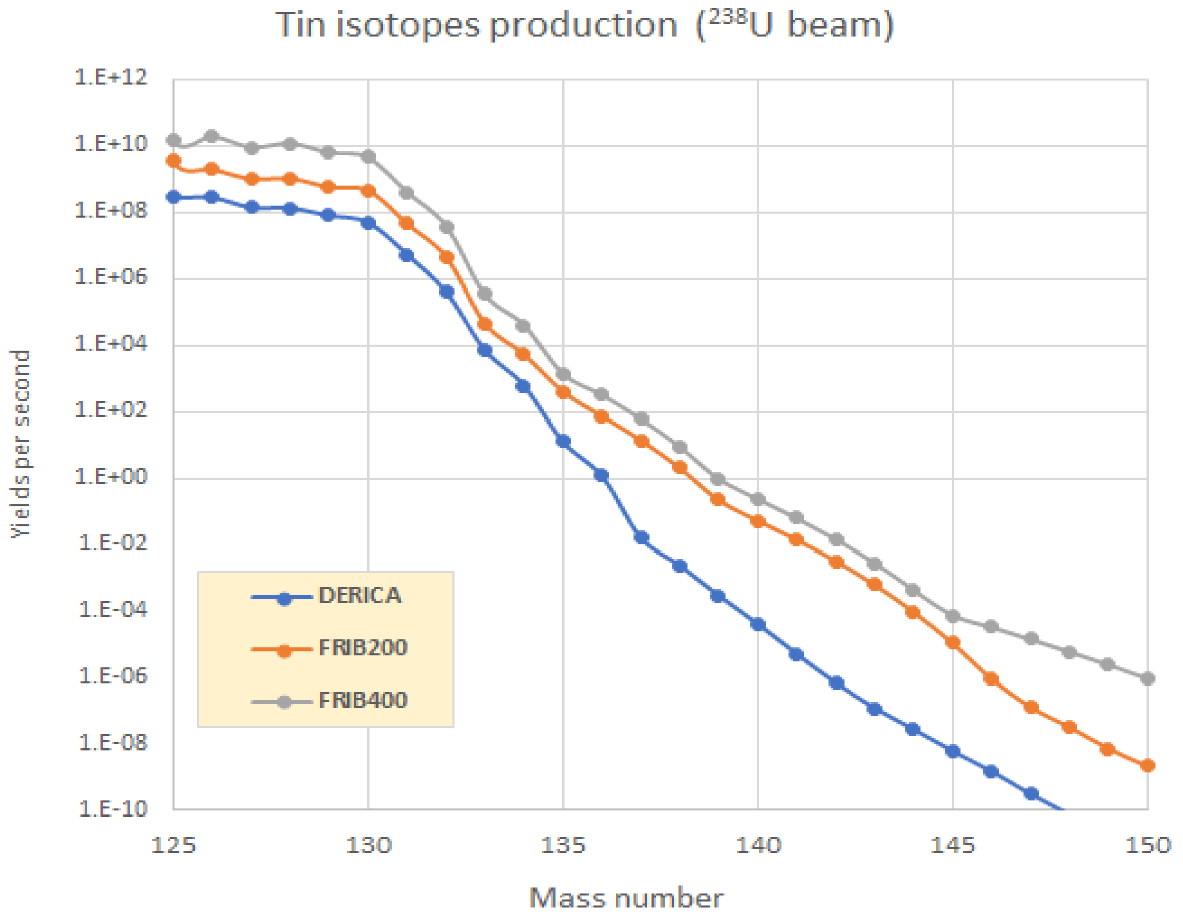


1. We did not have a thin target in the 2014 experiment
2. Data from the RIPS experiment ^{48}Ca(64 MeV/u)+Ta were used with scale parameter (1./2.1) to compare with current data.
3. Fair agreement is observed in this comparison

DERICA yields

DERICA Ca & Sn yields vs …





Prim.React-EPAX2
Sec.React- EPAX2
Convolution model
Winger
Atima

	I, KW	E, MeV/u	Angular acceptance, mrad (ellipse)	Momentum accetance, %	Reaction target Factor
NSCL	0.4	140	120 x 80	5	1.74
DERICA	700	100	100 x 60	6	1
FRIB200	400	200	80 x 80	10	3.2
FRIB400	800	400	80 x 80	10	10.2

Due to momentum compression

- Remember about a Reaction target factor !
- It looks like very potential, and exceeding by two order of magnitude an operating RIB facility
- 700 kW at 100 MeV/u is .. Let's say it difficult…
  So there is reserve to decrease a little bit the power
  (see the next slide)

DERICA target requirement (based on H.Simon's slide)

Target and Catcher requirements

FAIR

	type	ion	[kW] power	[MeV/u] E/m	in carbon [MeV/(mg/cm^2)] dE/dx	P*dE/dx	I,pps
DERICA	linac	40Ca U	700	100	2.6 48.4	1 820 33 880	1.1e15 1.8e14
RIBF	cyclotr.	U67+	80	345	25.2	2017.9	6.1e12
RIBF	cyclotr.	U67+	3.3	345	25.2	83.2	2.5e11
FRIB	linac	U78+	400	200	32.3	12915.2	5.2e13
NSCL	cyclotr.	Ca20+	0.54	140	2.0	1.1	3.5e11
FAIR	synchr.	U28+	17	1500	17.1	290.4	3.0e11
GSI/FRS	synchr.	U73+	0.04	1000	18.1	0.7	1.0e09
J-PARC	synchr.	H+	750	30000	0.0020	1.5	1.5e14
J-PARC	synchr.	H+	470	30000	0.0020	1.0	
ESS	linac	H+	5000	2000	0.0018	8.8	1.6e16
PSI	cyclotr.	H+	1400	590	0.0023	3.2	
SNS	ring	H+	1400	1000	0.0019	2.7	
SNS	ring	H+	2800	1300	0.0019	5.4	1.3e16

High energy → power deposit moderate

design goal

Short pulses 50-100ns

H. Simon • Dubna 20190208

modified by OT

DERICA characteristics and beam intensity [pps] have been implemented

- Enormous value.. Probably it's required a liquid target
- Nowadays Target technology is a weakest place high-power RIB production
- Do not forget about flexibility
- 70 kW is more realistic, and then think about a possible upgrade

Energy domain

L.Grigorenko's presentation

Primary beams for RIB production

RIBF (RIKEN)	370 AMeV
FAIR (Darmstadt)	1800 AMeV
FRIB (MSU)	240 AMeV
RAON (S.Korea)	200 AMeV
HIAF (China)	800 AMeV

NO REASON TO COMPETE IN "ENERGY DOMAIN"

Possible strategy of RIB production

To focus on the INTENSITY of primary beam for modest energy 100-150 AMeV

Enjoy the advantages of relatively low-energy RIBs:
- Easier to study reactions in 20-70 AMeV energy range
- Easier to operate stopped RIBs

500 MeV/u (more optimal for RIB) high-power facility of RIB costs ~ 1 B$

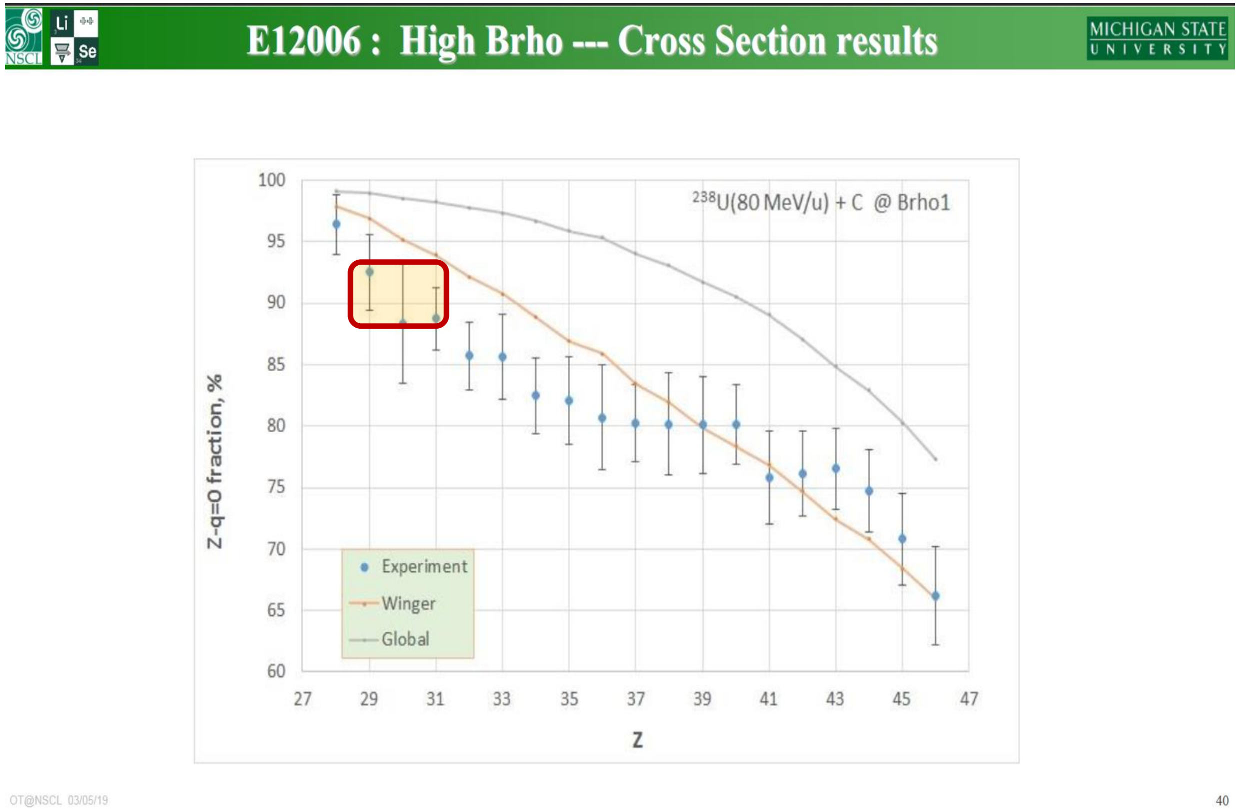
Study reactions, stopped beams in 50-100 MeV/u

But no easy…

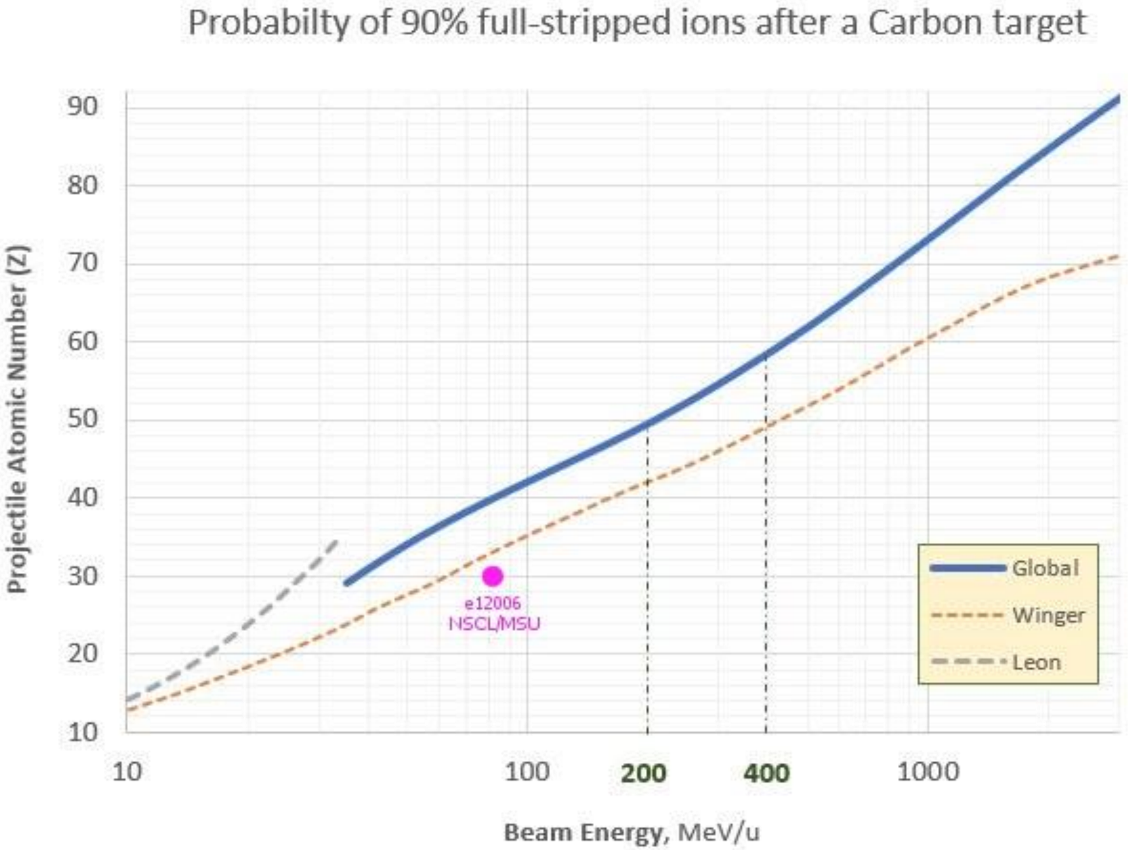
High-Z beams

at low and intermediate energies

RIB vs Charge state



M.Bowry, O.B.Tarasov et al., in preparation



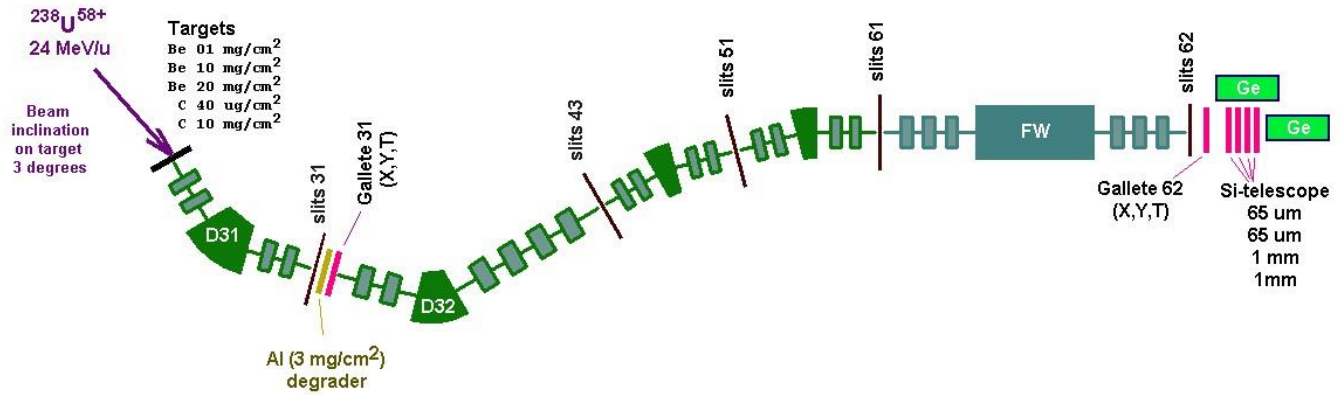
It's even more pessimistic..

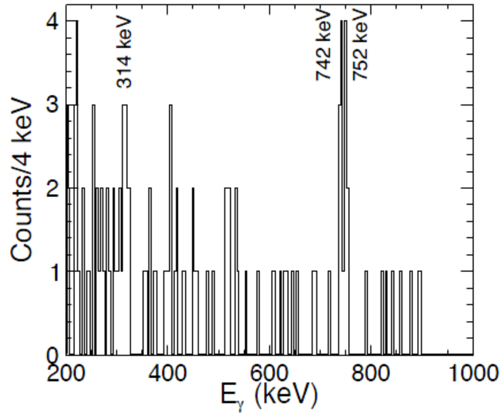
'Reasonably pure' 100 MeV/u RIB can be obtained up to Z=35?

Working with stopped RIBs

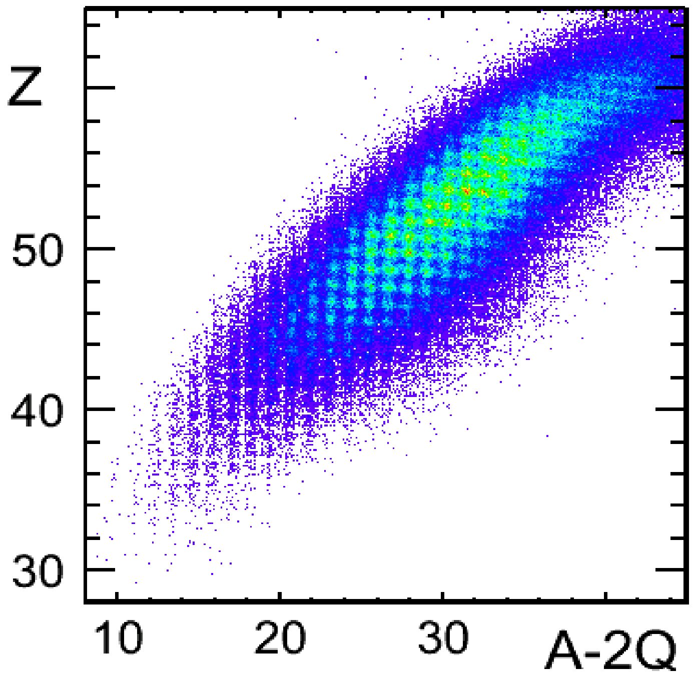
- High-Z Primary and Radioactive beams @ FLNR
- Physics with RI stopped beams
  - ❖ Half-life
  - ❖ P_n
  - ❖ Isomers ($T_{1/2}$> 100 ns)
  - ❖ Beta-gamma
  - ❖ Production cross-sections (reaction mechanism)
  - ❖ Interaction and total cross sections (halo study)
  - ❖ Decay mode
  - ❖ Search for new isotopes
  - ❖ …..

LISE3 @ GANIL





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

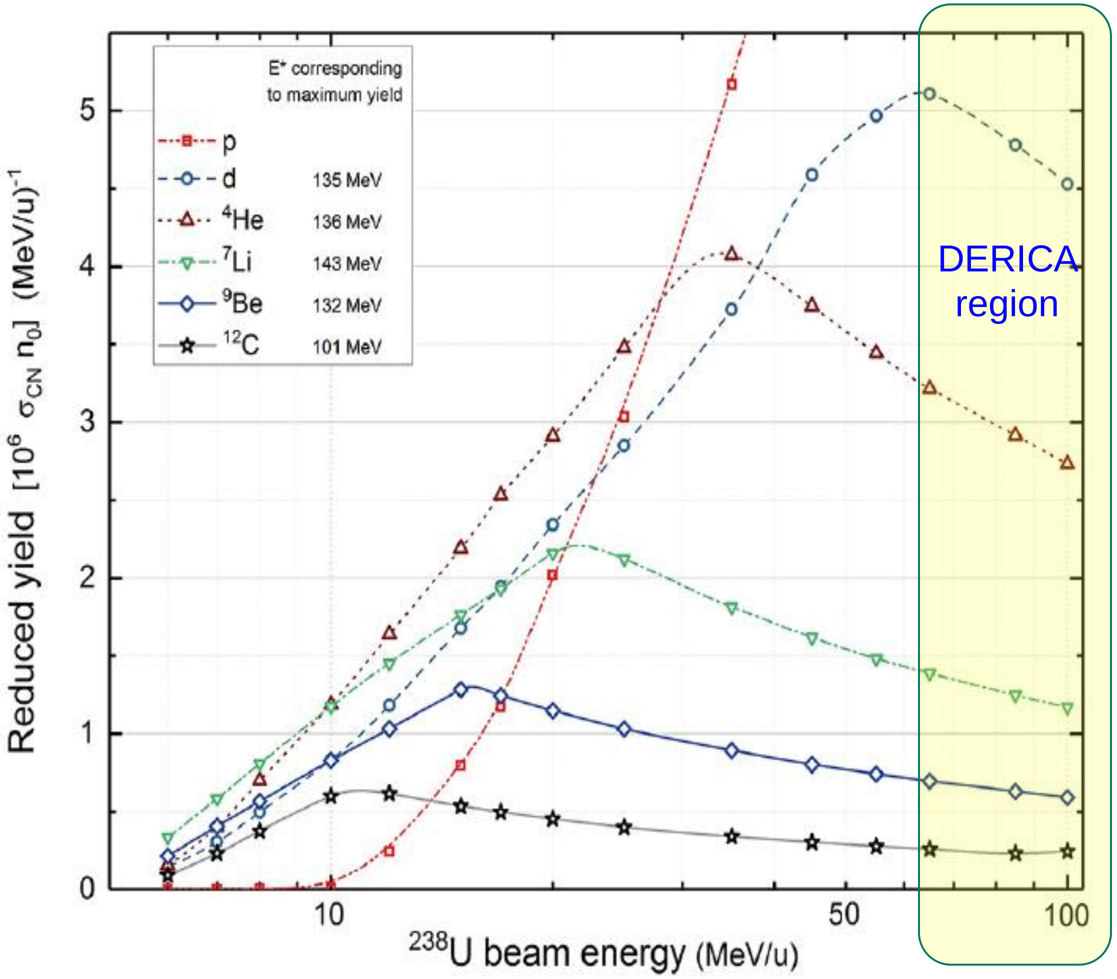


- A ^{238}U beam at 24 MeV/u with a typical intensity of 10^9 pps, was used to irradiate a series of beryllium targets and a carbon target.
- The beam was incident at an angle of 3° in order not to overwhelm the detectors with the beam charge states.
- Fragments were detected in a Silicon telescope at the end of the separator. Fission fragments produced by inverse kinematics are identified by ΔE-TKE-Bρ-ToF method.

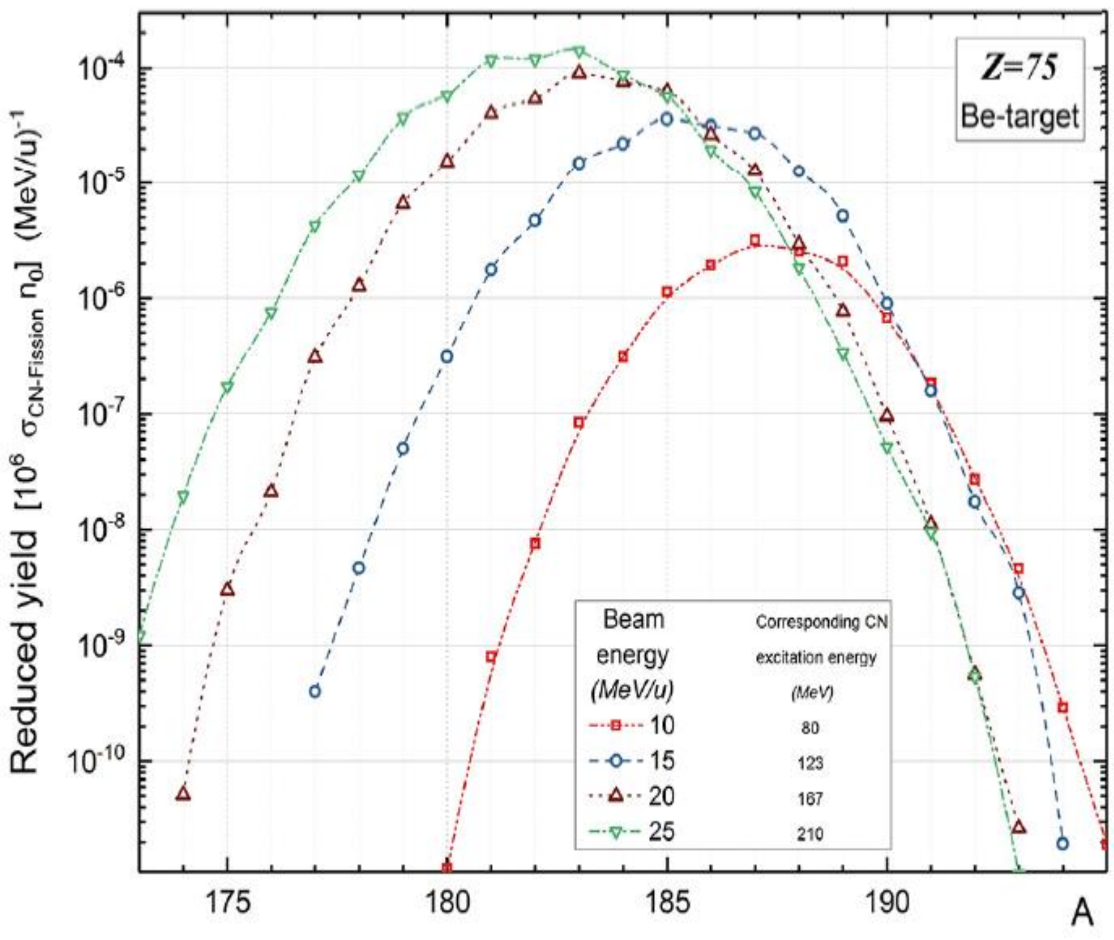
OT et al., Eur. Phys. J. A (2018) 54: 66

Rare Isotopes with Fusion-Fission Reactions

Calculated CN formation rates in reaction of ^{238}U projectiles with various light targets as function of a primary beam energy



Reduced yield of rhenium (Z = 75) isotopes calculated for fusion-fission fragments produced in reaction of the ^{238}U ions with a Be target



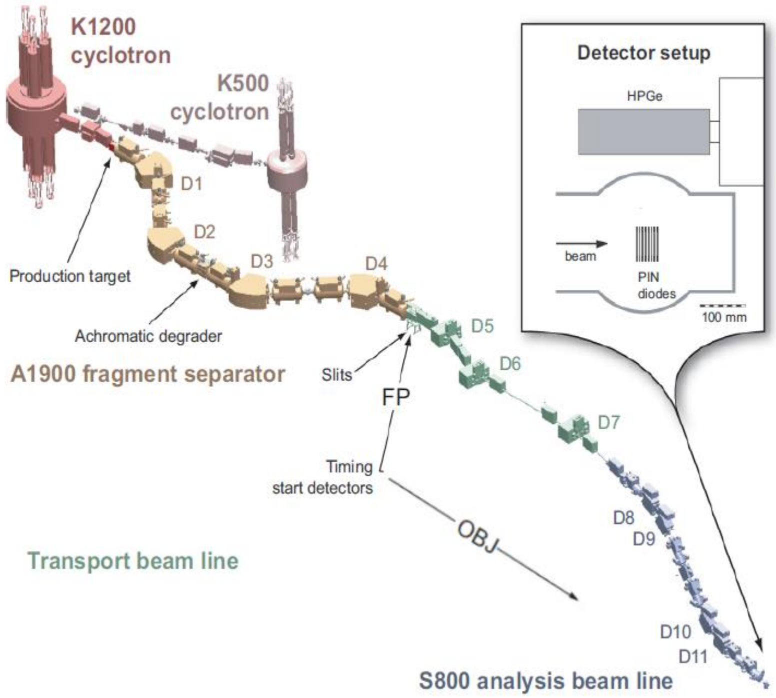
- thickness corresponds to a 1 MeV/u loss of primary beam energy
- a beam fluence of 10^6

- Complicated secondary bam productions regarding to charge states (beam and fragments)

OT et al., Eur. Phys. J. A (2018) 54: 66

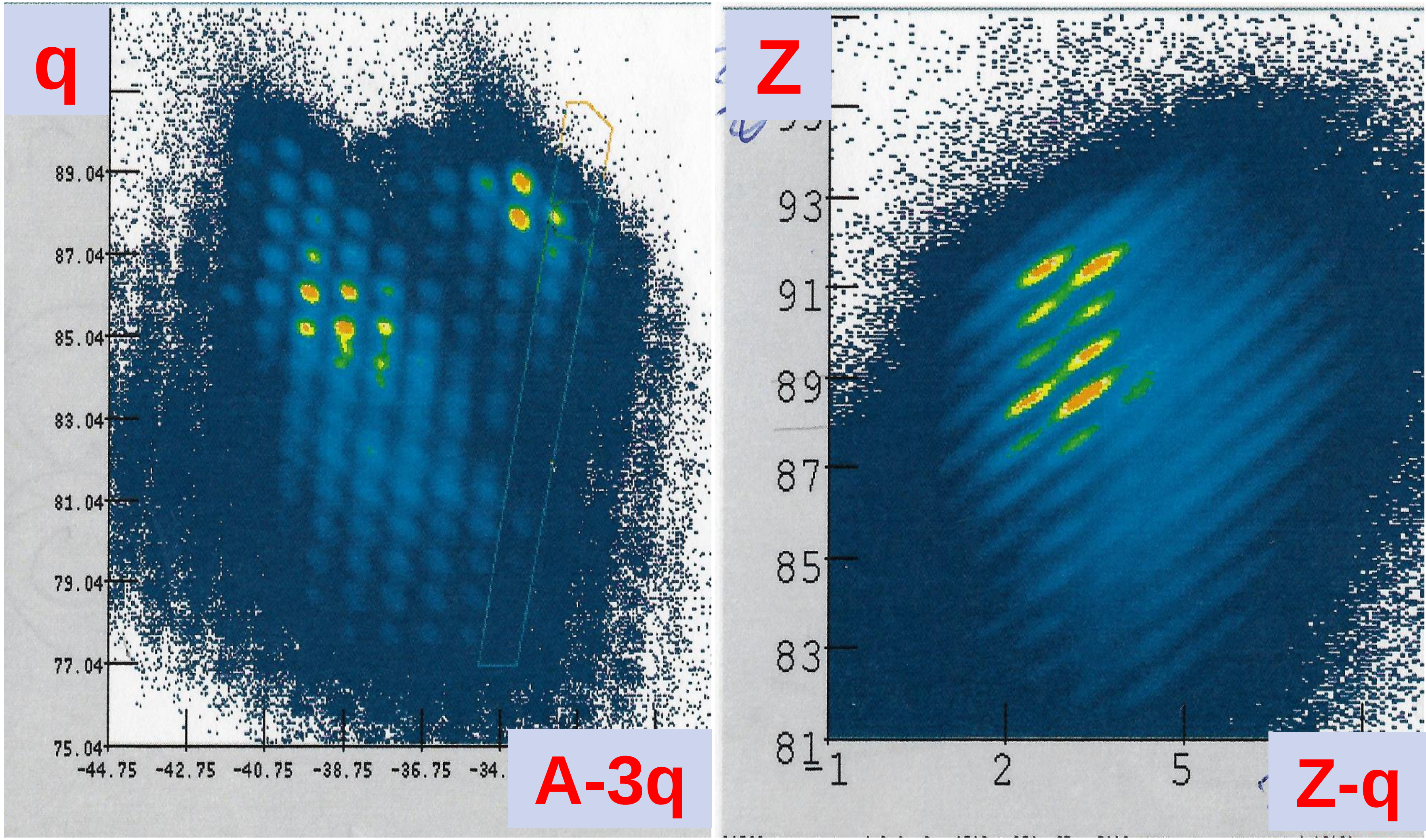
^{238}U (80MeV/u) + Be @ A1900+S800BL

E.Kwan, O.T. et al.,
will be published soon



- Below primary beam charge states
- Momentum acceptance dp/p=0.1 %
- Double achromatic at the Final Focal Plane
- No wedge
- Thin ToF Sci, no more materials in line

A,Z,q – separation in the Z=92 region



- Long ToF-base (45.5m)
- Non-cooled PIN-diodes (50x50 mm^2 0.5mm)

Working in High-Z region at intermediate energies

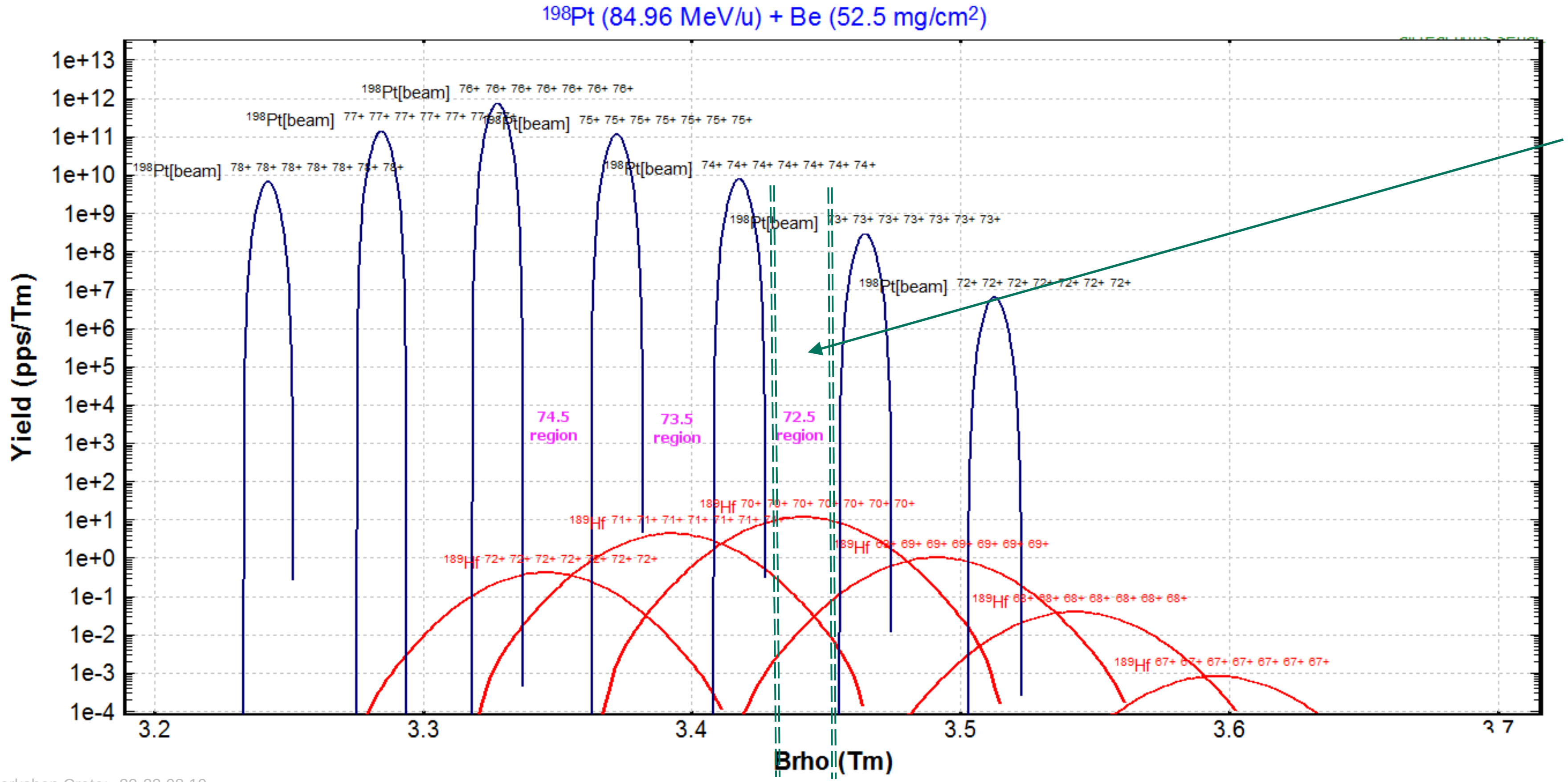
07 / 2019

NSCL E15130
"Search for isotopes and isomers in the Hf region"

PIs:

- Partha Chowdhury (UML)
- Oleg Tarasov (MSU)
- Andrew Rogers (UML)

- Working between primary beam charge states
- Try to avoid in-flight detectors (charge state production)
- No in-flight detectors in Dispersive plane ("wedge" property)
- New "Separator + *Long* Spectrometer" method

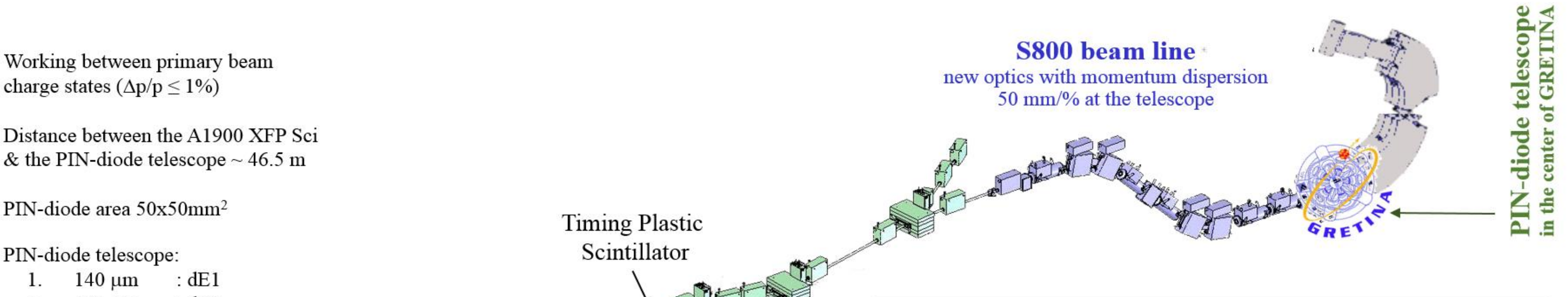


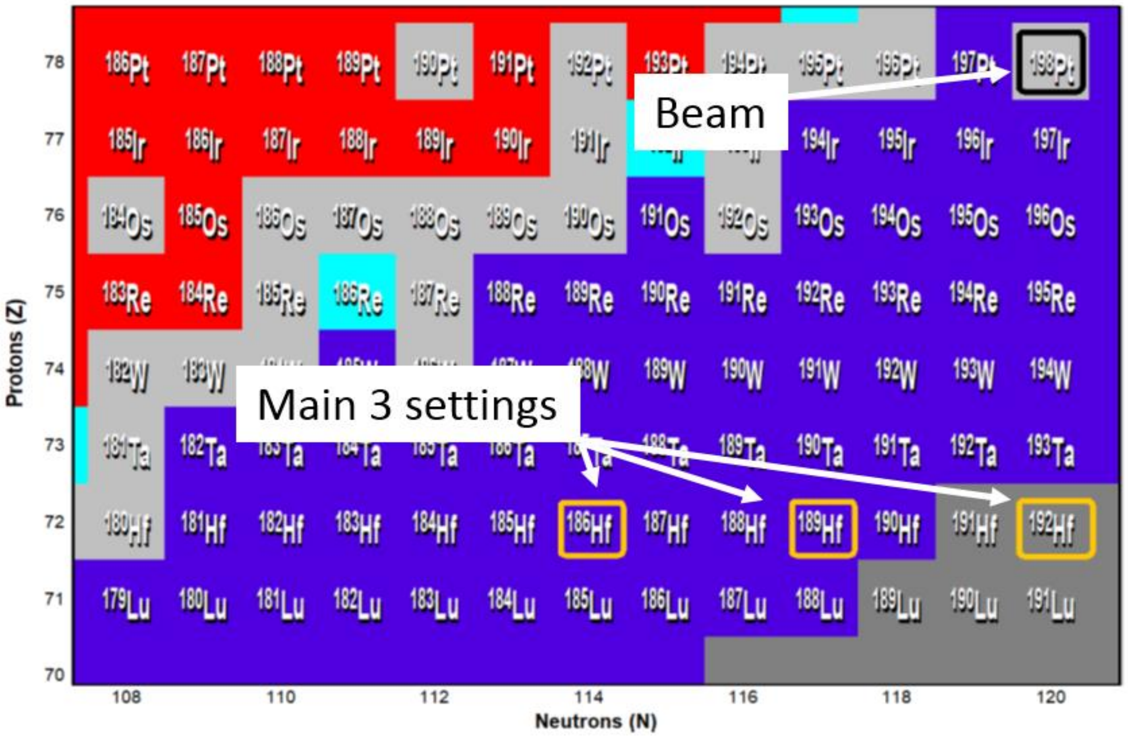
Working region
dP/P ~ 0.7-0.9%

Layout of the e15130 experiment at NSCL / MSU (07/2019):

"Search for isotopes and isomers in the Hf region"

- Working between primary beam charge states ($\Delta p/p \leq 1\%$)
- Distance between the A1900 XFP Sci & the PIN-diode telescope ~ 46.5 m
- PIN-diode area 50x50mm^2
- PIN-diode telescope:
  1. 140 μm : dE1
  2. 140 μm : dE2
  3. 500 μm : 16 strips
  4. 1000 μm : implantation
  5. 500 μm : veto



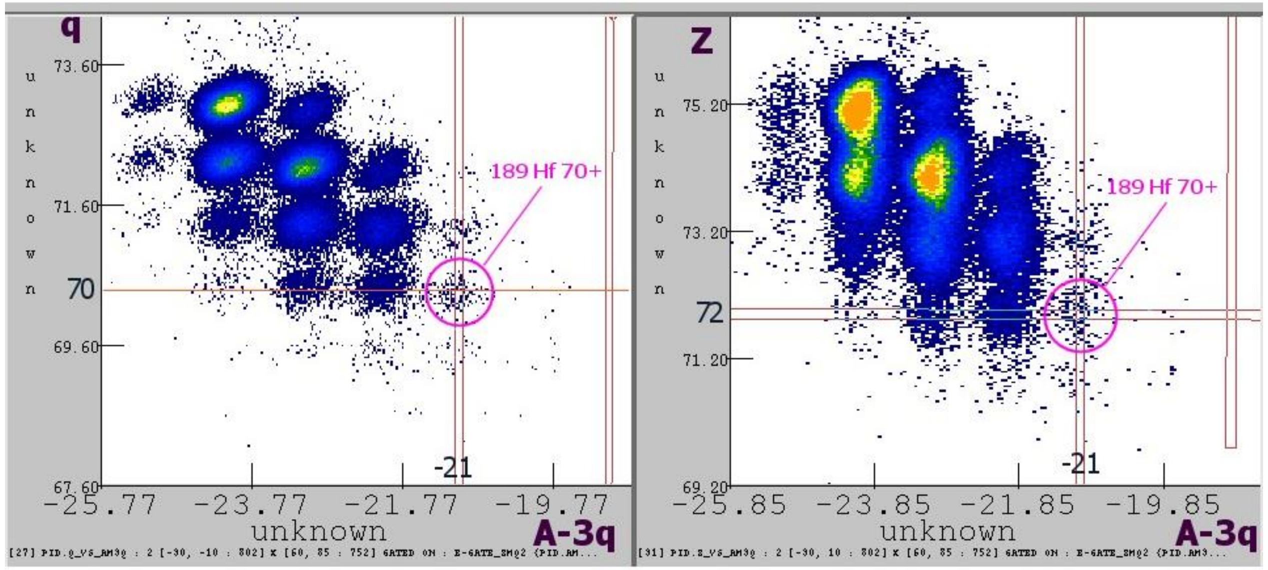


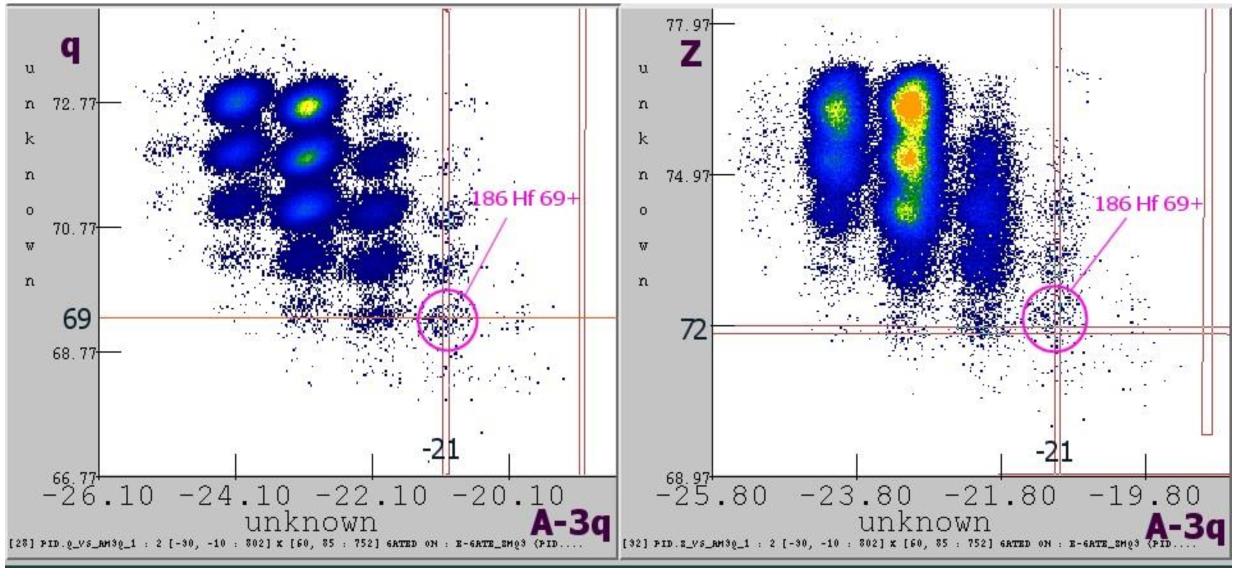
Experiment #e15130; July 2019 @ NSCL/MSU

^{198}Pt (85 MeV/u) + Be (47 mg/cm^2) -> Wedge -> $^{189}Hf^{70+}$

selection Z-q=2

selection Z-q=3





- New isotopes have been observed in the $^{192}Hf^{70+}$ settings
- Similar experiment (High-Z beam, working between charge states, dispersion at the FP detectors) will be held in RIKEN (11/2019)
- DERICA capabilities are very potential to compete in this region for new isotopes in PF and MNT reactions
- DERICA fragment-separator layout should prevent THIS experimental technique

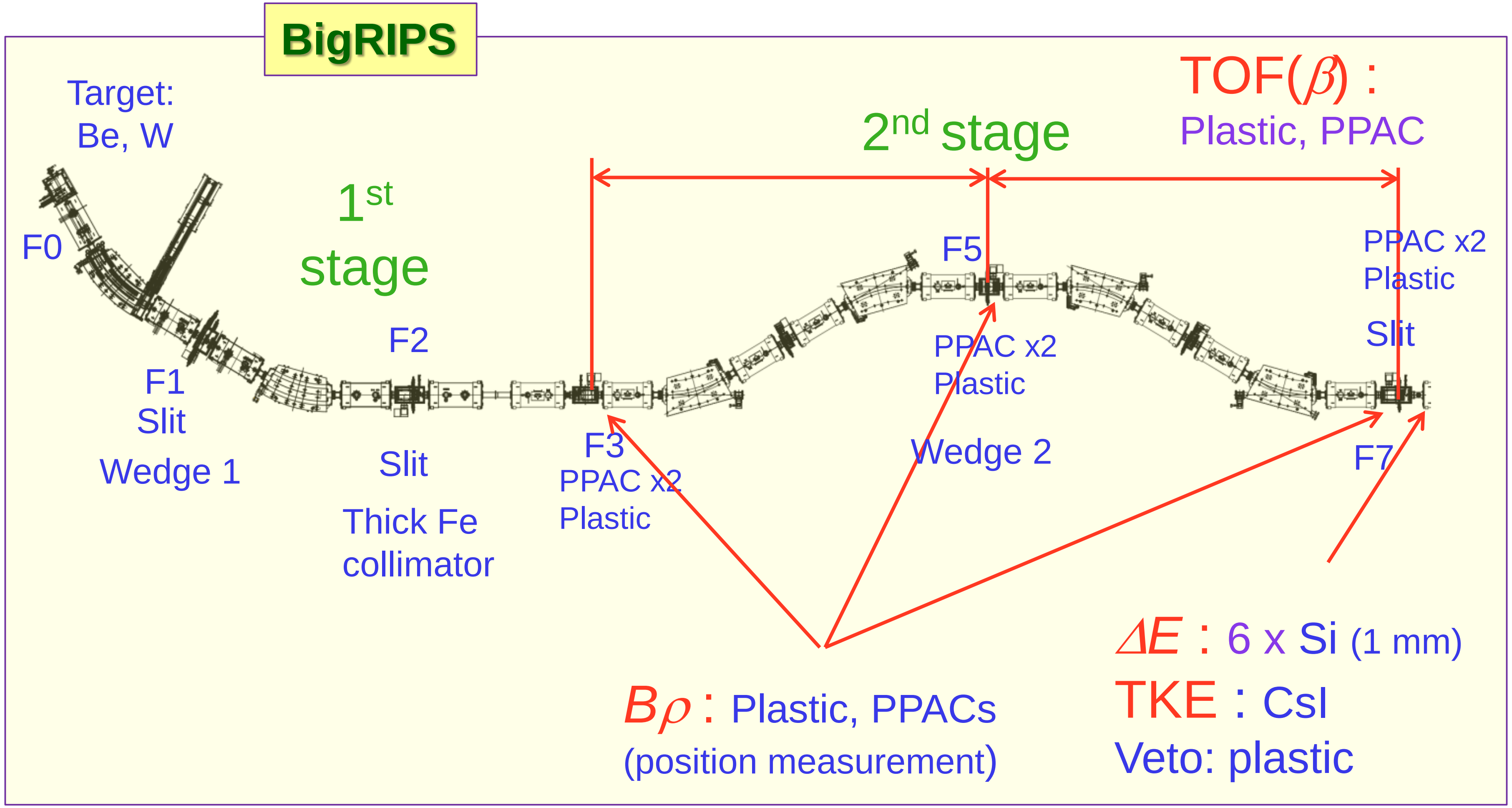
Production of super neutron-rich isotopes

^{60}Ca: Experimental setup and particle identification at BigRIPS

^{70}Zn beam @ 345 MeV/u
<I> = 200 pnA (1.25e12pps)

PID by TOF-Bρ-ΔE-TKE method: → Z, A/q, Q

- **New isotopes search**
- **Production cross section and momentum distribution measurement**
- **Secondary reactions yield measurement as target thickness**
- **New isomers search**



Total Experiment : 7 days

New isotopes search : 100.9 h (4.2 days)

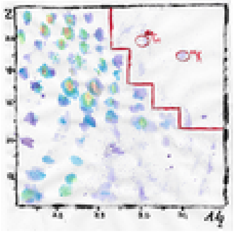
Final results

Editors' Suggestion

Discovery of ^{60}Ca and Implications For the Stability of ^{70}Ca

O. B. Tarasov *et al.*

Phys. Rev. Lett. **121**, 022501 (2018) – Published 11 July 2018



Eight newly discovered neutron-rich nuclei act as key discriminators between different mass models.

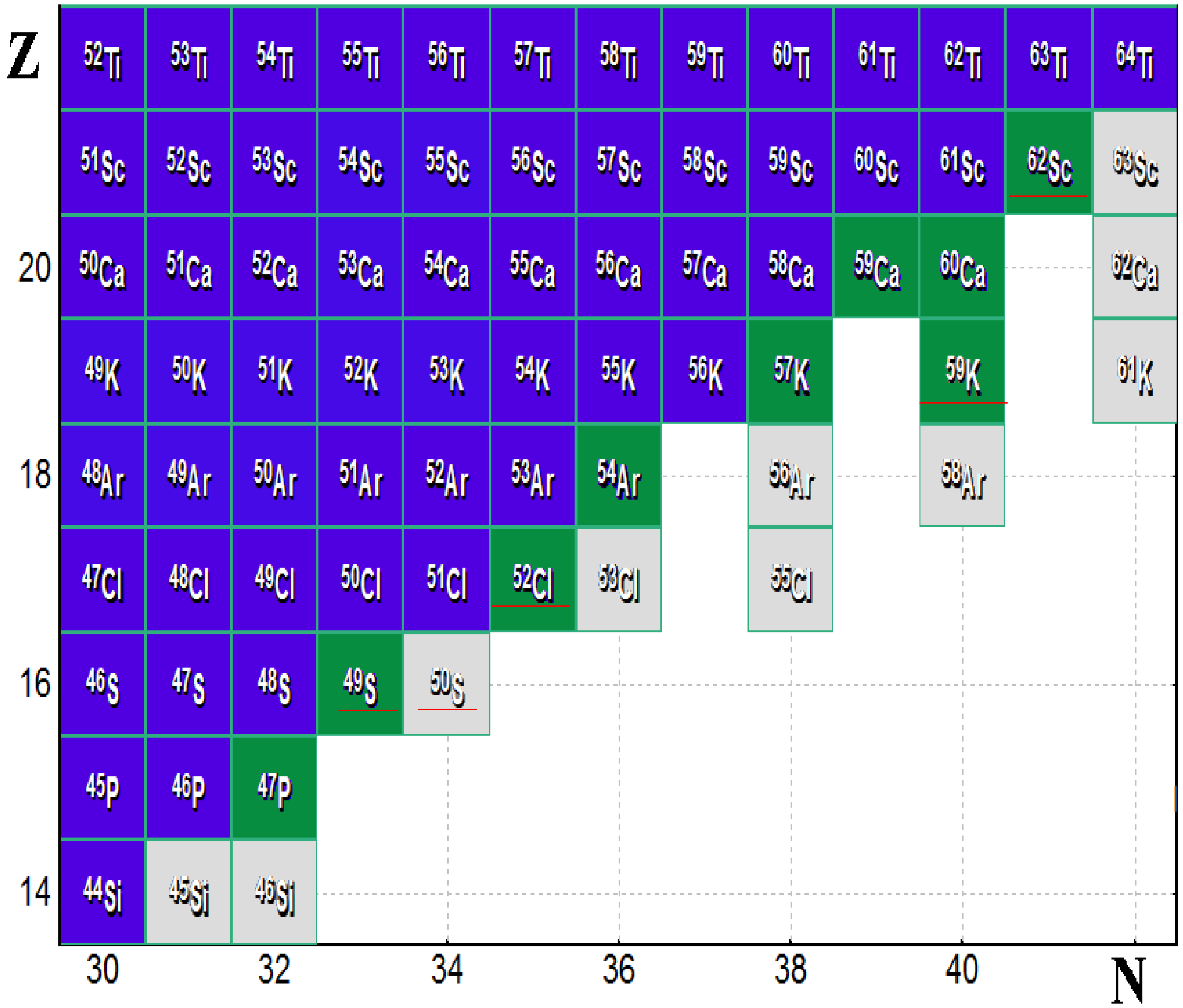
- Cross sections are still under analysis
- Production of ^{62}Sc is -9p, +1n
- Pickup is suppressed at these energies
- Two-step reactions through a charge-exchange channel?

  ^{70}Zn(p,n)^{70}Cu → ^{70}Cu(-8p)^{62}Sc or

  ^{70}Zn(-8p)^{62}Ti → ^{62}Ti (p,n) ^{62}Sc

- Charge-exchange reactions become important mechanism for RI production

8 new isotopes including ^{60}Ca (+^{59}K)



Green color : observed at the first time

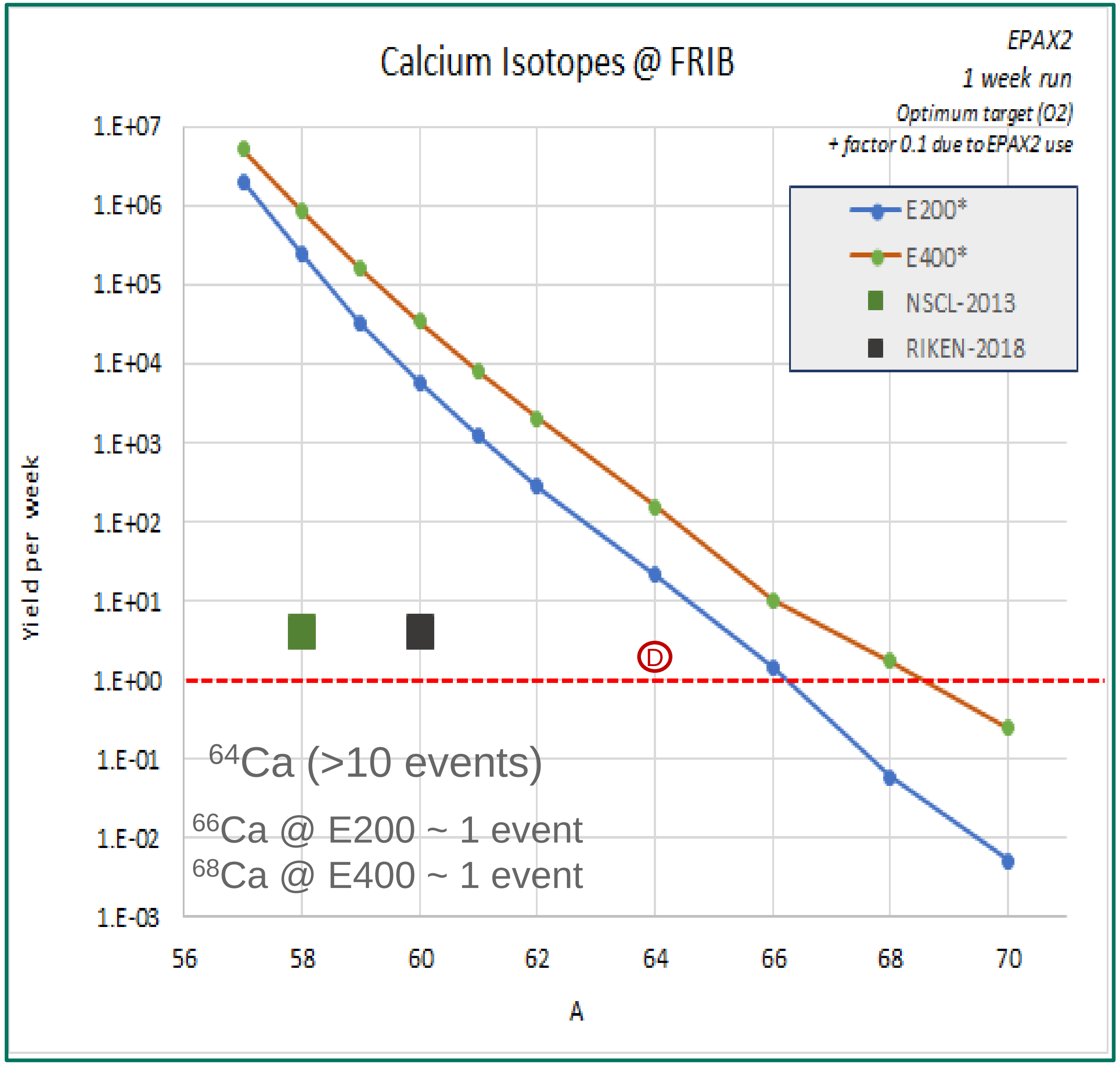
Red color : particularly interesting isotopes

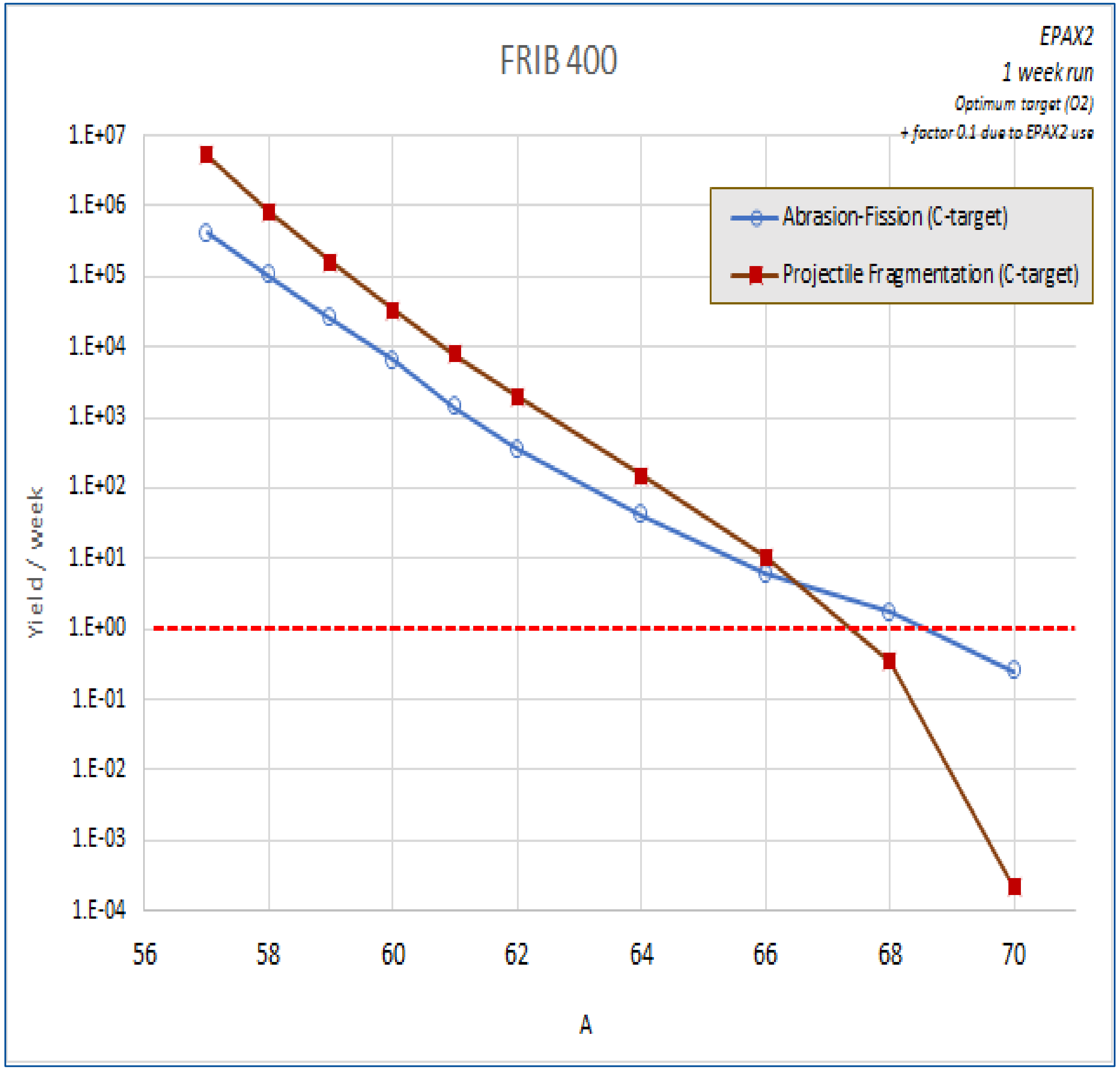
Production of new calcium isotope : past, current and future

^{A}Ca	year	N of stages	N of wedges	Reaction	Beam	Energy, MeV/u	Intensity, pps	Be-target, thick g/cm2	I*t, pps* atons/cm2	Lab	Reference	
54-56	1997	1	0	AF	^{238}U	1000	2.00E+07	1.00	1E+30	GSI	M.Bernas et.al., PLB415 (1997)	
57,58	2009	2	1	PF	^{76}Ge	130	1.25E+11	0.63	5E+33	MSU	OT et al., PRL 102, 142501 (2009)	
57,58*	2013	2	1	PF	^{82}Se	140	2.20E+11	0.70	1E+34	MSU	OT et al., PRC87, 054610 (2013)	0.4 kW
59,60	2018	2	2	PF (+SR?)	^{70}Zn	345	1.25E+12	2.80	2E+35	RIKEN	OT et al., PRL 122, 022501 (2019)	5 kW
62	>2020	3	2	PF+SR	^{76}Ge, ^{82}Se?				>1e36			50 kW
64	>2023	3	2	PF+SR	^{76}Ge, ^{82}Se?				>1e37			400 kW
66	>2026	≥ 3	≥ 2	AF or PF +SR	^{76}Ge, ^{82}Se, ^{238}U?							
68	>2030	≥ 3	≥ 2	AF+2SR	^{238}U							
70	>2036	≥ 3	≥ 2	AF+3SR??	^{238}U		liquid metal target?					

AF: Abrasion-Fission	FYI:		
PF: Projectile Fragmentation	FRIB	1.1E+37	400 KW vs 1g/cm2
SR: Secondary (MultiStep reactions)	FRIB-400	4.00E+37	800 KW vs 3.5g/cm2

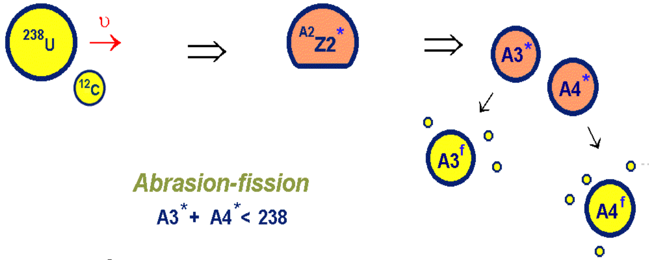
Calcium isotopes production at FRIB



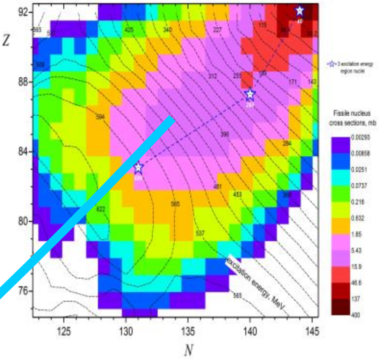


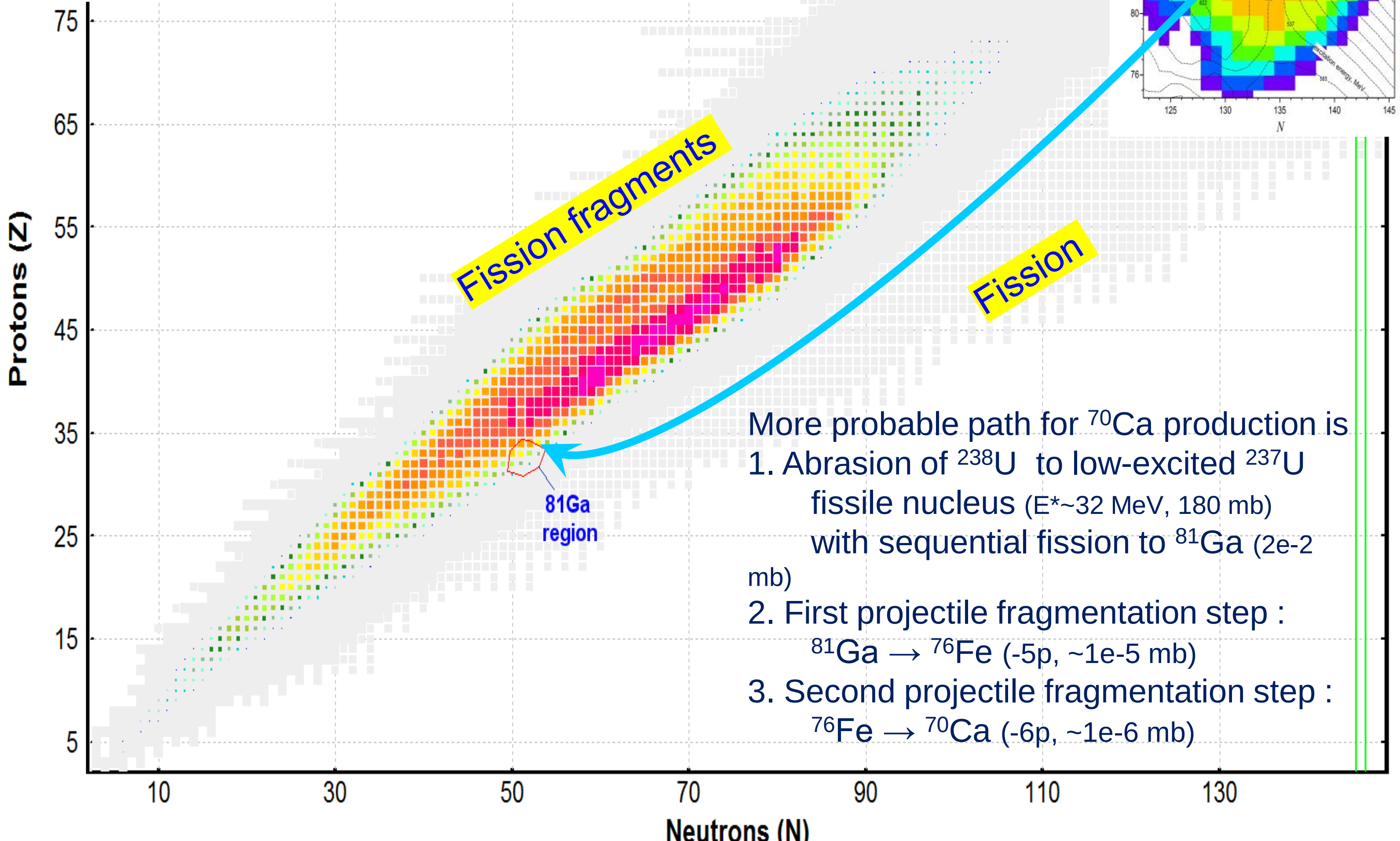
LISE++ Abrasion-Fission model; Projectile-Fragmentation steps

3 Excitation energy regions model : O.T., EPJA 25 (2005) 751;
O.T., Tech. Rep. MSUCL1299, NSCL, MSU, 2005.



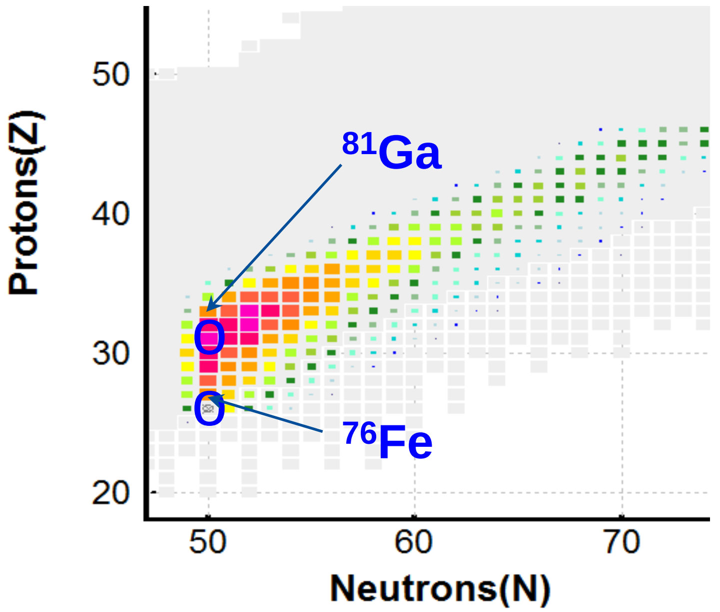
Ocean of fissile nuclei after abrasion of ^{238}U



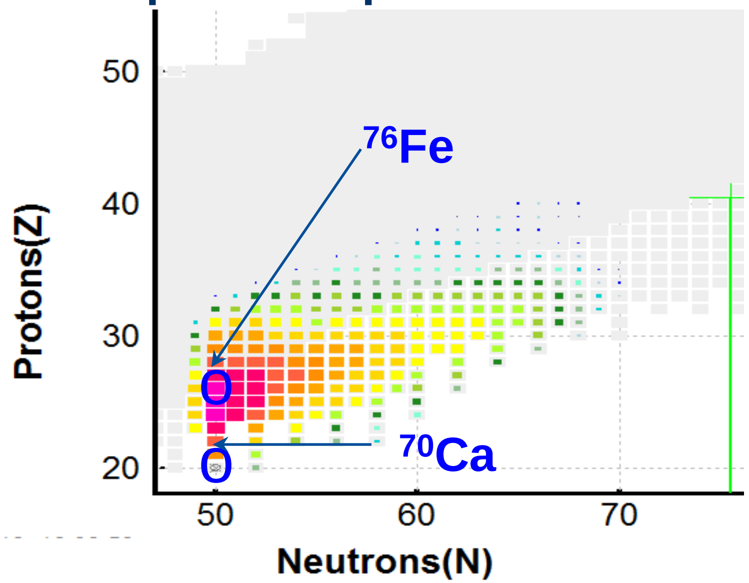


More probable path for ^{70}Ca production is
1. Abrasion of ^{238}U to low-excited ^{237}U fissile nucleus (E*~32 MeV, 180 mb) with sequential fission to ^{81}Ga (2e-2 mb)
2. First projectile fragmentation step : ^{81}Ga → ^{76}Fe (-5p, ~1e-5 mb)
3. Second projectile fragmentation step : ^{76}Fe → ^{70}Ca (-6p, ~1e-6 mb)

More probable parents of ^{76}Fe



More probable parents of ^{70}Ca



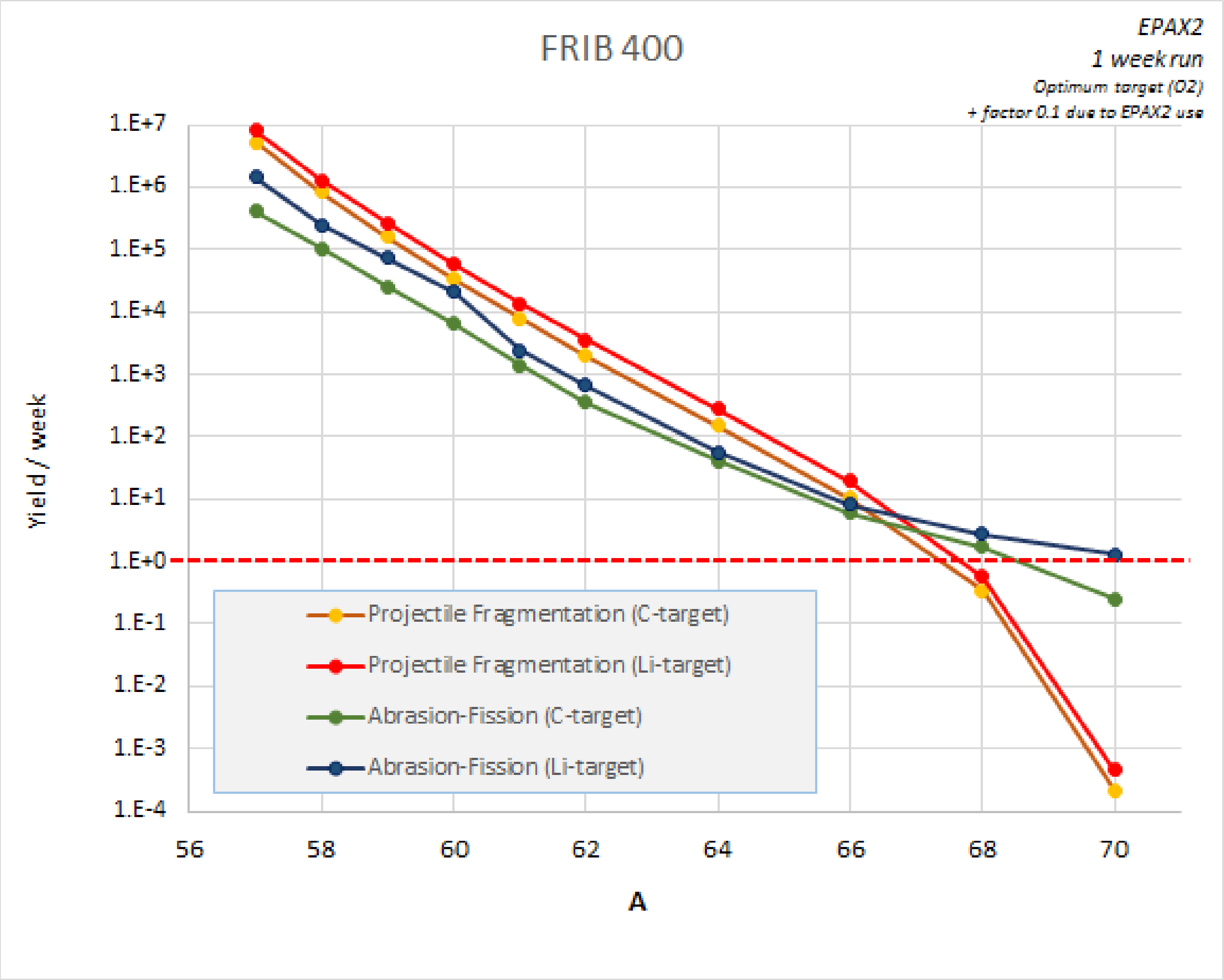
^{70}Ca from fission

	Energy, MeV/u	Carbon target thickness, mm
^{238}U	412->0	**12.85**
	412->200	8.37
	412->100	11.2
^{238}U(412 MeV/u)->^{237}U fission -> ^{81}Ga (peaks 370 & 450 MeV/u)		
^{81}Ga	450	41.3
^{76}Fe	450	55
^{70}Ca	450	86
Optimum target thickness to produce ^{70}Ca is **43** mm		
	final ^{70}Ca energy peak ~200 MeV/u, Brho~ 7.7Tm	
	Energy deposition in the target 800 kW	

Carbon target in mm

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
238U								200				beam stops																														
					81Ga production																								81Ga stop													
								76Fe production																																		
									70Ca production																															

Calcium isotopes production vs. target material



^{70}Ca @ E400 & Liquid Li target
~ 1 event !!

	Beam			Target		
	AZ	Energy	Intensity	thickness		settings
		MeV/u	1e11 pps	mm	1e22 atoms/cm2	
FRIB E400	82Se	520	1170	C-65	74	70Ca
FRIB E400	82Se	520	1170	Li-298	137	70Ca
FRIB E400	238U	412	509	C-43	60	70Ca
FRIB E400	238U	412	509	Li-245	113	70Ca

0.3 m target thickness
from the realm of fantasy…

High-Power Beams
Separator Requirements

(Moved to the FRS presentation)

Requirements for Separator for High-Power Beams

- Smart planning for future updates: energy, intensity, ISOL
- 3 stage separation (combination of 2 stages – high resolution and 3 stages - high purification)
- Super Conducting device, Compact
- “High-Z disperse” mode
- Momentum compression mode
- Angular emittance cut device
- Multi-user FRS approach
- Isotope harvesting
- Flexibility: target (more than one target thickness), fragment-separator (not so complicated tuning) and so on
- Beam inclination on a target??

What we have to know working
at the new generation facilities?

Some non-prevented difficulties…

Separator for High-Power Beams : BigRIPS

Smart planning for future updates: energy, intensity, ISOL	No
3 stage separation (combination of 2 stages – high resolution and 3 stages - high purification)	Yes-No-Yes
Super Conducting device	Yes
“High-Z disperse” mode	Yes? Will be checked: 11/2019
Momentum compression mode	No
Angular emittance cut device	Yes
Multi-user FRS approach	Yes
Flexibility: target (more than one target thickness), fragment-separator (not so complicated tuning) and so on	Yes
Isotope harvesting	No
Beam inclination on a target??	Possibility exists

Working at BigRIPS

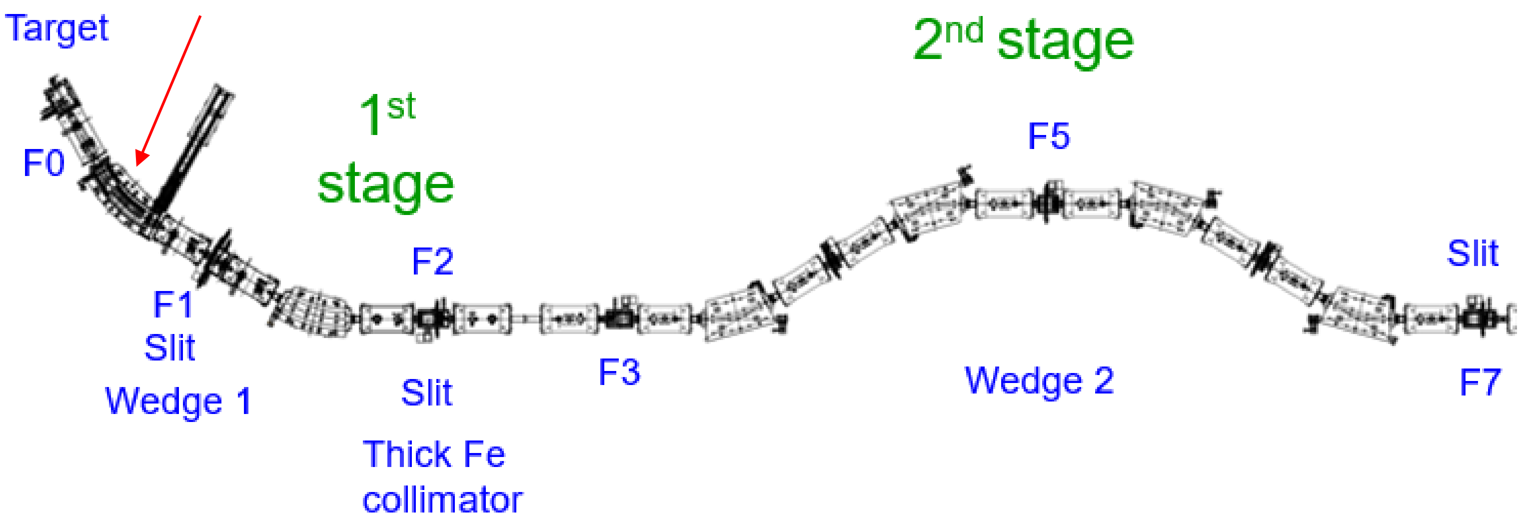
new generation facility

- Reactions in the 1st dipole beam-dump
- High-order aberrations at the wedge selection plane
- [^{70}Zn] Huge background of light particles @ F3 (first detectors of the 2nd stage)
- [^{70}Zn] Huge background of light particles @ F7 Ge-detectors
- No momentum compression foresight
- Beam-dump is far from a focus plane
- 1st SC segment: NMR-probe
- High-Z Abrasion-Fission production cross sections

- Angular emittance cut device
- Quality optic reconstruction
- Very precise RIB tagging by A/q (e.g. $^{132}Sn^{50+}$ beam)
- Advance diagnostic and fast in-flight detectors

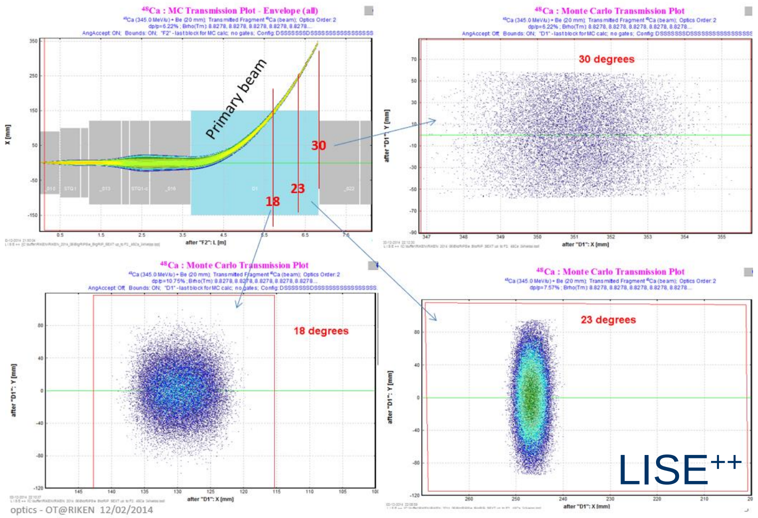
Reactions in the 1st dipole beam-dump

V-shape internal beam-dump



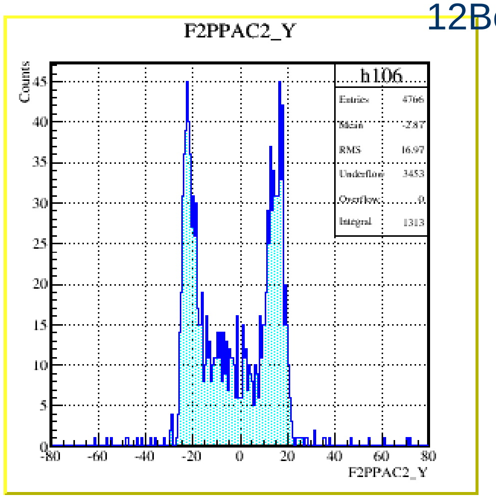
- ^{48}Ca beam for ^{33}F, ^{36}Ne, ^{39}Na isotopes search
- Large unexpected yield of A/q=3 isotopes using a thick wedge
- Two peaks vertical distribution at F2 & F3
- Distance between peaks depends from fragment Z

Beam profile at different dipole angles

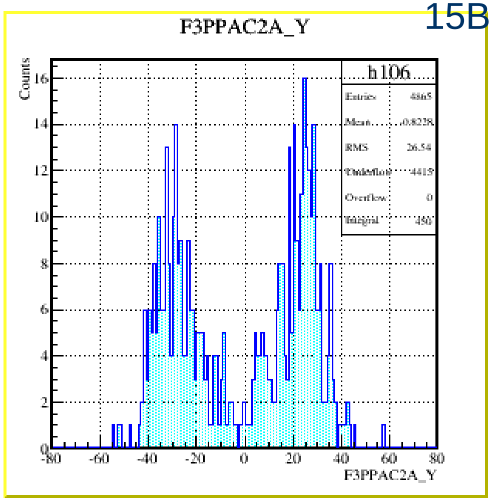


- Reasons
  - Reactions in the dipole beam dump
  - Lightest particles passed slits
- Troubleshoot
  - Thick Fe (~0.5m) collimator @ F2

F3trigger 12Be



F3trigger 15B



High-order aberrations at the wedge selection plane

^{180}Er settings

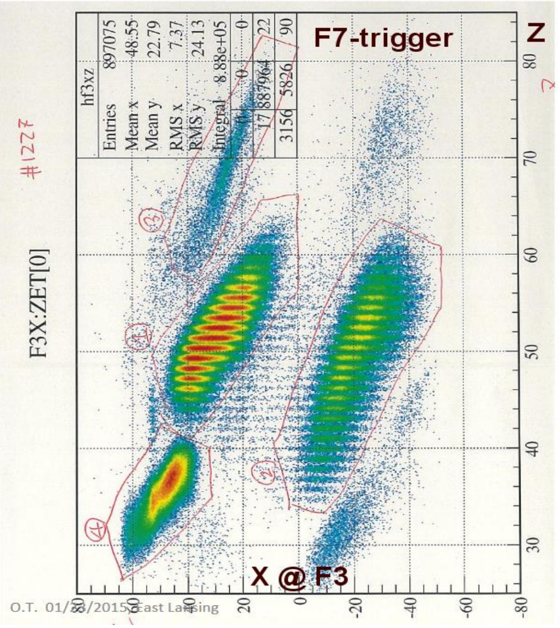
Rates :

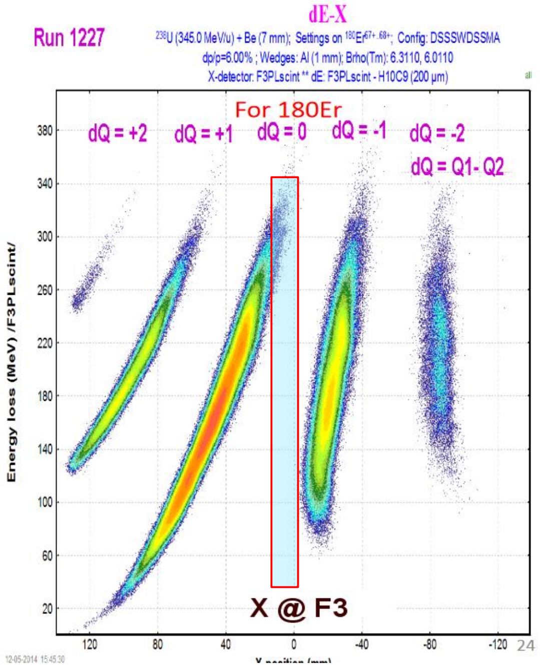
Beam (15 pnA) : 9.4e10 pps
LISE^{++} @ F1
(^{180}Er) : 4.6e8 pps
Experiment : ~ 1e8 pps

F3-rate
LISE^{++} : 1e3 pps
Experiment: 2e5 pps

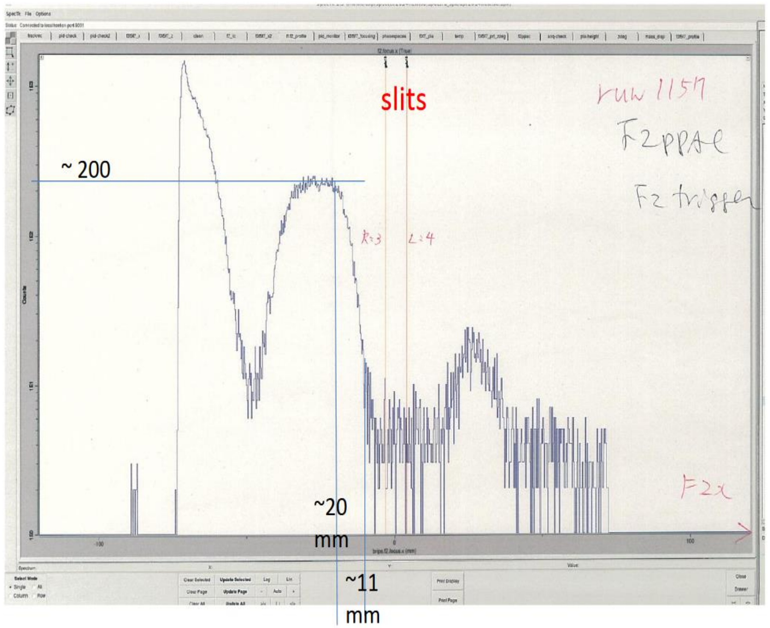
F7-rate
LISE^{++} : 2e2 pps
Experiment: 5e3 pps

Special settings for Wedge to work between charge state blops

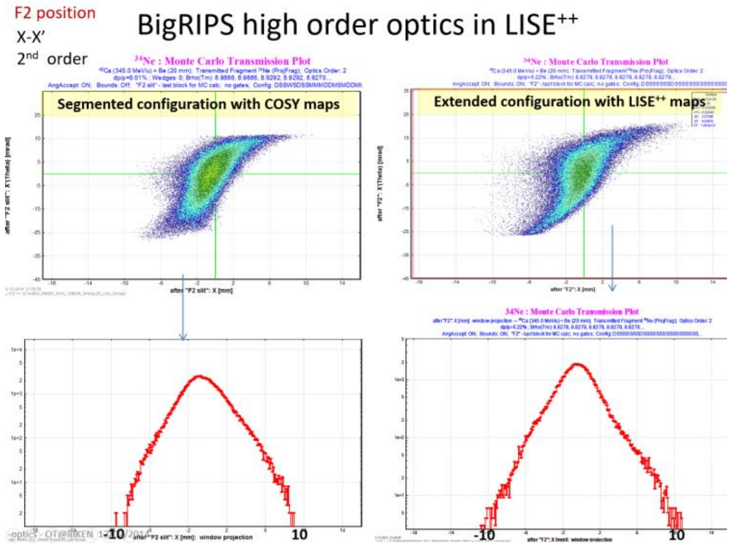




F2 PPAC – F2-trigger



BigRIPS high order optics in LISE^{++}



Background

a. Reactions in wedge?
b. Primary beams?
c. Bad first order Optics?
d. High order optics contribution?
e. Energy straggling?
f. Coulomb scattering?

Not 1st order gaussian tails..

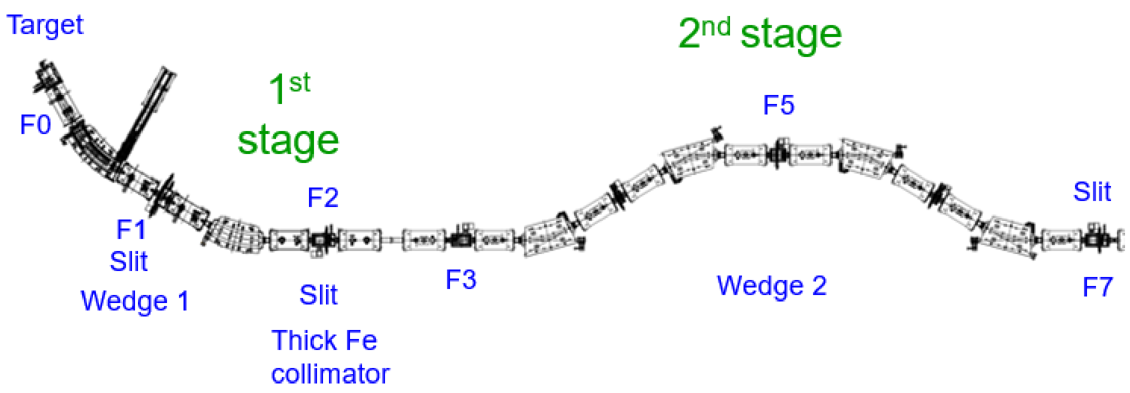
Exponent tails!

[^{70}Zn] Huge background of light particles @ F3, F7

- [^{70}Zn experiment] Huge background of light particles @ F3 (first detectors of the 2nd stage)

With thick Fe collimator @ F2 & Fast F3 detectors (10^5)

It's necessary to use 3-stage separation technique.
Detectors should me removed from F3 & F5



350 (450) MeV/u triton range in

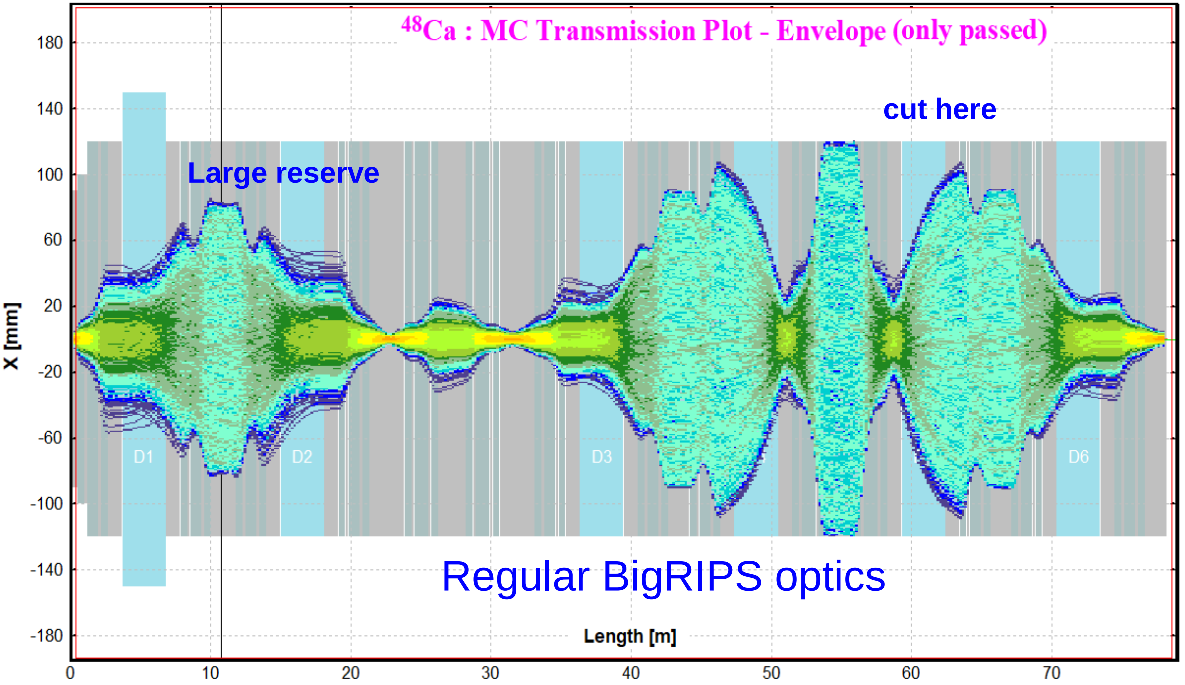
Iron: 0.36 (0.54) m
Air: 1.9 (2.82) **km**

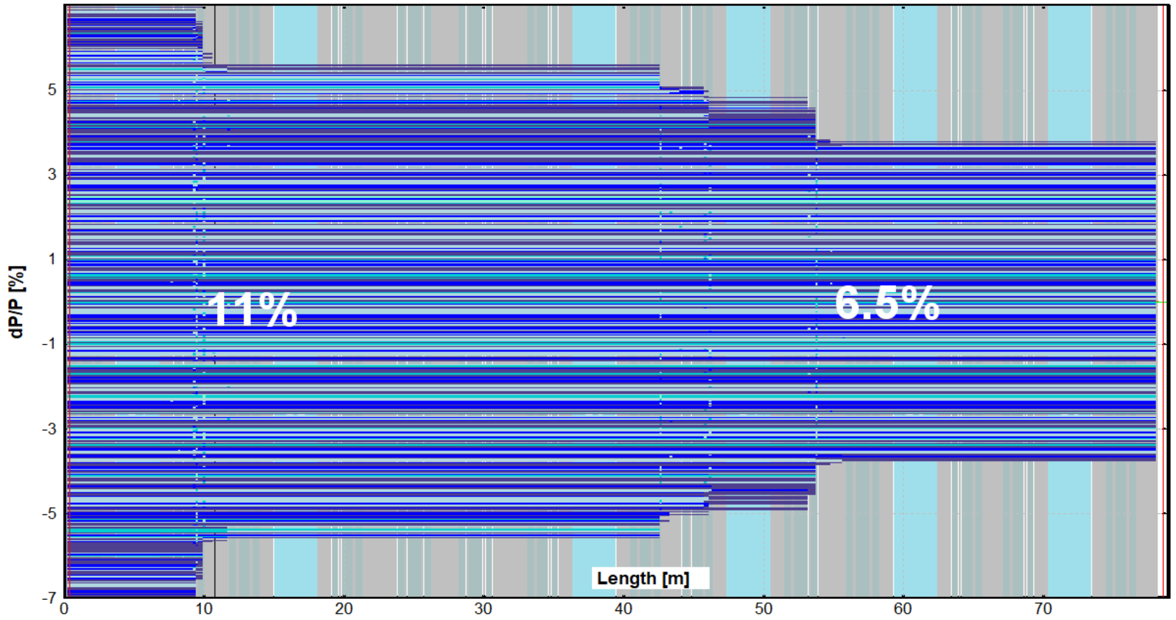
- [^{70}Zn experiment] Huge background of light particles @ F7 Ge-detectors

But Rate @ the F7 telescope was < 100 cps

It's necessary to use the 3-stage separation technique,
or construct a wall to get closed from light particles produced at the 1st stage

Momentum compression foresight





Momentum compression is accomplished by design of a fragment separator system that has the appropriate momentum dispersion provided by the dipoles and by properly shaping the energy degrader.

L. Bandura et al. / Nuclear Instruments and Methods in Physics Research A 645 (2011) 182–186

Attempt to find solution for momentum compression optics using LISE++

compression factor equal to 5/3

Total transmission results are shown in figure below

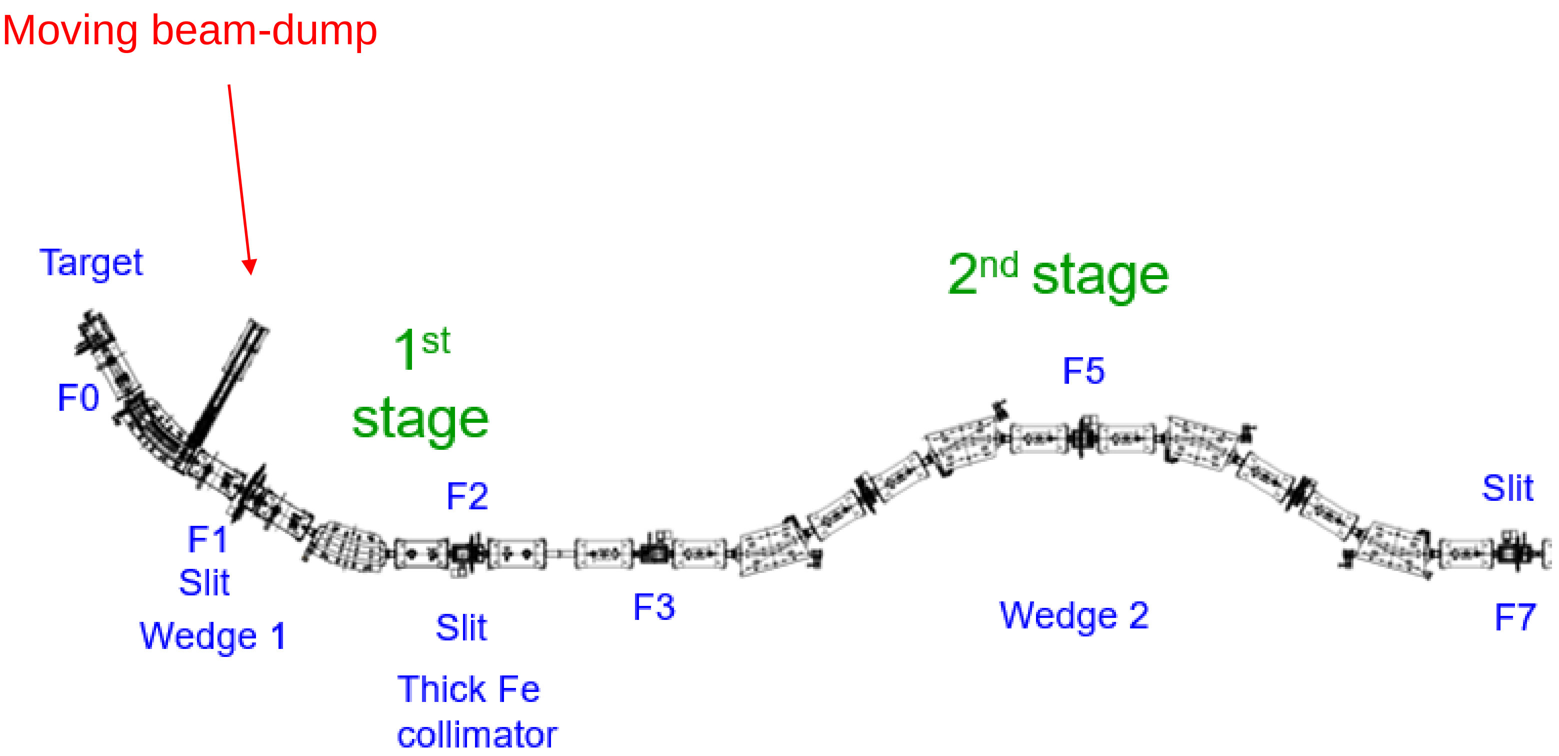
	F0-F2	F2-F7	total
regular	63.40%	50%	32%
compressed v4.	49.80%	83%	41%
	F0-F1		
regular	68.10%		
compressed v4.	64.30%		

It means total gain in transmission with compressed optics v.4 (compression factor is equal to 5/3) is equal to **31%**.

As you can see mainly the transmission loss for compressed optics has place in F1-F2 segment (probably due to large F0-F1 angular magnification).

For compressed optics version 3 with the compression factor equal to 2 the transmission gain was obtained even **64%** (!!!), but the first quad was overloaded.

Beam-dump is far from a focus plane



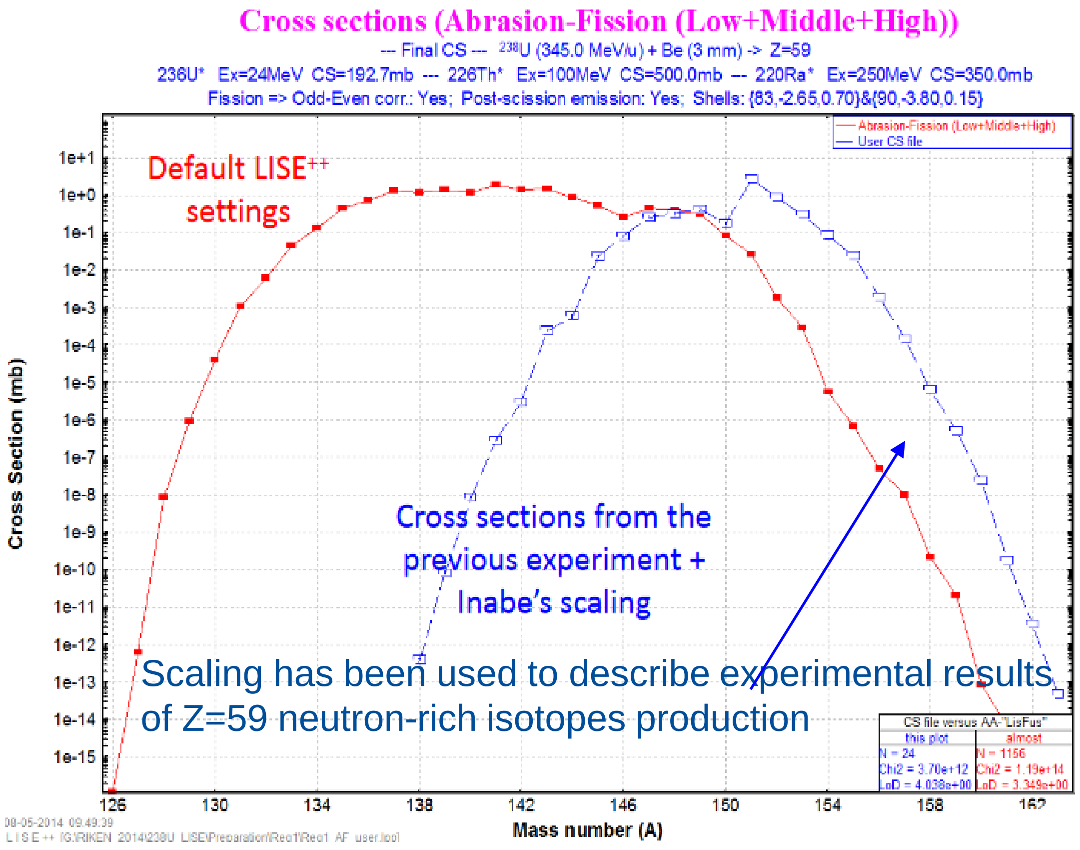
Global matrix

-1.54893	2.27459	0	0	0	-10.37375	[mm]
-0.24995	-0.27855	0	0	0	-5.00012	[mrad]
0	0	-3.77917	0.50887	0	0	[mm]
0	0	-0.90737	-0.14243	0	0	[mrad]
-0.5152	1.42628	0	0	1	-1.416	[mm]
0	0	0	0	0	1	[%]
/[mm]	/[mrad]	/[mm]	/[mrad]	/[mm]	/[%]	

Serious complications to work between primary high-Z beam charge states

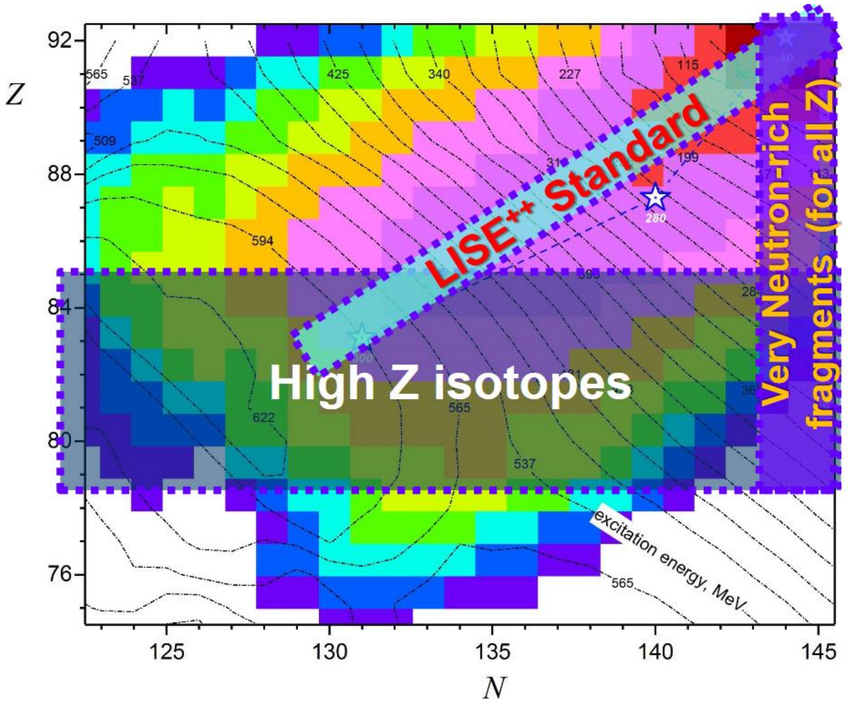
Development and improvement of LISE++ reactions models

Cross sections Z=59



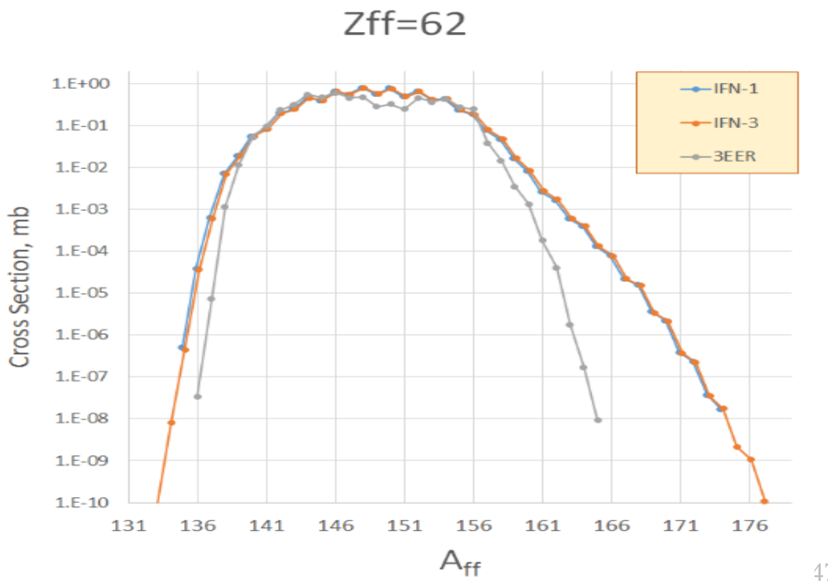
Version 10.1.127

3 Excitation Energy Region (3EER) model settings for production high Z isotopes



Version 11.0.38

Initial Fissile Nuclei (IFN) Analyzer



Summary

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- Optimum energy for RIB production has been discussed
- Results of Charge state distributions, momentum and angular transmission, target thickness, secondary reaction factor analysis as function of primary beam energy has been shown
- DERICA fission fragment transmission and yields of Calcium and Tin isotopes were done. It looks like very potential, and exceeding by two order of magnitude an operating RIB facility
- 100 MeV/u ^{238}U high-power (700 kW) beam makes enormous difficulties for target and beam-dump construction
- Physics with stopped RIBs in 70-100 MeV/u is multifarious and perspective
- Production of new Calcium isotope is huge challenge in future (> 2036)
- Experience of new-generation facilities should be considered
- From DERICA FRS presentation: smart planning for future updates (energy, intensity, ISOL), 3 stage separation, Super Conducting device, “High-Z disperse” mode, momentum compression mode, angular emittance cut device, multi-user FRS approach