Oleg B. Tarasov
NCSL / MSU, USA

Production of Fast Rare Ion Beams

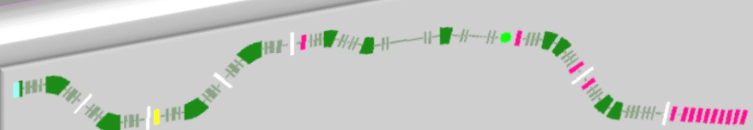
Euroschool on Exotic Beams 2013, Dubna
Euroschool on Exotic Beams 2013, Dubna

26-31 / 08 / 2013

LISE++

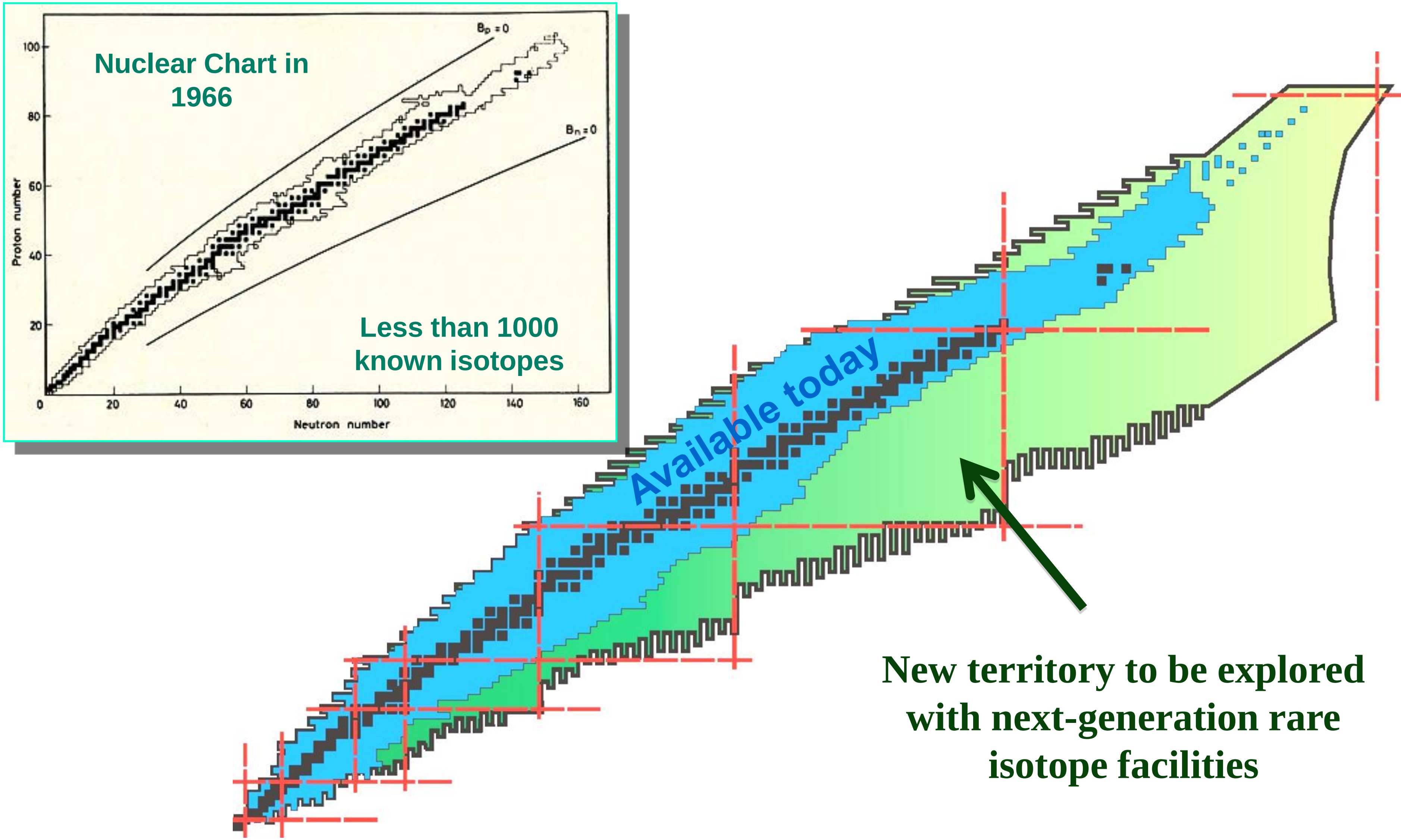
1. Introduction to production of Fast Rare Ion Beams
2. Production Area
3. Separation
4. Identification
5. Production of new isotopes
6. LISE^{++}: Utilities
7. Radioactive beam physicist task

LISE++



- Rare Isotope Science and Applications
- How do we make rare isotopes?
- Production Mechanisms
  - ✓ High energy
  - ✓ Low energy
  - ✓ Production Cross Sections
- Rare Isotope Production Techniques
  - ✓ ISOL
  - ✓ In-Flight
  - ✓ Fragment separators
  - ✓ Methods: Pros and Cons
  - ✓ Rates comparison
- In-Flight facilities
- Brief "Summary"

The availability of rare isotopes over time

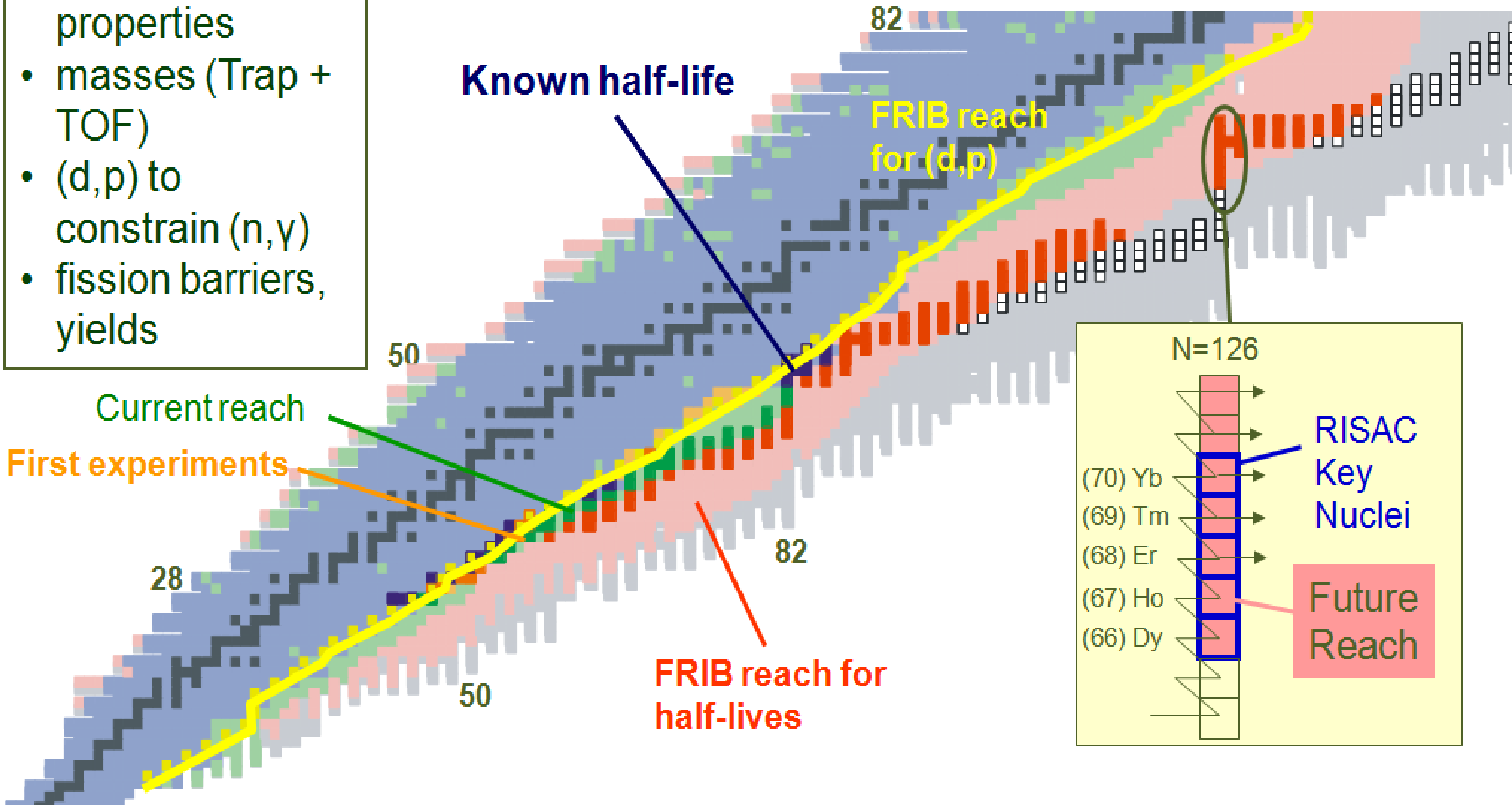


blue – around 3000 known isotopes

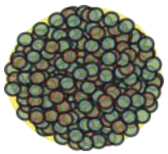
Black squares are the around 260 stable isotopes found in nature (> 1 Gy)

New Rare IF – Will Allow Modeling of the r-Process

- β-decay properties
- masses (Trap + TOF)
- (d,p) to constrain (n,γ)
- fission barriers, yields

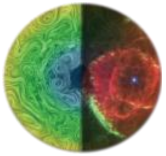


Rare Isotope Science and Applications



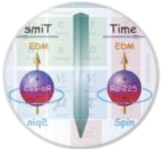
Properties of nucleonic matter

- Classical domain of nuclear science
- Many-body quantum problem: intellectual overlap to mesoscopic science – how to understand the world from simple building blocks



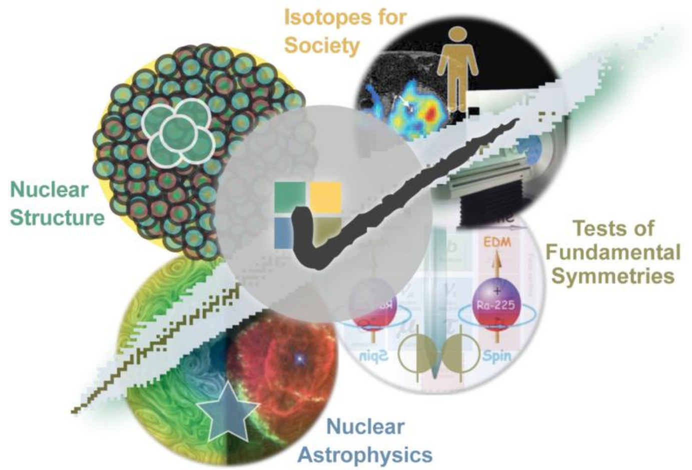
Nuclear processes in the universe

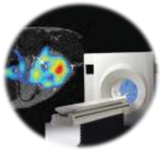
- Energy generation in stars, (explosive) nucleo-synthesis
- Properties of neutron stars,
  EOS of asymmetric nuclear matter



Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei



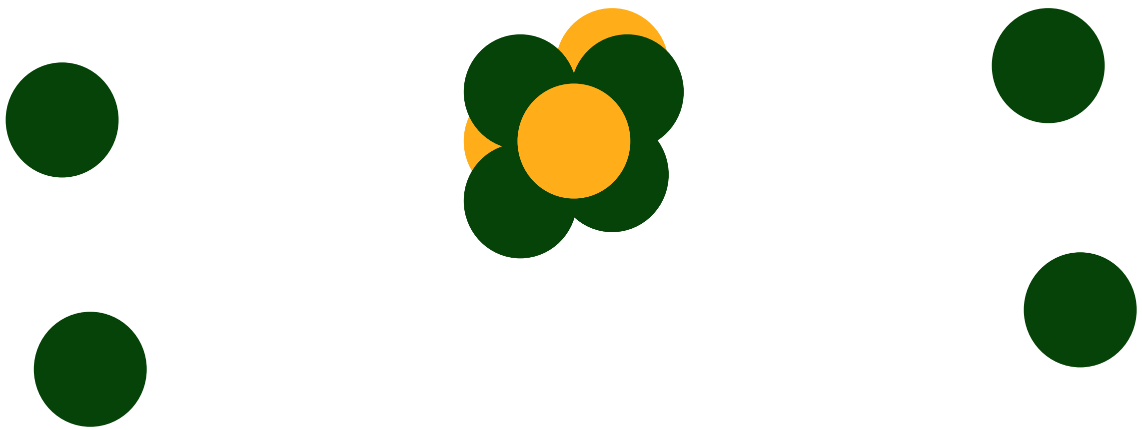


Societal applications and benefits

- Bio-medicine, energy, material sciences, national security

How do we make rare isotopes?

Lithium-7
3 protons, 4 neutrons

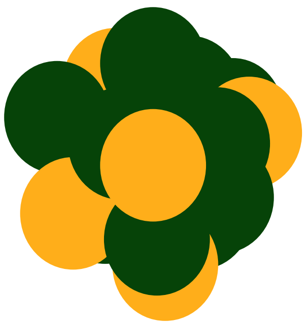


Suppose we want to study Lithium-11
3 protons, 8 neutrons

B.Sherrill

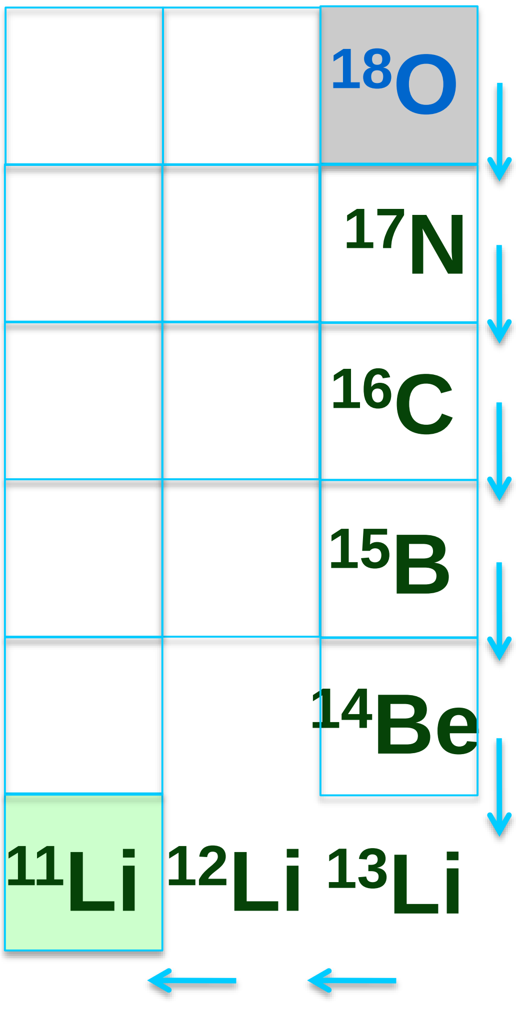
An alternative

Start with a nucleus with enough neutrons and to make ^{11}Li (e.g. ^{18}O) and remove protons



^{18}O

^{11}Li



B.Sherrill

18-Oxygen **Collision** **11-Lithium**

To use this mechanism (projectile fragmentation), an ^{18}O nucleus is accelerated to a velocity of greater than around 50 MeV/u.

B.Sherrill

Production Mechanisms – High Energy

Fragmentation (used at NSCL, GSI, RIKEN, GANIL, FRIB)

- Projectile fragmentation of high energy (>50 MeV/A) heavy ions
- Target fragmentation with high energy massive ion.

Spallation (ISOLDE, TRIUMF-ISAC, EURISOL, SPES, …)

- Name comes from spalling or cracking-off of target pieces.
- Major ISOL mechanisms, e.g. ^{11}Li made from spallation of Uranium

Fission (HRIBF, ARIEL, ISAC, JYFL, …)

- There is a variety of ways to induce fission (photons, protons, neutrons [thermal, low, high energy])
- The fissioning nuclei can be the target (HRIBF, ISAC) or the beam (GSI, NSCL, RIKEN, FAIR, FRIB)

Coulomb Fission (GSI)

- At beam velocities of > 200 MeV/u the equivalent photon flux is so high the GDR excitation cross section is many barns

Charge Exchange (GSI, NSCL, FRIB)

- a neutron or proton can change its charge with a proton or neutron; cross sections can be ≈mb at >100 MeV/u

Production Methods – Low Energy

(p,n) (p,nn) etc.

- $E_p < 50$ MeV
- Used for the production of medical isotopes
- Selective, large production cross sections (100 mb), and intense (500 mA) primary beams
- Used at HRIBF(ISOL), LLN (ISOL), ANL (in-flight) and Notre Dame (in-flight), Texas A&M (in-flight with MARS, e.g. ^{23}Al)

Fusion-Evaporation

- Low energy 4-15 MeV/A and “thin” targets (mg/cm^2)
- Selective with fairly large production cross sections
- Used for example at JINR, ANL(in-flight), JYFL (Jyväskylä)

Fusion-Fission

- ^{238}U+^{12}C (basis of Laser acceleration idea D. Habs et al.)
- ^{238}U(24MeV/u) +^{9}Be @ LISE3.GANIL.FR

Low Energy - Continued

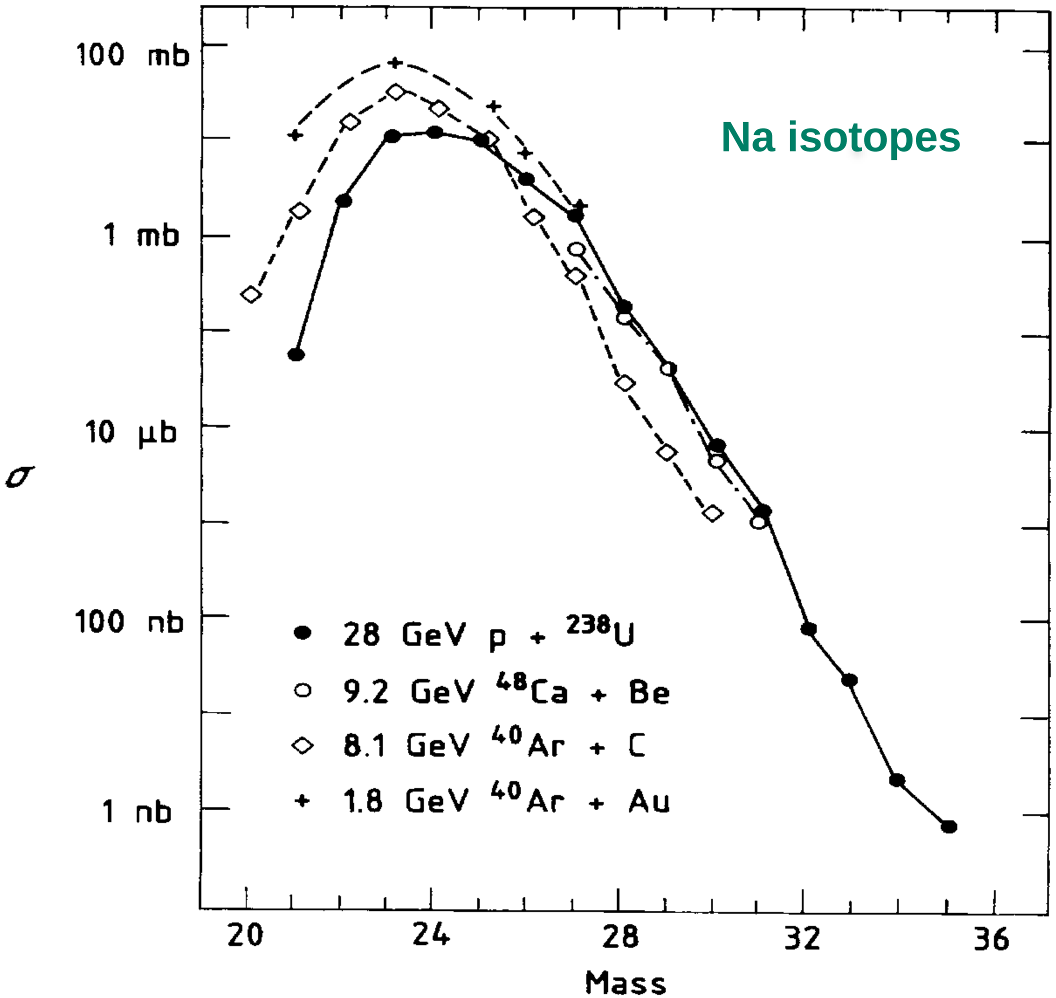
Multi-Nucleon Transfer reactions (two body final state)

- **Significant cross section between 10 - 50 MeV/A**
- **High production of nuclei near stability.**
- **Multi-nucleon reactions can be used to produce rare or more neutron rich nuclei.**

Deeply inelastic reactions (10 - 50 MeV/u range)

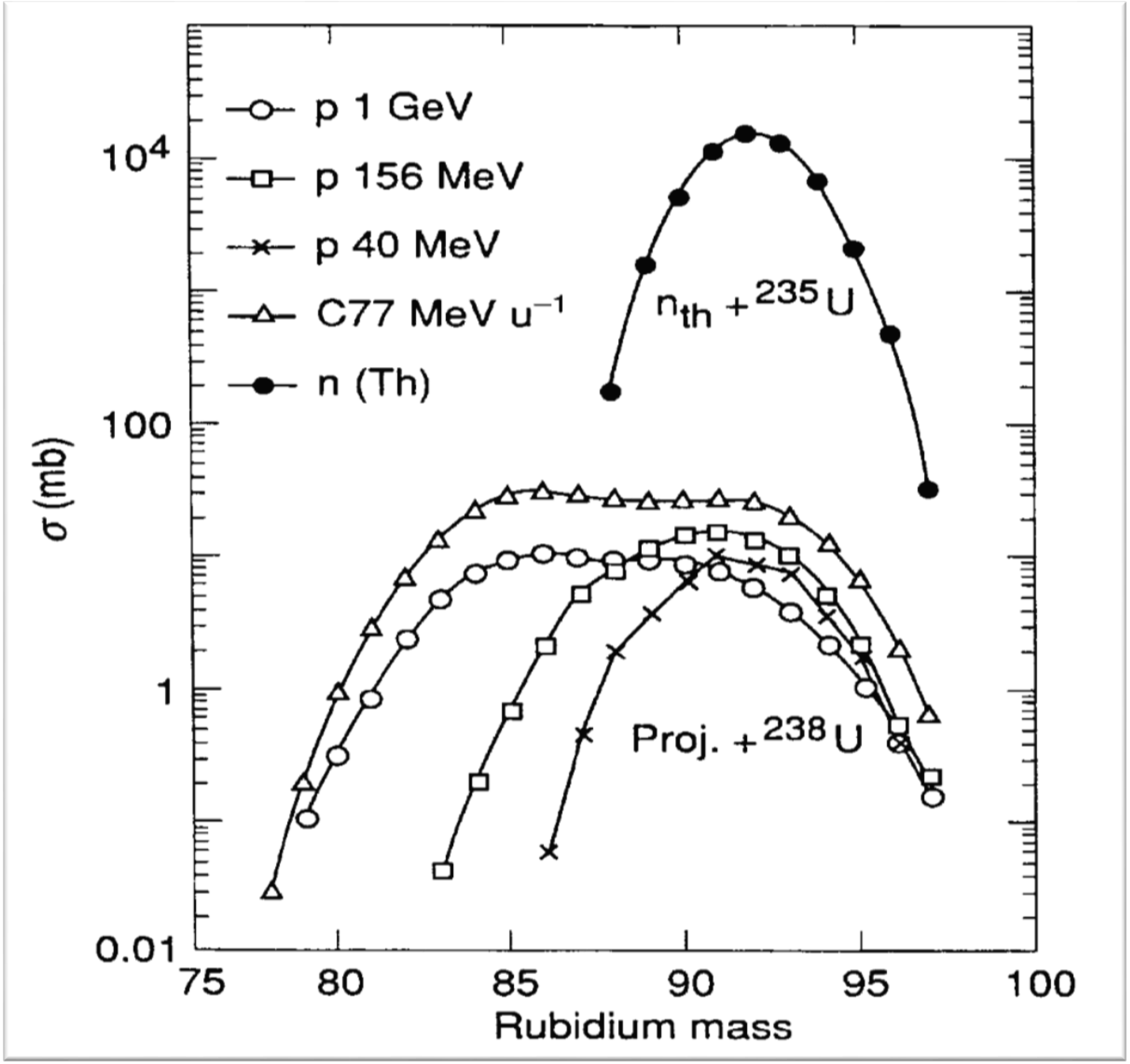
- **Deep inelastic - KE of the beam is deposited in the target. Products are emitted away from the beam axis.**
- **Was used to first produce many of the light neutron rich nuclei**
- **Is used to study neutron rich nuclei since the products are "cooler" and fewer neutrons are evaporated than in fusion reactions.**
- **Large cross sections for production of some exotic isotopes**

Universality of Production Cross Sections



H Ravn, CERN

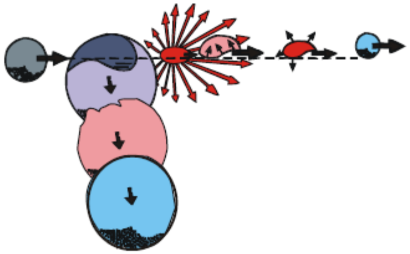
Fission Cross Sections



Low energy fission can lead to higher yields for certain nuclides.

This is the basis of the electron driver upgrade of the TRIUMF (ARIEL).

Projectile fragmentation

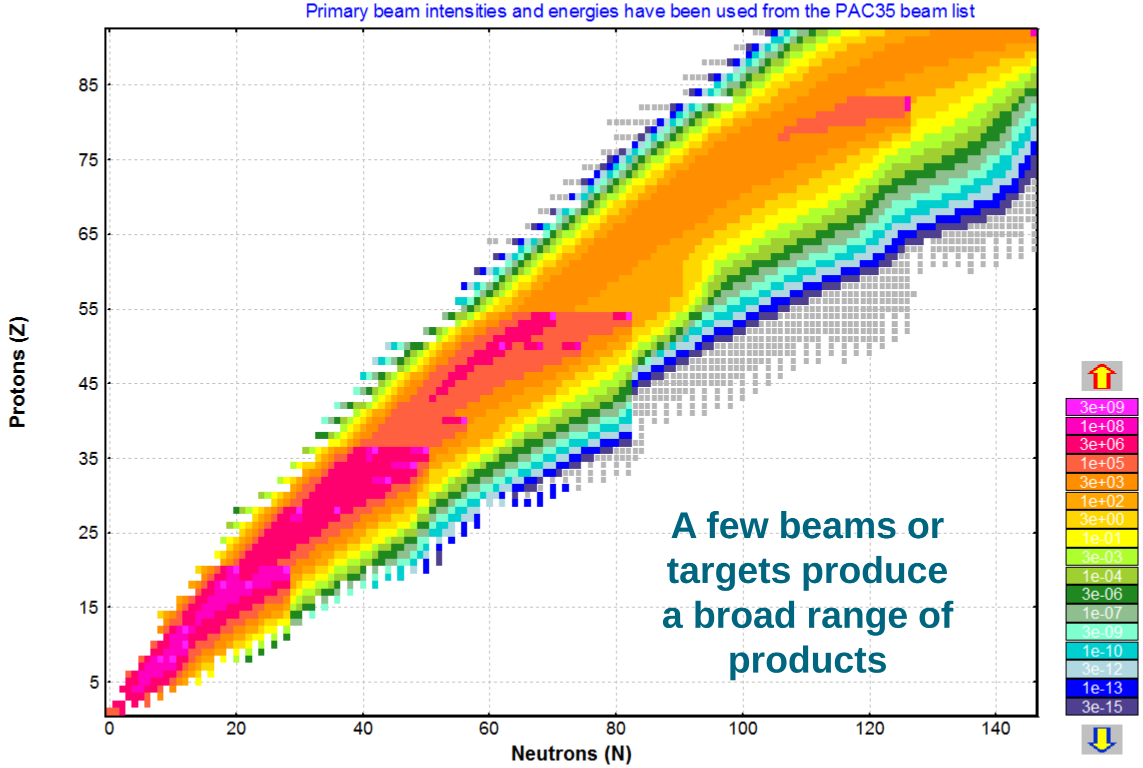


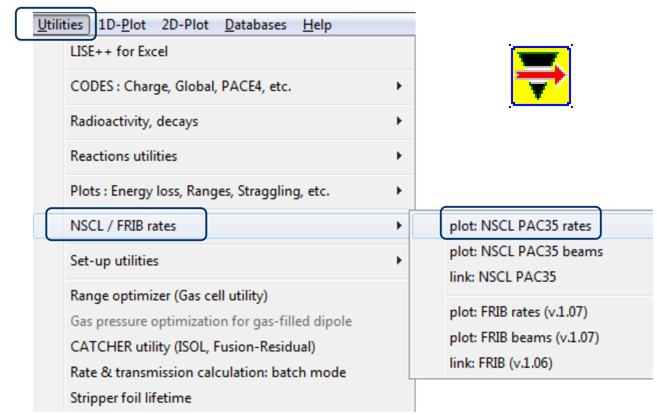
Simple nuclear reactions provide a broad range of nuclei

- **General features of the reactions are well-known but some details are not**
- **Projectile fragments are produced at nearly the speed of light**
- **Projectile fragments:**
  - ❖ **Rapid physical separation of fragment in a magnetic system**
  - ❖ **Requires: Z, A, and q identification/separation in 0º spectrometer**

NSCL PAC35 rates (v.1.03)

https://groups.nscl.msu.edu/frib/rates/nscl_pac35_rates.html The rates are estimated based on the EPAX 2.15 cross section parameterization for fragmentation and the LISE++ 3EER model for in-flight fission. Primary beam intensities and energies have been used from the PAC35 beam list



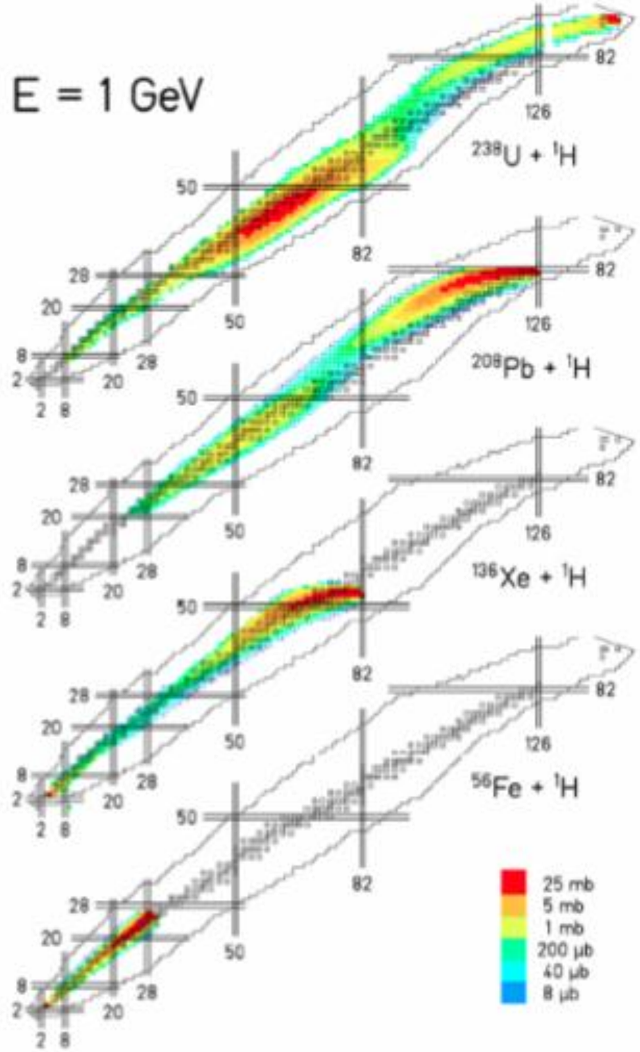


More details in the "Production area" lecture

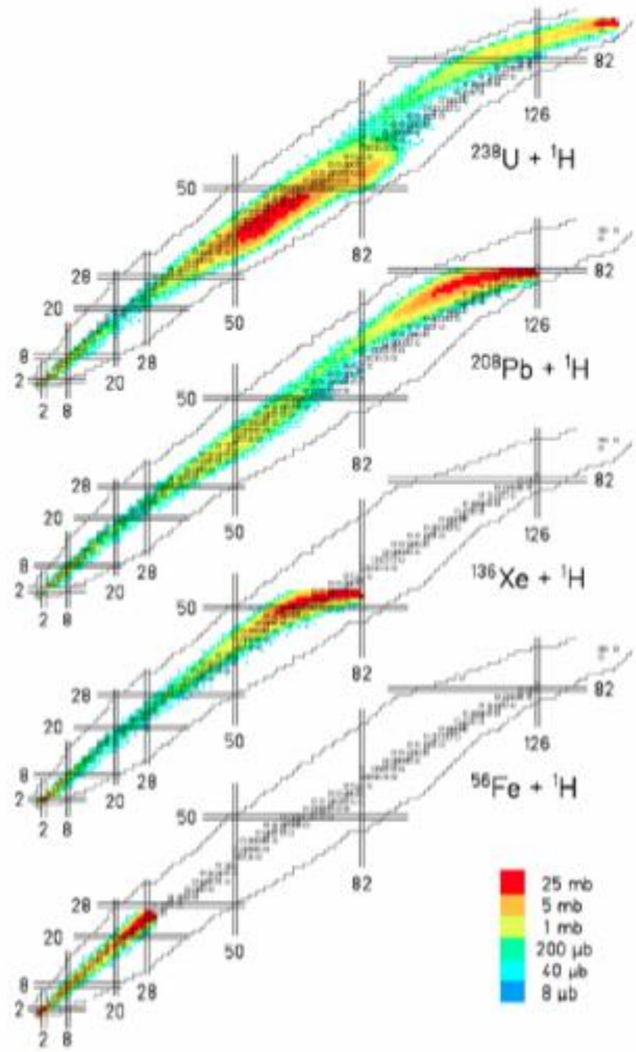
Summary of High Energy Production Mechanisms

http://www-win.gsi.de/charms/

A. Kelić, S. Lukić, M. V. Ricciardi, K.-H. Schmidt

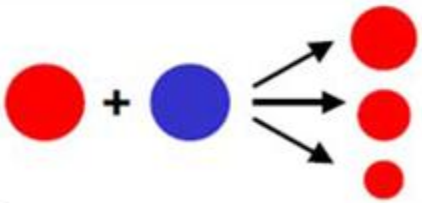
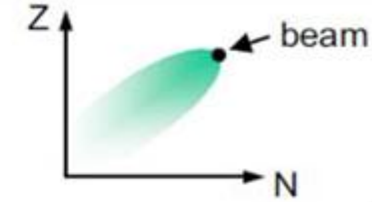
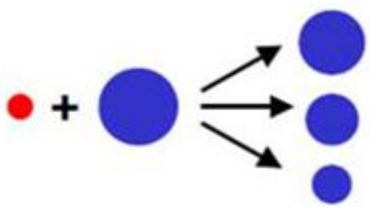
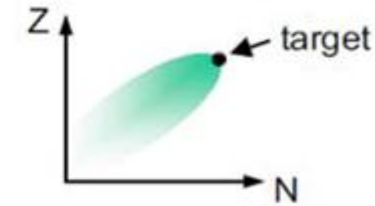
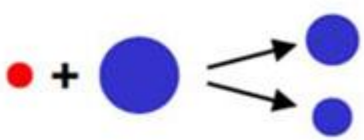
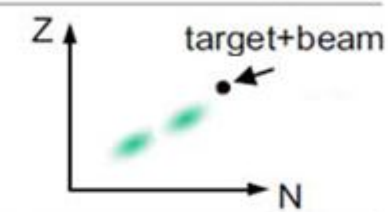
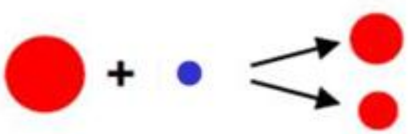
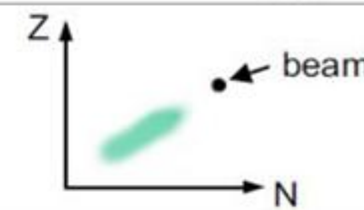
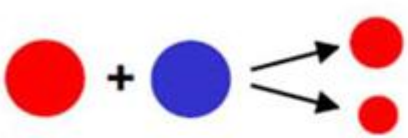
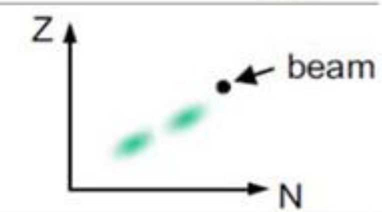
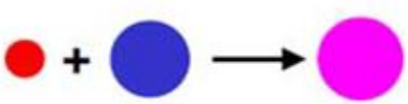
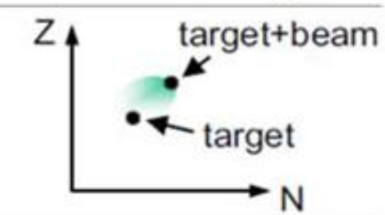


Experiment (FRS)



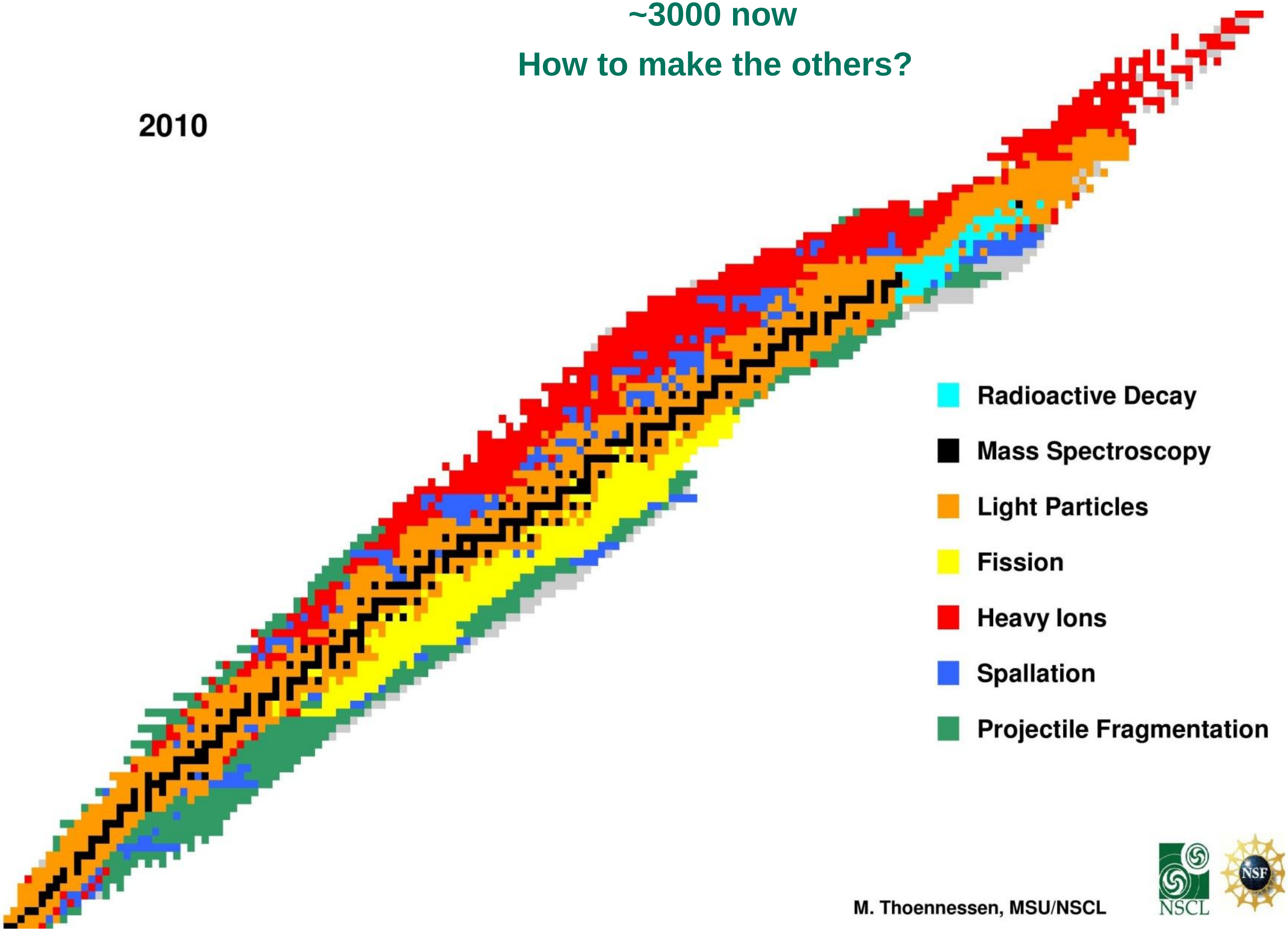
ABRABLA07

Sketch of main production mechanisms for RIB

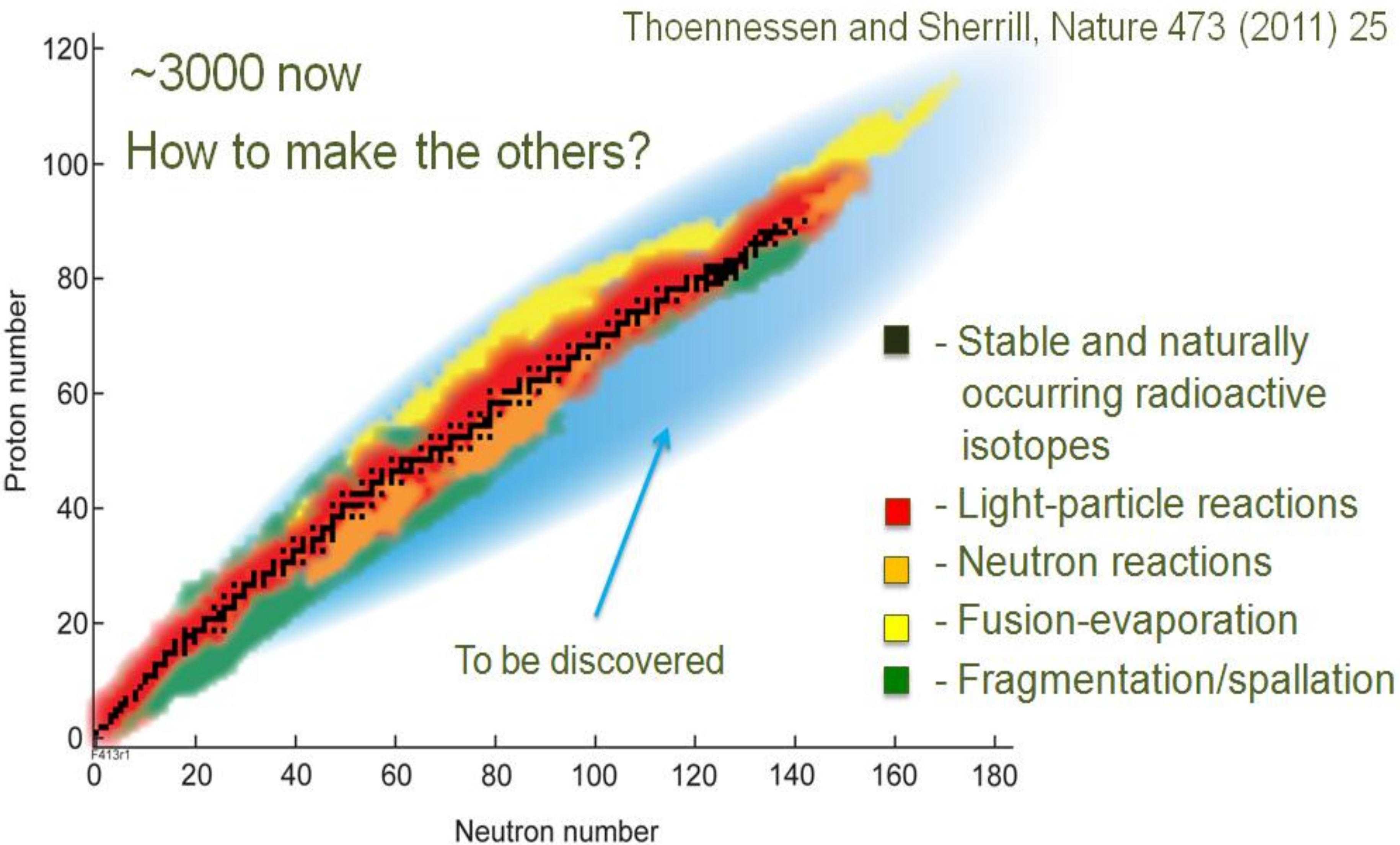
	projectile fragmentation	$v_{product} = v_{beam}$	up to 1000	
	spallation	few MeV/u	up to 1000	
	fusion-fission new : inverse	~1 MeV/u ~10-25 MeV/u	few 100	
	abrasion-fission	$v_{product} = v_{beam}$	few 100	
	Coulomb fission	> 200 MeV/u $v_{product} = v_{beam}$	few 100	
	fusion-evaporation	$E_R = \frac{m_p}{m_p + m_t} E_P$	few (≤ 20)	

~3000 now

How to make the others?



How to make others?

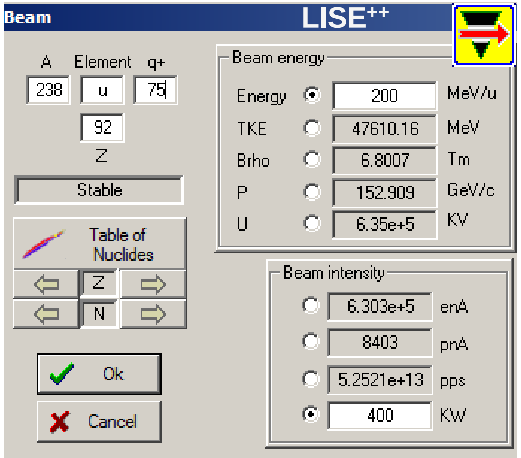


Accelerators

The particle accelerator used for production is often called the "driver"

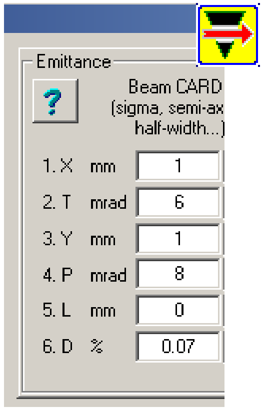
Types

- **Cyclotron** (NSCL, GANIL, TRIUMF (proton driver), HRIBF (proton driver), RIKEN RIBF)
- **Synchroton** (GSI, FAIR-GSI)
- **LINAC** (LINear ACcelerator) (FRIB, ATLAS – ANL)
- Others like FFAGs (Fixed-Field Alternating Gradient) are currently not used



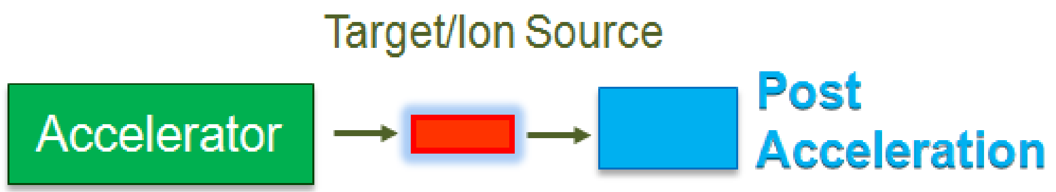
Main Parameters

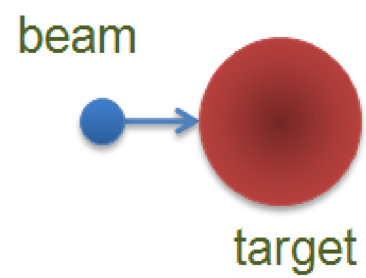
- **Top Energy** (e.g. FRIB will have 200 MeV/u uranium ions)
- **Particle range** (TRIUMF cyclotron accelerates hydrogen, hence is used for spallation)
- **Intensity** (1pμA = 6.25 x 10^{12} /s)
- **Beam Power** = Intensity x Beam Energy (so FRIB 400 KW)
- **Emittance of primary beam**



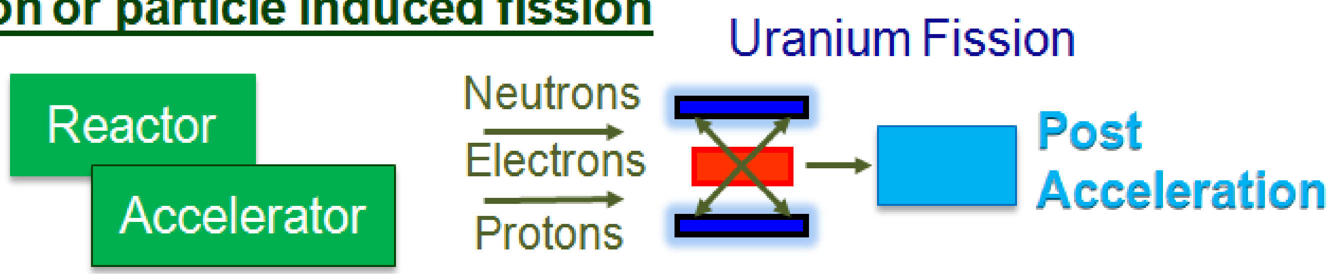
Rare Isotope Production Techniques

- **Target spallation and fragmentation by light ions (ISOL – Isotope separation on line)**

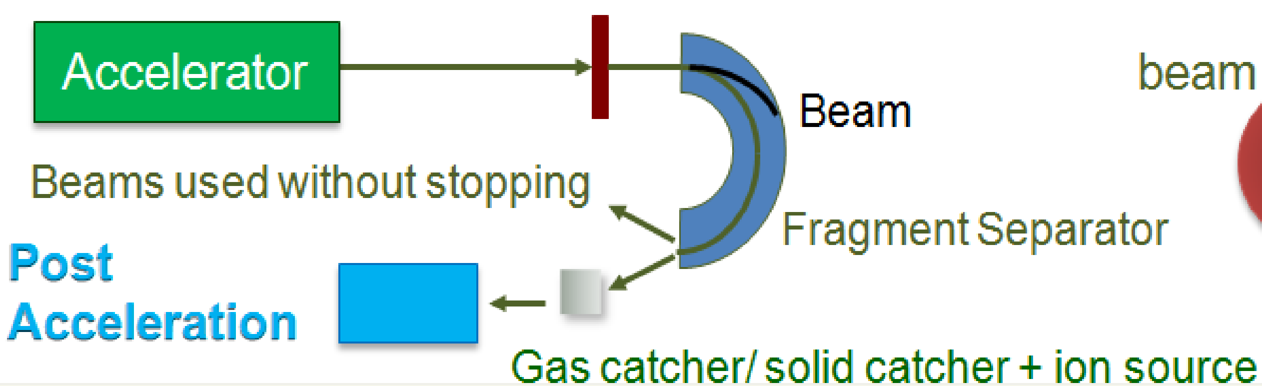


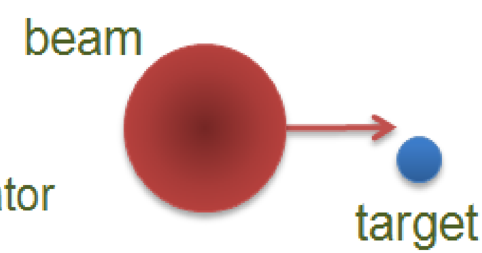


- **Photon or particle induced fission**



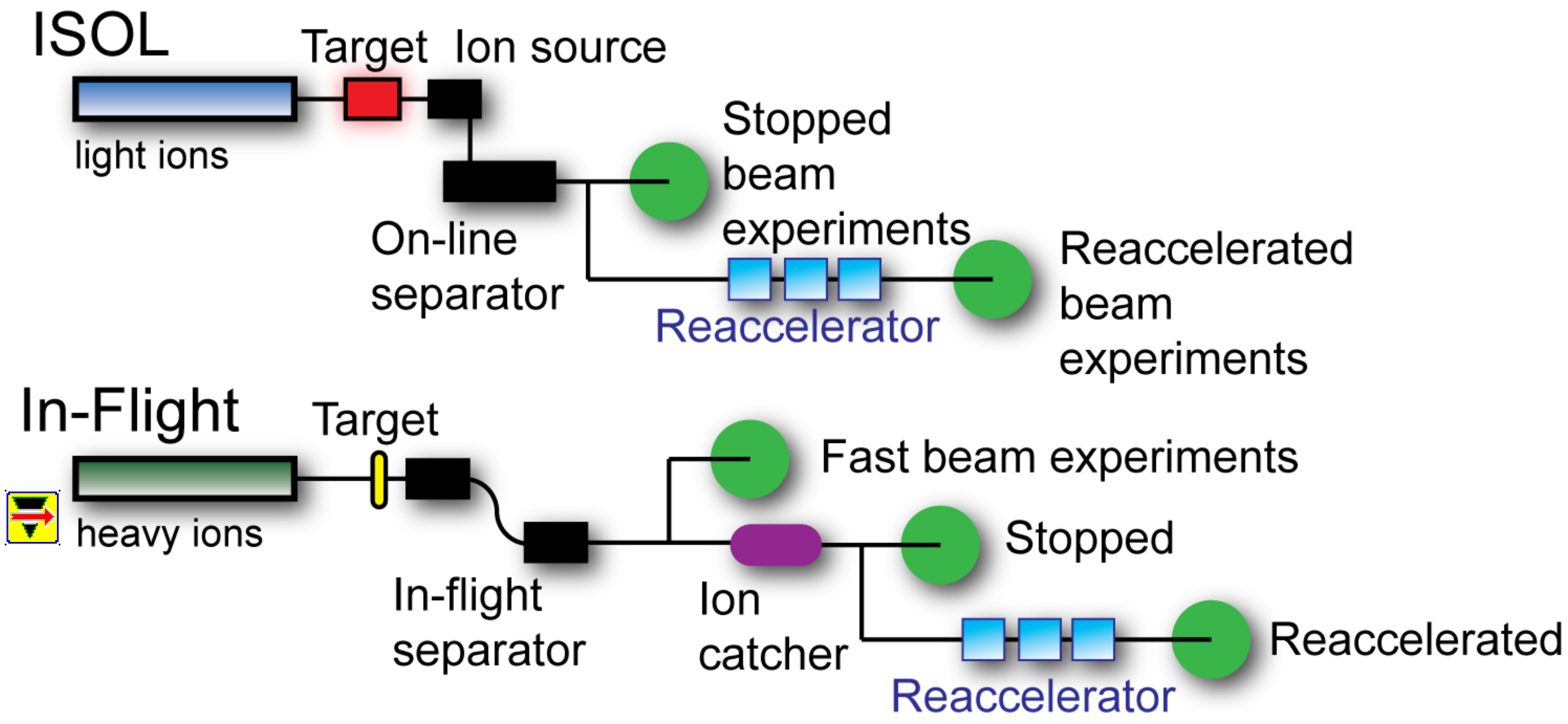
- **In-flight Separation following nucleon transfer, projectile fragmentation, fission**



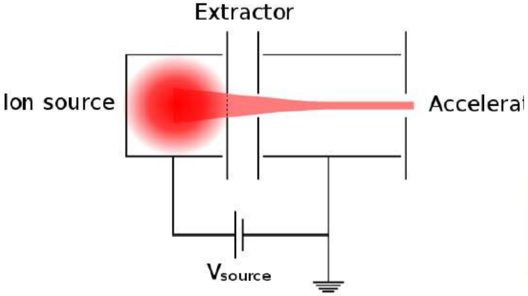


B.Sherrill

Jargon : ISOL & In-Flight

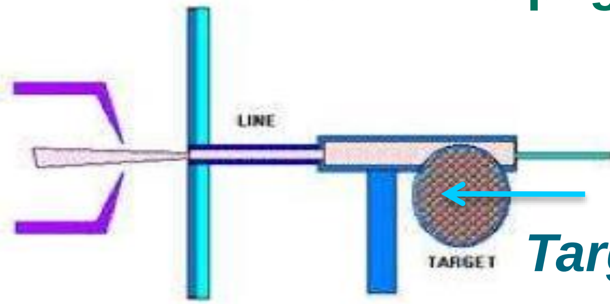


Types of ISOL Ion Sources



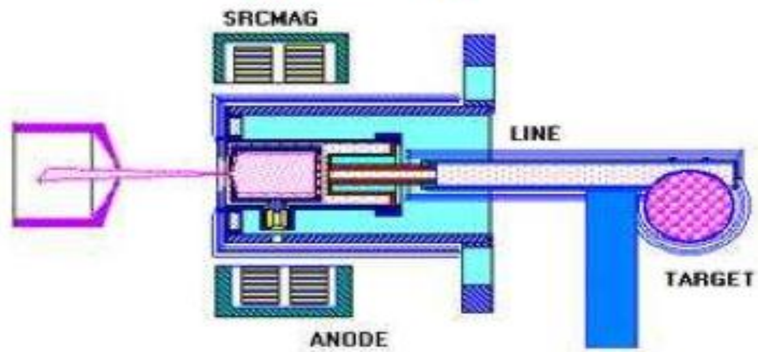
Beam into page

Surface ion source

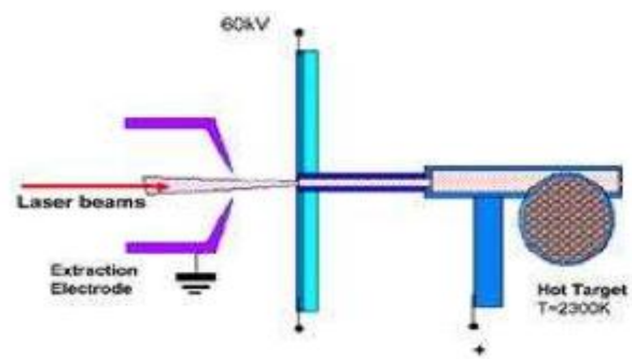


Target

Plasma ion source



Laser ion source



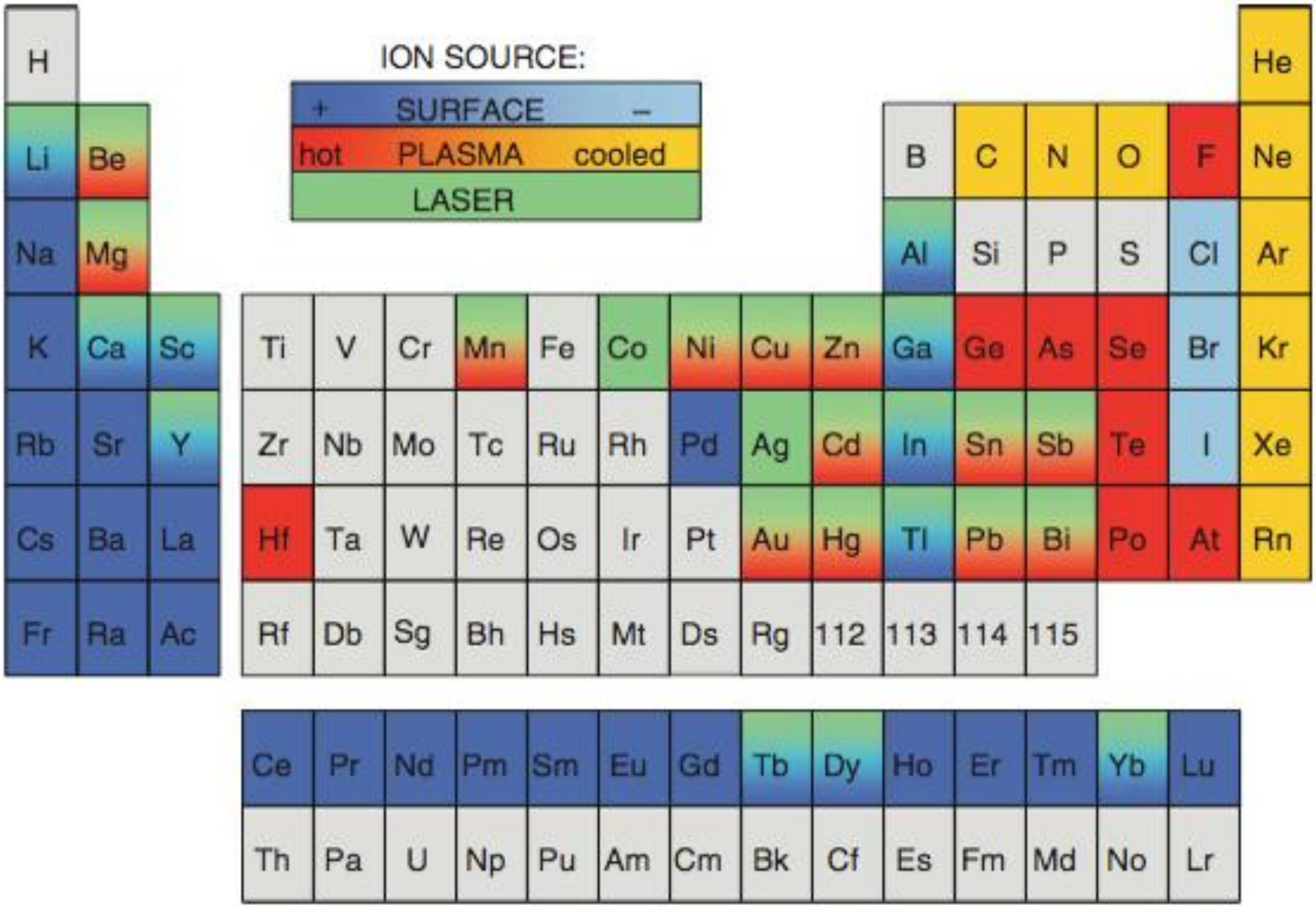
P. Butler

For details : "Production and acceleration of rare-isotope beams" by Giovanni Bisoffi

ISOL & In-flight methods, ion sources, accelerators et al.

http://iks32.fys.kuleuven.be/files/euroschool/2012_Giovanni_Bisoffi.zip

Isotope production with ISOL technique

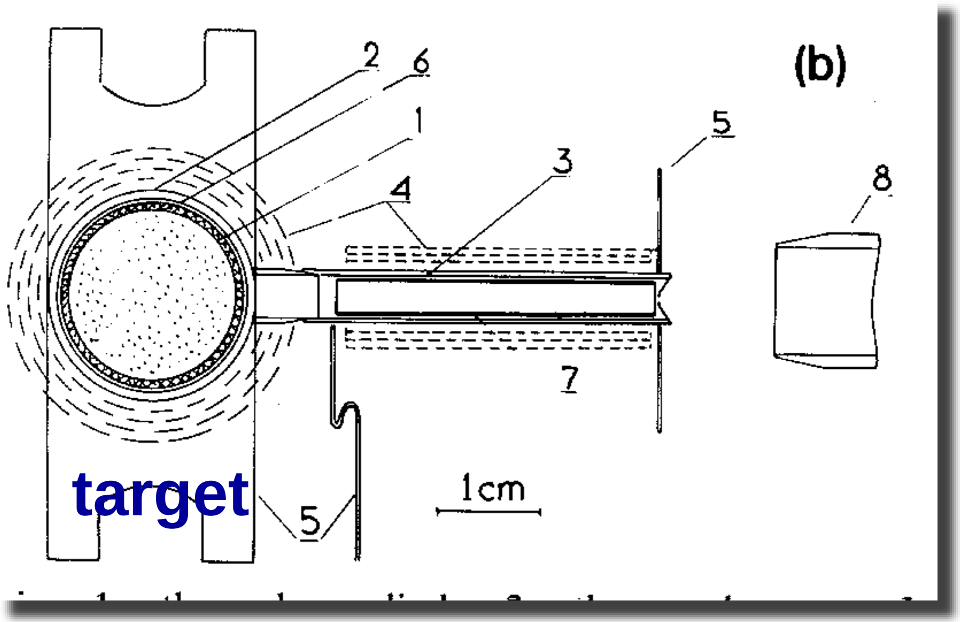


Production is only one part of the equation

$$I = \sigma \; I_b \; T_{useable} \quad \varepsilon_{diff} \, \varepsilon_{des} \, \varepsilon_{eff} \, \varepsilon_{is\_eff} \, \varepsilon_{accel\_eff}$$

σ - production cross section
I_b - beam intensity
$T_{useable}$ - usable target thickness

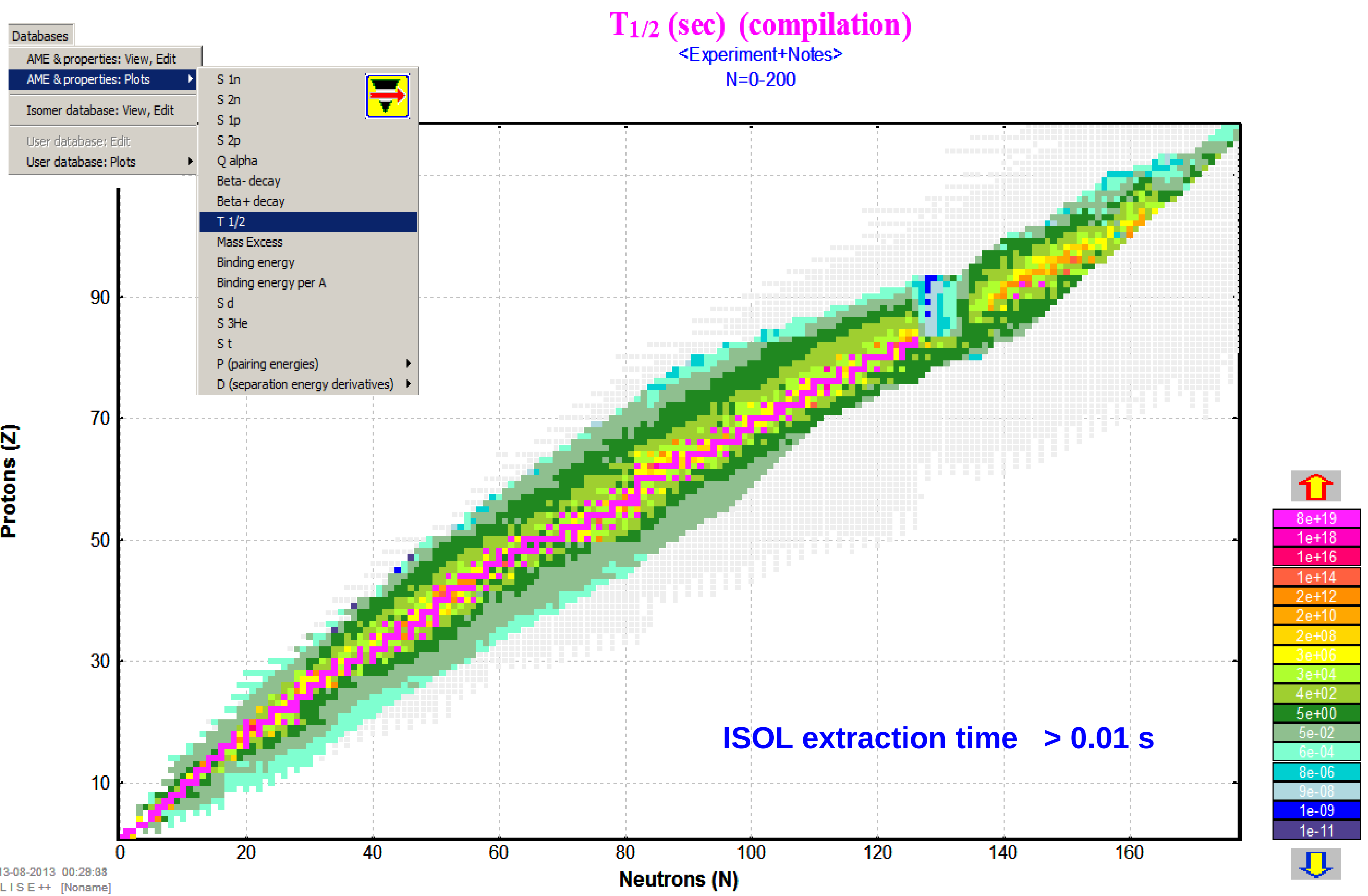
ε_{diff} – diffusion efficiency
ε_{des} – desorption efficiency
ε_{eff} – effusion efficiency
ε_{is_eff} - ionization efficiency
ε_{accel_eff} - acceleration efficiency



H. Ravn

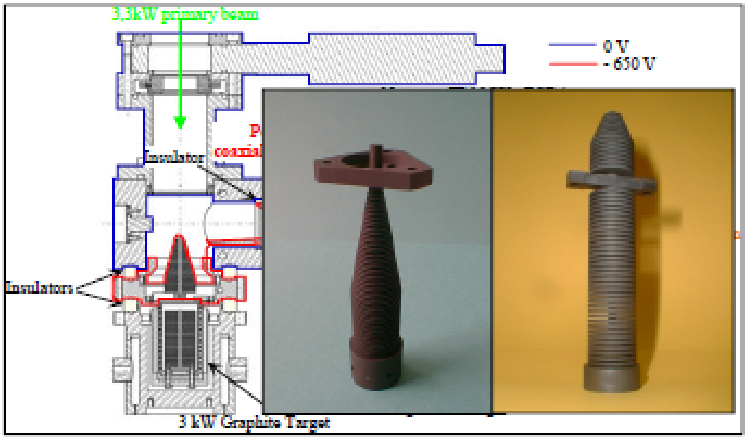
Some efficiency examples* can be found in
https://groups.nscl.msu.edu/frib/rates/FRIB_rates_readme.pdf
* from Georg Bollen

Isotope Half-lives



ISOL: beam-target choice

$I_{reac\ prod} = \sigma\ (cm^2)\ N_{target}\ (cm^{-2})\ \Phi_{in}\ (A)$



GANIL 3 kW graphite target

Primary beam:

- p (3-100 MeV, or 500-1500 MeV)
- light, HI (4-100 MeV/u)
- n (3-100 MeV)
- e^- (50 MeV)
- n_{therm} (sometimes through converter, changing p, e^- into flux of n,γ rays, inducing nuclear reaction)

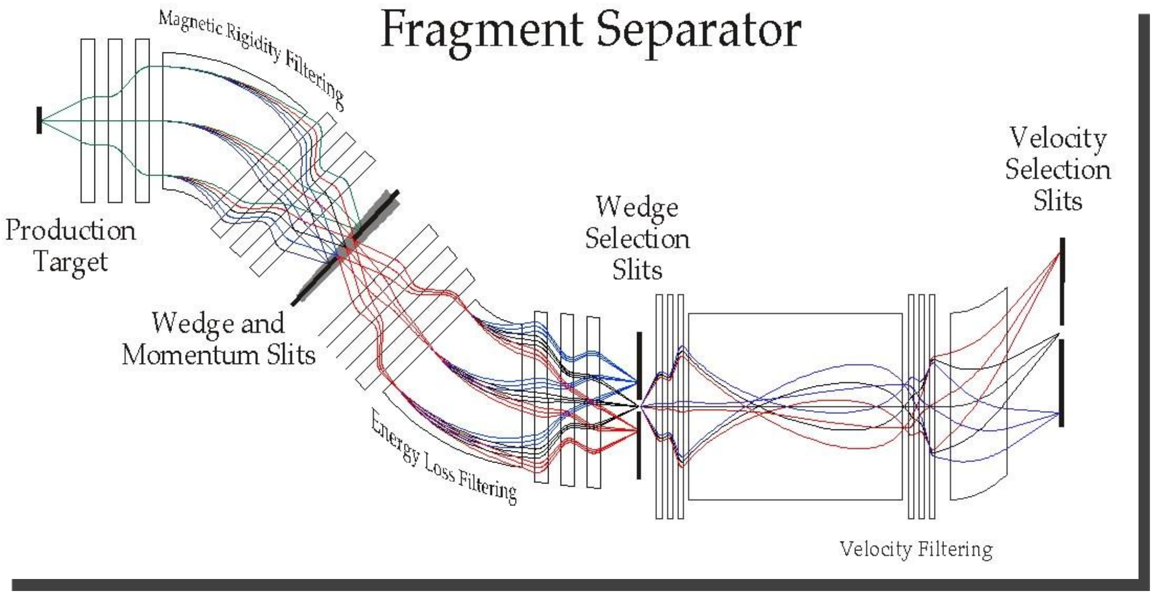
Laboratory	Projectile	Projectile energy	Projectile current	Main reaction
ISOLDE (CERN) 1 step	p	1,4 GeV	5 µA	Fission, Spallation
ISOLDE (CERN) 2 steps	p	1,4 GeV	5 µA	Fission (n-induced)
Spiral1 (GANIL, F)	Ar, C, Ne	50 MeV/A	100 nA	Fragmentation
ISAC (TRIUMF, Ca)	P	500 MeV	100 µA	Spallation
HRIBF (ORNL, USA)	p	40 MeV	5 µA	Fission, Fusion-Evaporation
EXCYT (LNS-INFN, I)	C	45 MeV/A	10 µA	Fusion-Evaporation
ALTO (Orsay, F)	e	50 MeV	10 µA	Photofission

Giovanni Bisoffi

HRIBF example will be used for comparison between In-Flight & ISOL

In-Flight : Basic principle of operation

1. Production



3. Identification

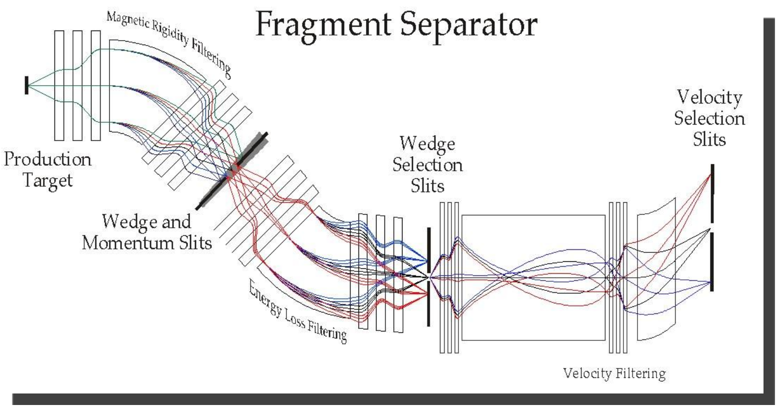
2. Separation

Production, Separation, Identification -- our next lectures

In-flight RIB yields

$$Y = I \;\; t \;\; N_t \;\; \sigma \;\; \varepsilon_t \;\; \varepsilon_s \;\; \varepsilon_i$$

1. Production Area



2. Separation

3. Identification

Y number of registered events

σ production cross section

N_t number of target atoms

$N_t = d_t M_t \;/\; N_A$

where

- d_t target thickness
- N_A Avogadro number
- M_t atomic mass number

I beam intensity

t duration of measurement

ε_t efficiency transmission at target

ε_s efficiency transmission through separator

ε_i identification efficiency

ε_t **efficiency transmission at target**

- lost of primary beam and fragments of interest due to reaction in target and stripper
- charge state factor after target (stripper)
- Gain due to secondary reactions

ε_s **efficiency transmission through separator**

- lost of fragments of interest due to reaction in materials located in the separator
- charge state factor after materials
- Angular acceptance
- Momentum selection
- Wedge selection
- Other selections

ε_i **identification efficiency**

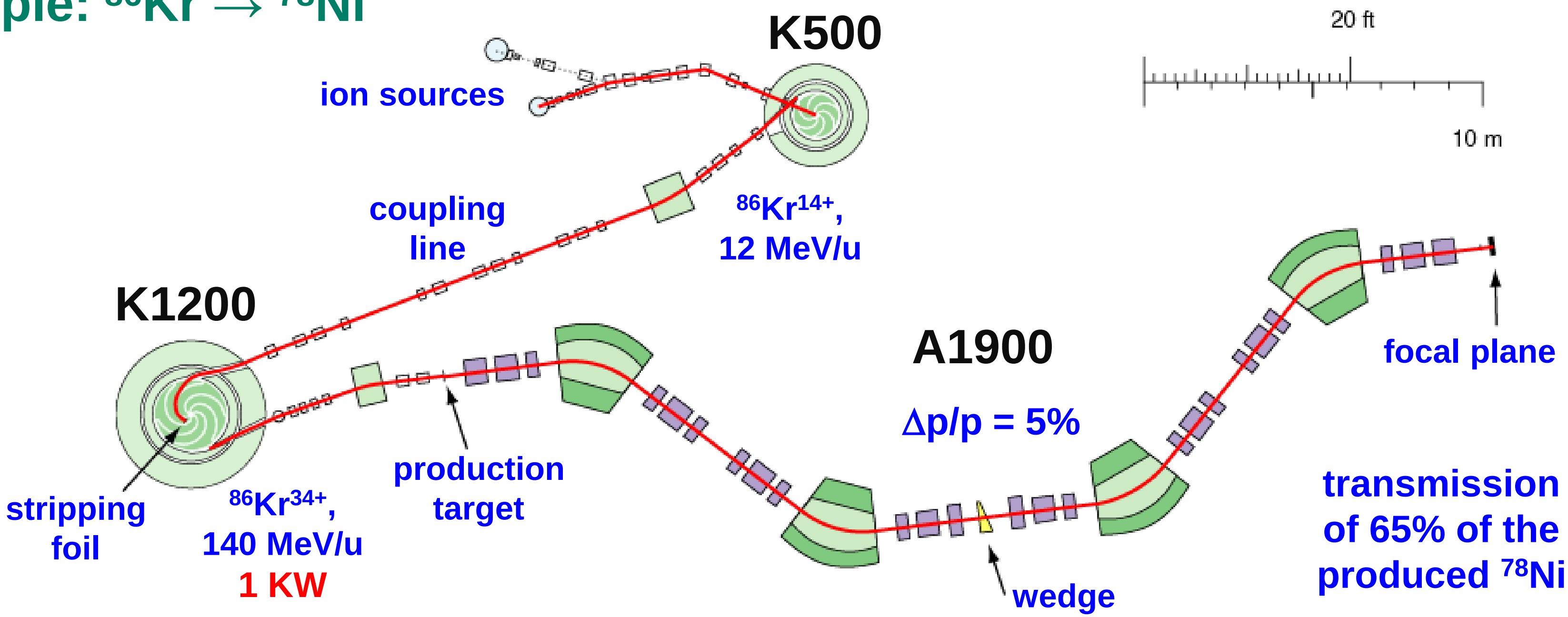
- lost of fragments of interest due to reaction in detectors
- Live time (as well pile-ups)

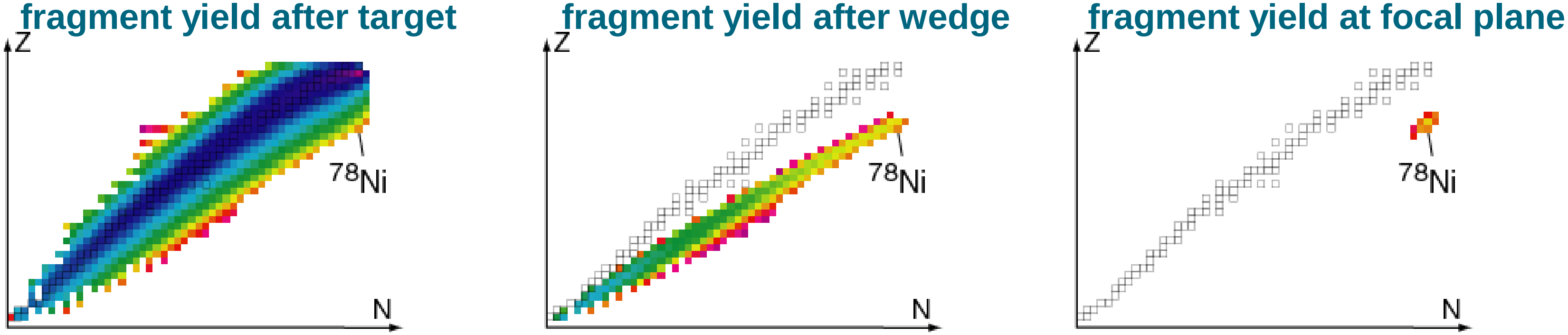
will be discussed in details in the next chapters

In-Flight Production Example: NSCL's CCF

D.J. Morrissey, B.M. Sherrill, Philos. Trans. R. Soc. Lond. Ser. A. Math. Phys. Eng. Sci. 356 (1998) 1985

Example: $^{86}Kr \rightarrow {}^{78}Ni$



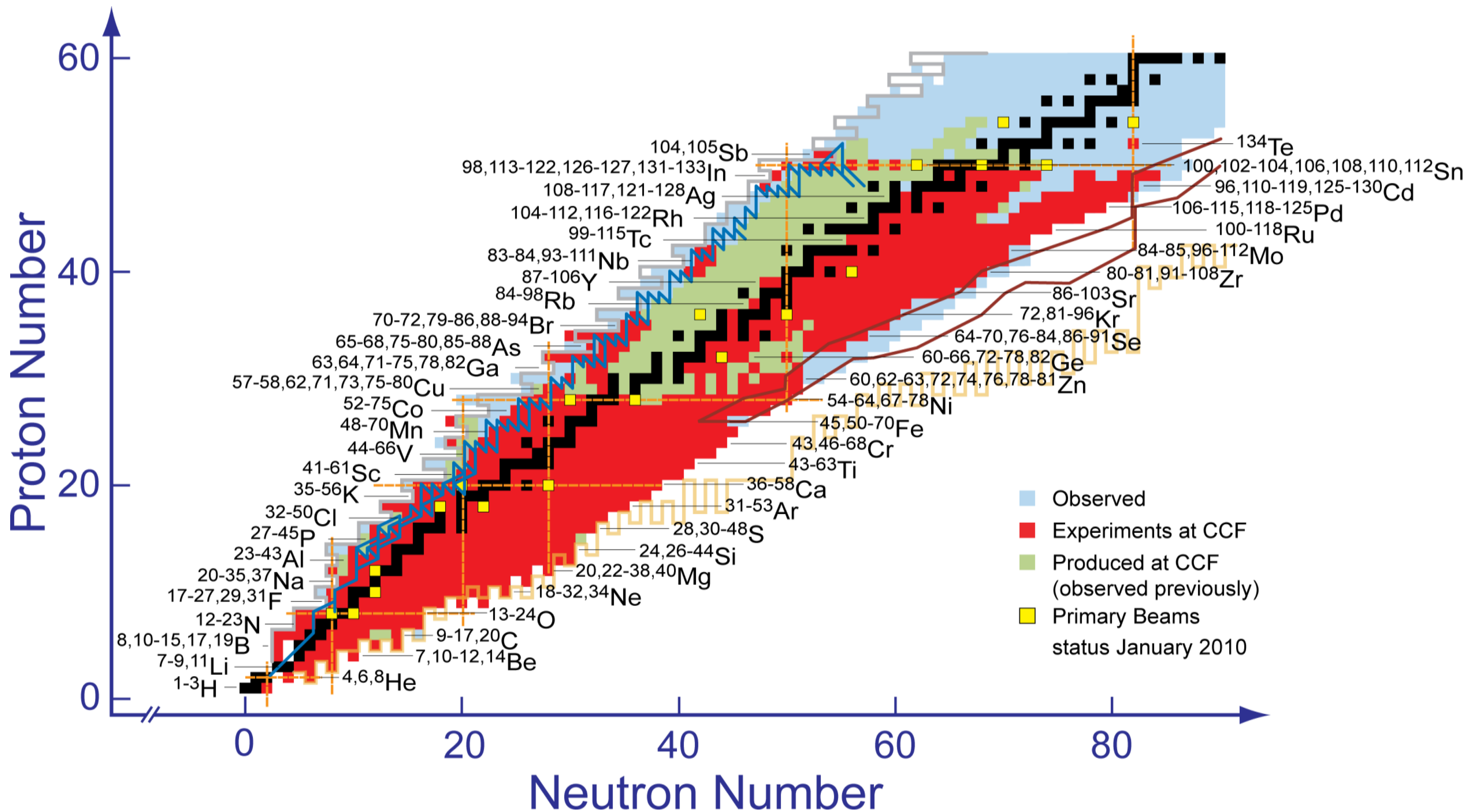


Rare isotope beams delivered to experimental vaults/areas for science with

- Fast beams (S800, Mona, …)
- Stopped beams (LEBIT, BECOLA)
- Reaccelerated beams with ReA3

Exotic Beams Produced at NSCL

More than 1000 RIBs have been made – more than 830 RIBs have been used in experiments



12 Hours for a primary beam change; 3 to 12 hours for a secondary beam

Fragment separator generation

First Experiments – LBL BEVALAC [late 70' s]

First Generation, used existing device: LISE @ GANIL

Second Generation, *construct specific device*:

A1200 @ NSCL, $K=K_{accel}$
superconducting, begins beamlines

- FRS @ GSI, $K=K_{accel}$
full acceptance, begins beamlines
- RIPS @ RIKEN, $K= 1.65\ K_{accel}$
large acceptance

Third Generation, *construct improved high-resolution device:*

- LISE3 @ GANIL, post selection in Wien filter
- A1900 @ NSCL, $K=1.6\ K_{accel}$ superconducting, begins beamlines

Fourth Generation – *preselection before high resolution separator:*

- A1900 & S800 beamline @ NSCL – recently tested
- BigRIPS @ RIKEN – just finished, recently tested
- SuperFRS @ GSI – in design

A2400 @ FRIB – in design

"K" – proton kinetic energy in MeV
(e.g. K500, K1200, A1200, A1900)

$$E = K\, q^2 / A$$

Maximum bending power is related to K

$$K = (e\, B\rho)^2 / \ (2\, m_0)$$

Fragment: ^{11}Li, $A/q = 3.67$
Beam: ^{18}O, $A/q = 2.25$
ratio $\Rightarrow$ 1.63

$K1200_{\text{accelerator}} \Rightarrow A1900_{\text{separator}}$

D.J.Morrissey

Pros for ISOL & In-Flight

In-flight:

GSI
RIKEN
NSCL
FRIB
GANIL
ANL
RIBBAS
…

- Provides beams with energy near that of the primary beam
  - ✓ Individual ions can be identified
  - ✓ Luminosity (intensity x target thickness) gain of 10,000 (one week experiment* = 3 x 10^{-18} barn)
- Efficient (can be close to 100%)
- Fast (100 ns)
- Chemically independent separation
- Production target is relatively simple
- Broad range of RIBs

ISOL:

HRIBF
ISAC
SPIRAL
ISOLDE
SPES
EURIOSOL
….

- Better separation of the selected nuclei
- Good beam quality (emittance)
- Small beam energy spread
- Post-acceleration allows to vary RIB energy
- Can use chemistry (or atomic physics) to limit the elements released
- 2-step targets provide a path to MW targets

* recent experiment : O.T. et. al., PRC 87, 054612 (2013)

Cons for ISOL & In-Flight

In-flight:

GSI
RIKEN
NSCL
FRIB
GANIL
ANL
RIBBAS
…

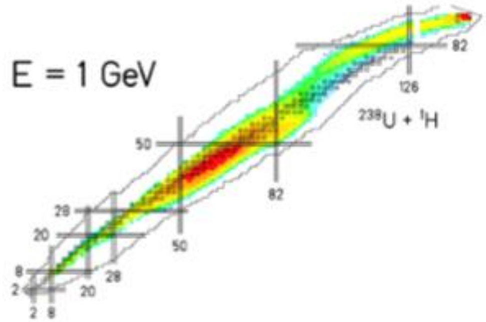
- Very low cross section for n-rich of some elements
- Large energy and transverse emittances
- Fixed high energy
- Contamination by secondary products
  - ✓ large size and cost of fragment separators

ISOL:

HRIBF
ISAC
SPIRAL
ISOLDE
SPES
EURIOSOL
….

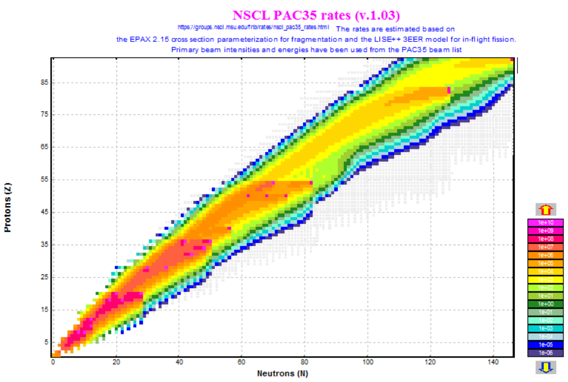
- Finite time to get the RIB out of source ($t_{1/2}$ > 10 ms)
- Some elements are tough to produce
- Large cost of high-temperature production target
- Chemistry is involved

HRIBF : p(40MeV, 5uA) + ^{238}U



Assumptions for ISOL method:
Total efficiency: 10%
Extraction time: 50 ms

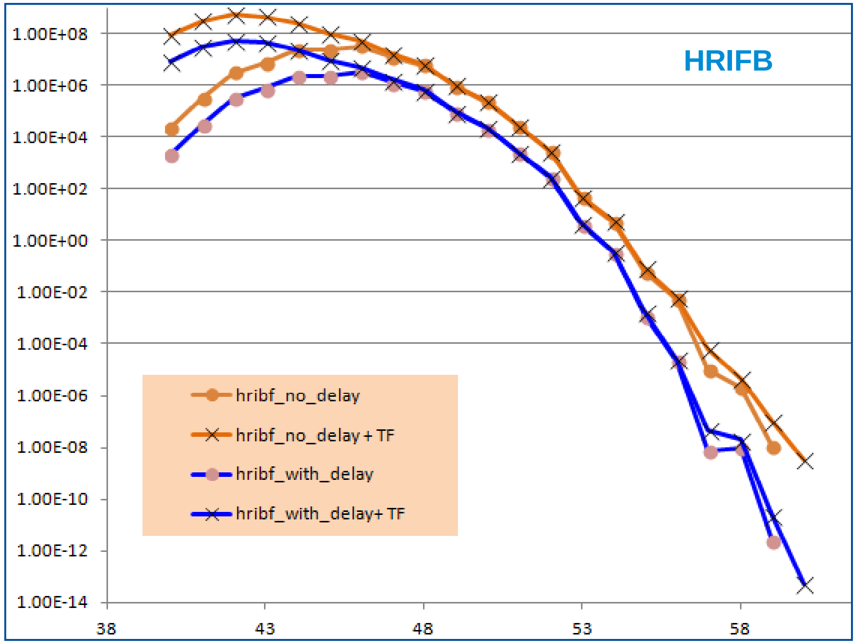
NSCL : from the beam list

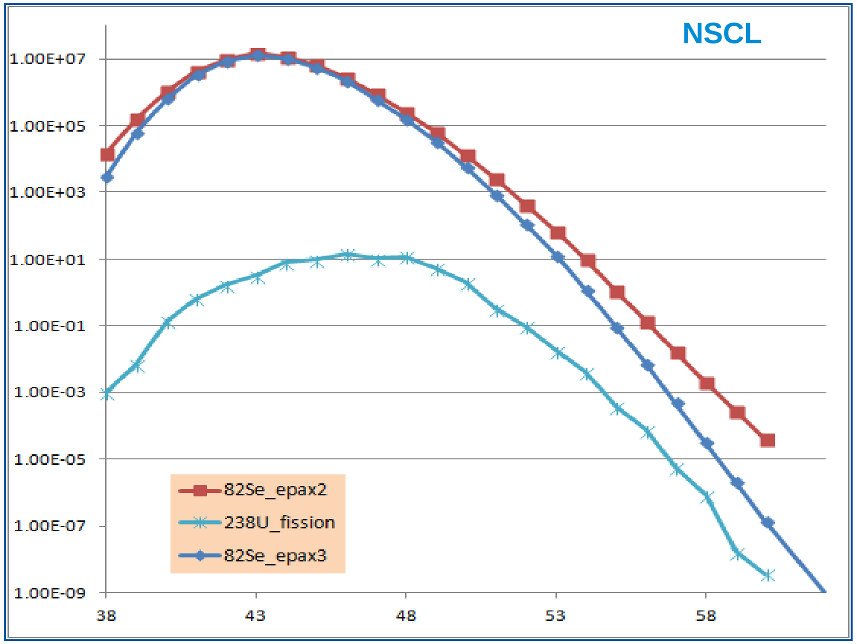


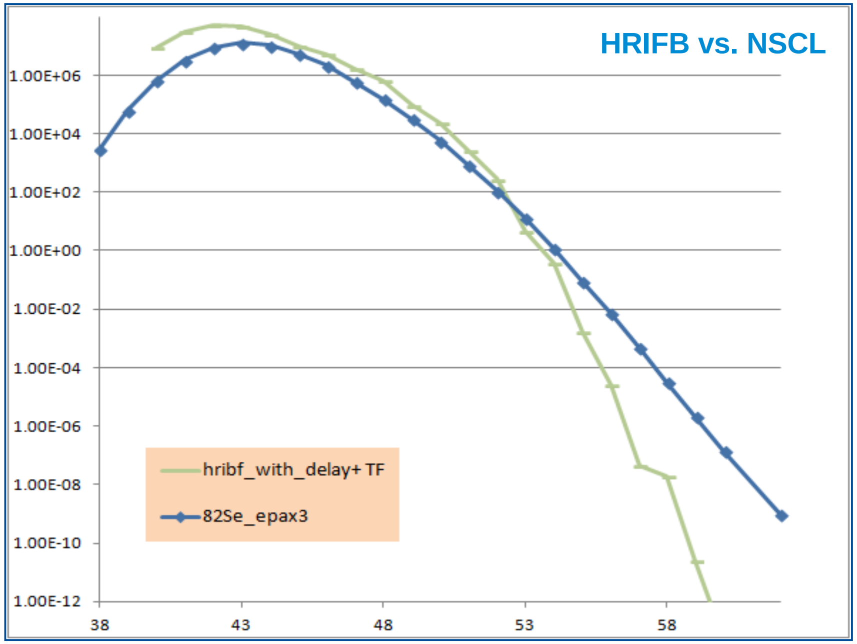
for Ca isotopes	**^{82}Se(140MeV/u, 35 pna)** **^{238}U(80MeV/u, 0.2 pna)**
for Kr isotopes	**^{136}Xe(120MeV/u, 2 pna)** **^{238}U(80MeV/u, 0.2 pna)**

Details of these calculations will be discussed in one of the next lectures

ISOL & In-Flight : Ca isotopes







“Delay” block

Total efficiency: 10%

Extraction time: 50 ms

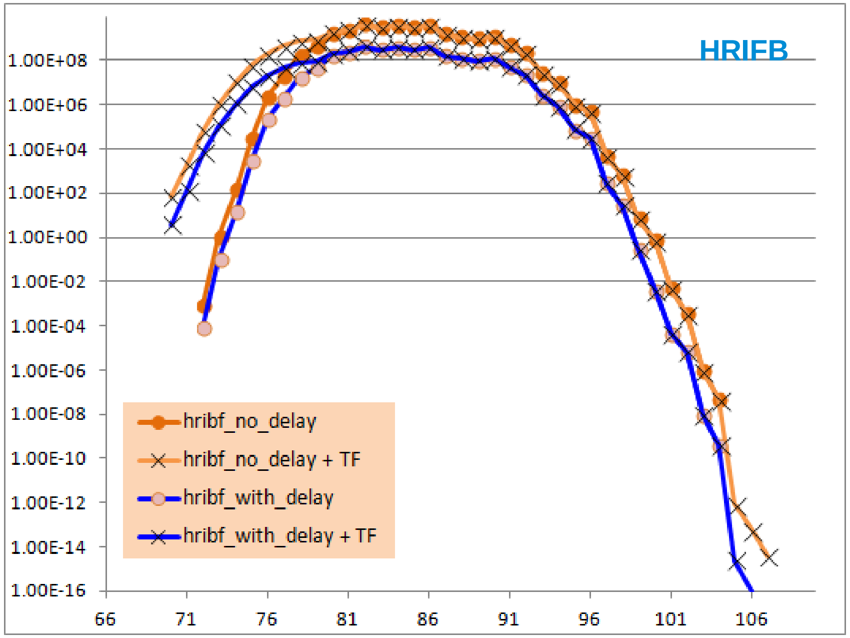
X-axis : Mass number

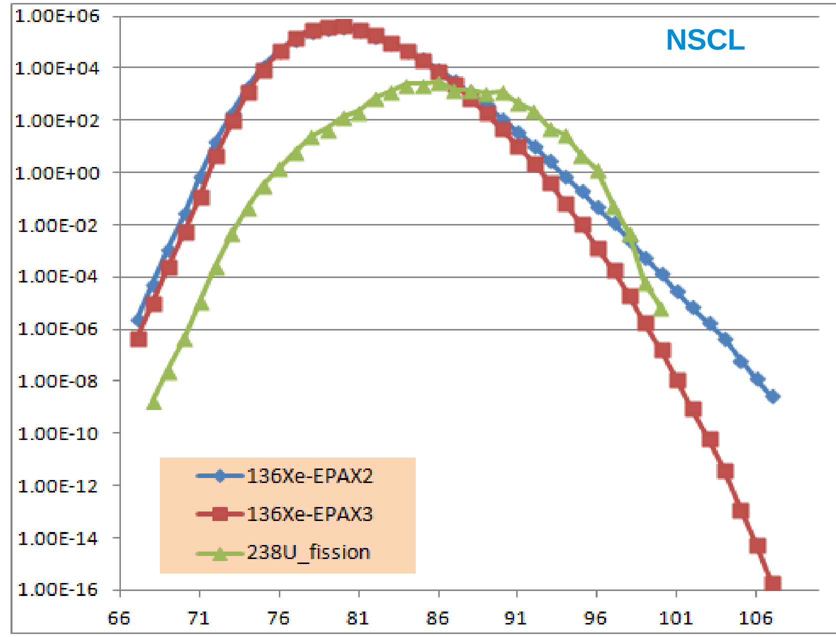
Y-axis : rate (pps)

TF – target fragmentation calculated with EPAX3

Last neutron-rich Calcium isotopes ^{57,58}Ca have been observed @ NSCL in projectile fragmentation of ^{76}Ge and ^{82}Se

ISOL & In-Flight : Kr isotopes





“Delay” block

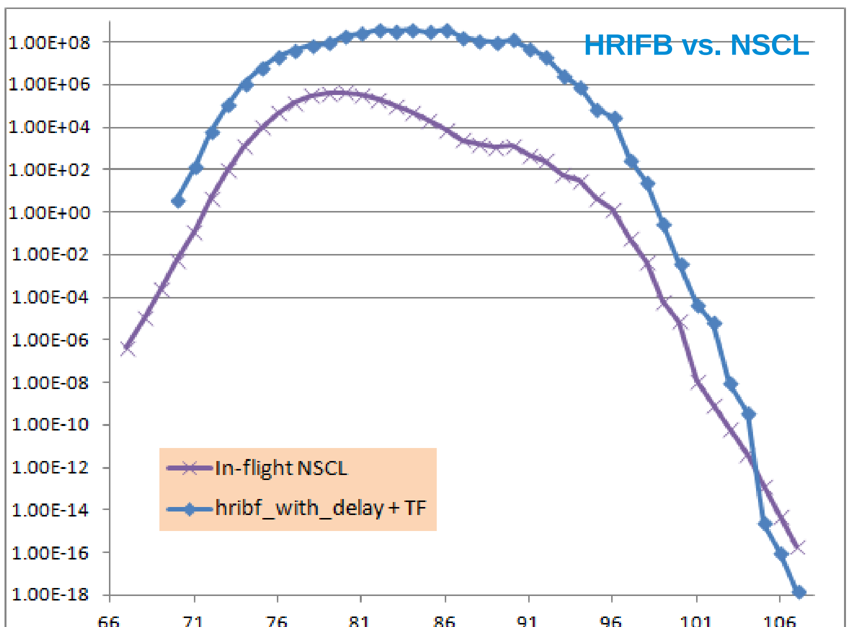
Total efficiency: 10%

Extraction time: 50 ms

X-axis : Mass number

Y-axis : rate (pps)

TF – target fragmentation calculated with EPAX3

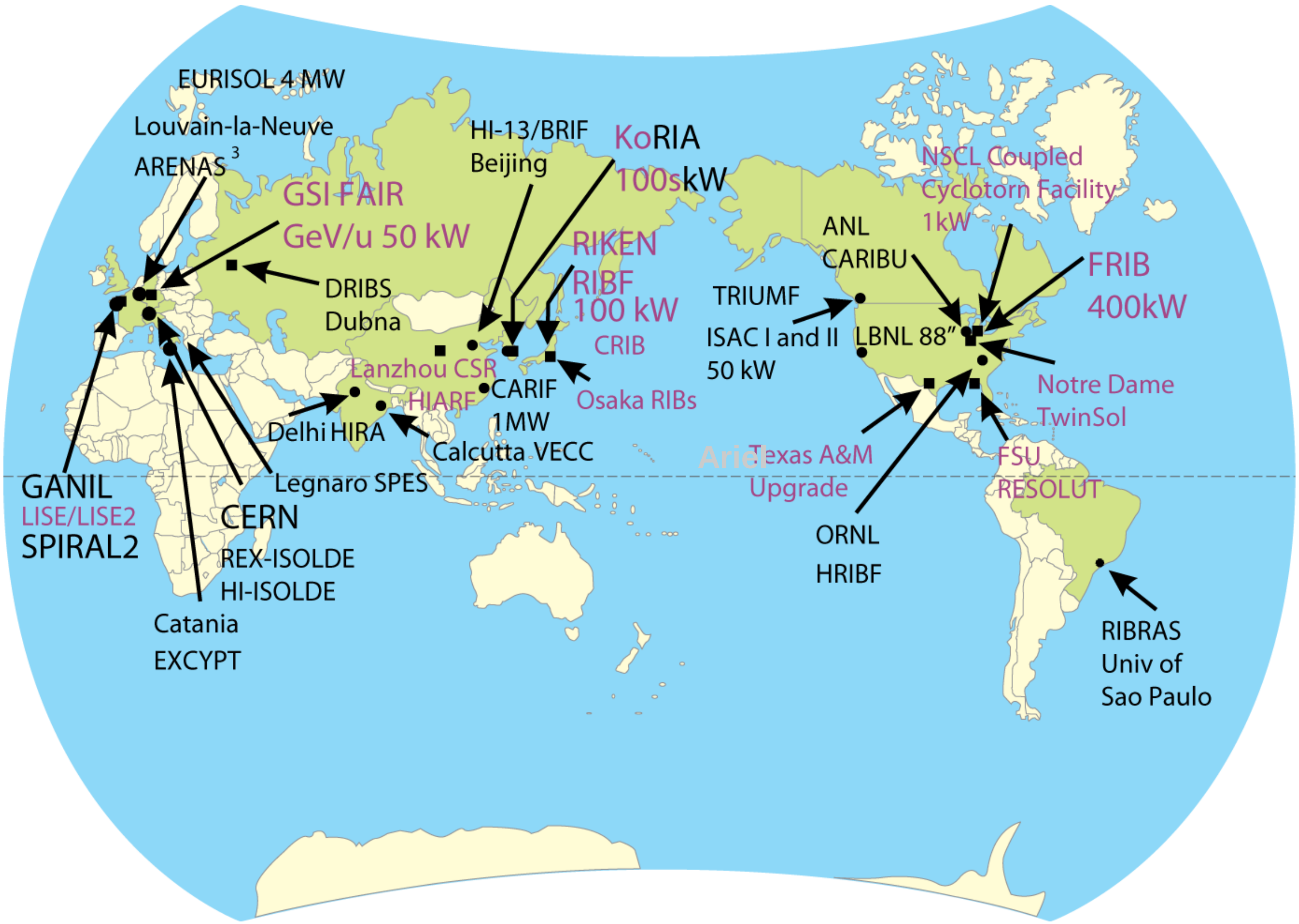


Last neutron-rich Krypton isotopes $^{98-101}$Kr have been observed @ GSI & RIKEN in in-flight fission of ^{238}U

Future for Two-step process?

1. **ISOL fission**
2. **In-flight PF**

World view of rare isotope facilities



Black – production in target

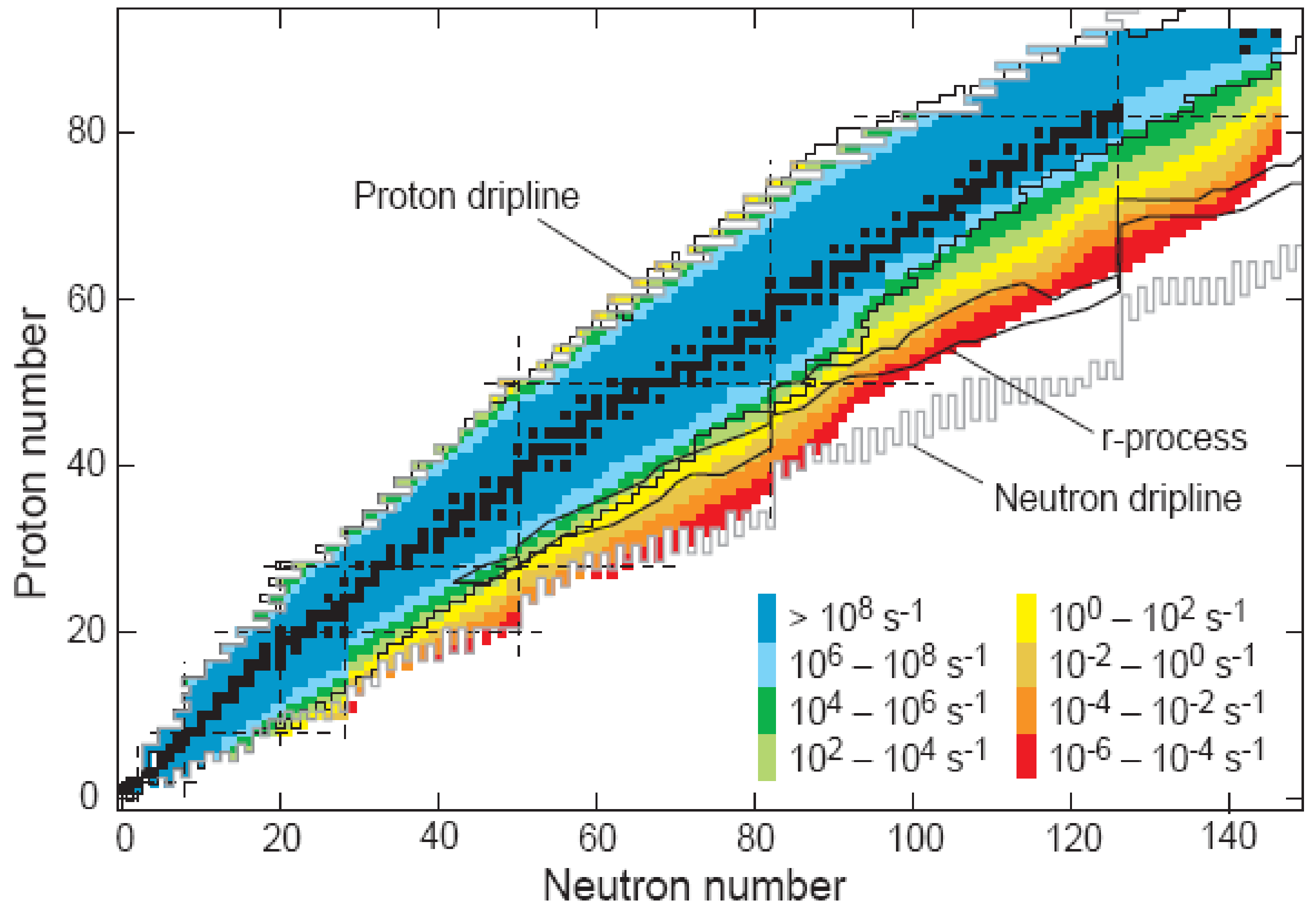
Magenta – in-flight production

In-Flight facilities

Facility	*Location*	*Driver*	*Primary Energy*	*Typical intensity*	*Fragment separator*
GANIL	France	2 separated sector cyclotrons	Up to 100A MeV	^{36}S 10^{13} pps ^{48}Ca 2 10^{12} pps	SISSI + ALPHA
GSI	Germany	Linac + Synchrotron	Up to 2A GeV	10^{10} ppspill	FRS
NSCL/MSU	USA	2 coupled superconducting cyclotrons	Up to 200A MeV	^{40}Ar 5 10^{11} pps (2 kW)	A1900
RARF RIKEN	Japan	Ring cyclotron	Up to 100A MeV	^{40}Ar 5 10^{11} pps	RIPS
RIBF RIKEN	Japan	3 Ring Cyclotrons	350A MeV	5 10^{12} pps ^{238}U (10-100 kW)	BigRIPS
FAIR	Germany	SIS 100 Synchrotron	Up to 2A GeV	10^{12} ppspill ^{238}U	Super FRS
F RIB	USA	LINAC	Up to 200A MeV	400 kW	A2400

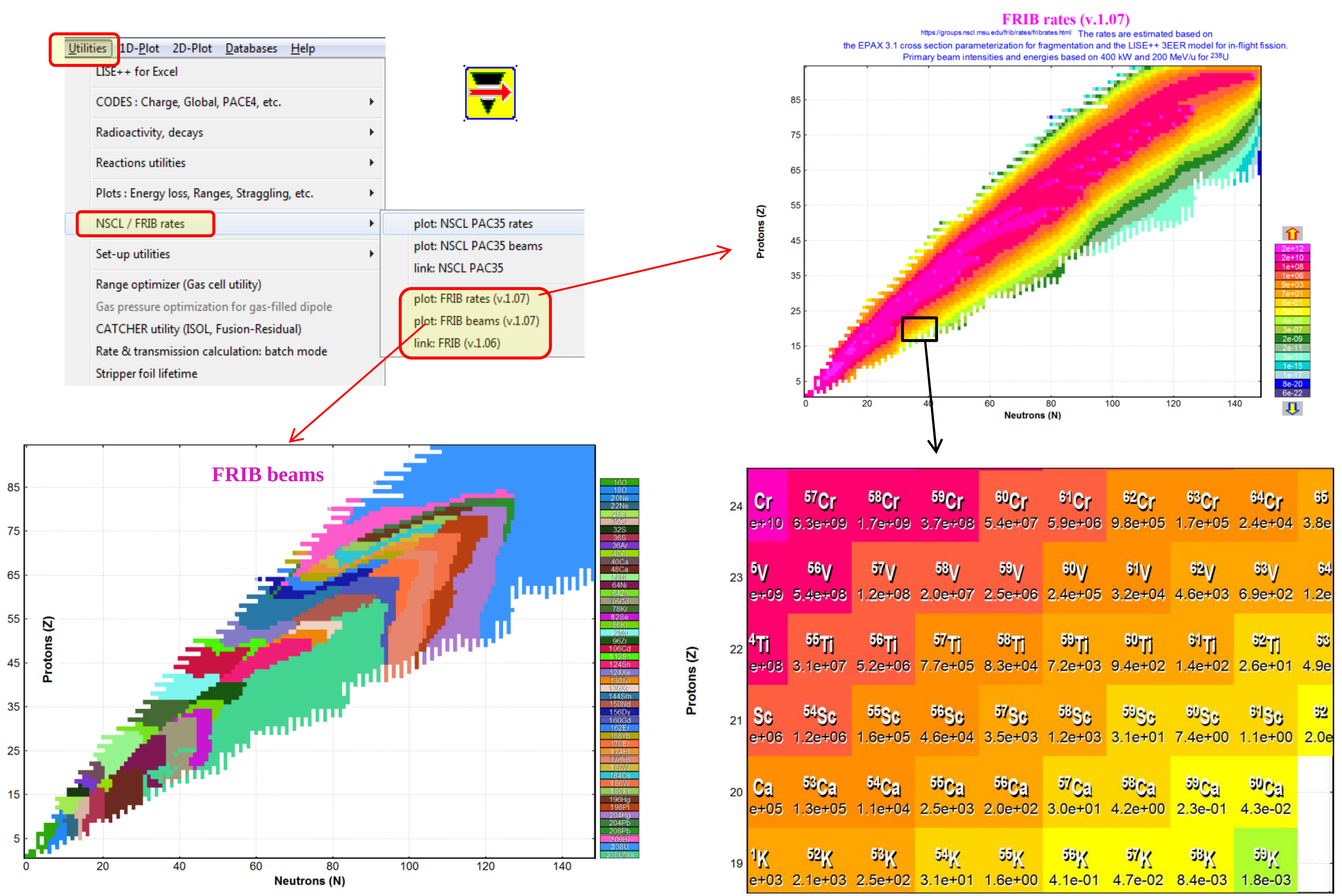
What New Nuclides Will Next Generation Facilities Produce?

- ✓ They will produce more than 1000 NEW isotopes at useful rates (4500 available for study)
- ✓ Theory is key to making the right measurements
- ✓ Exciting prospects for study of nuclei along the drip line to mass 120 (compared to 24)
- ✓ Production of most of the key nuclei for astrophysical modeling
- ✓ Harvesting of unusual isotopes for a wide range of applications



Rates are available at
http://groups.nscl.msu.edu/frib/rates/

Next Generation Facilities : Beams and Rates



O.Tarasov@Euroschool2013.JINR.RU

Major US Project – Facility for Rare Isotope Beams, FRIB

Funded by DOE Office of Science & MSU
– 2022 completion,
– 2020 early completion

Key Features:

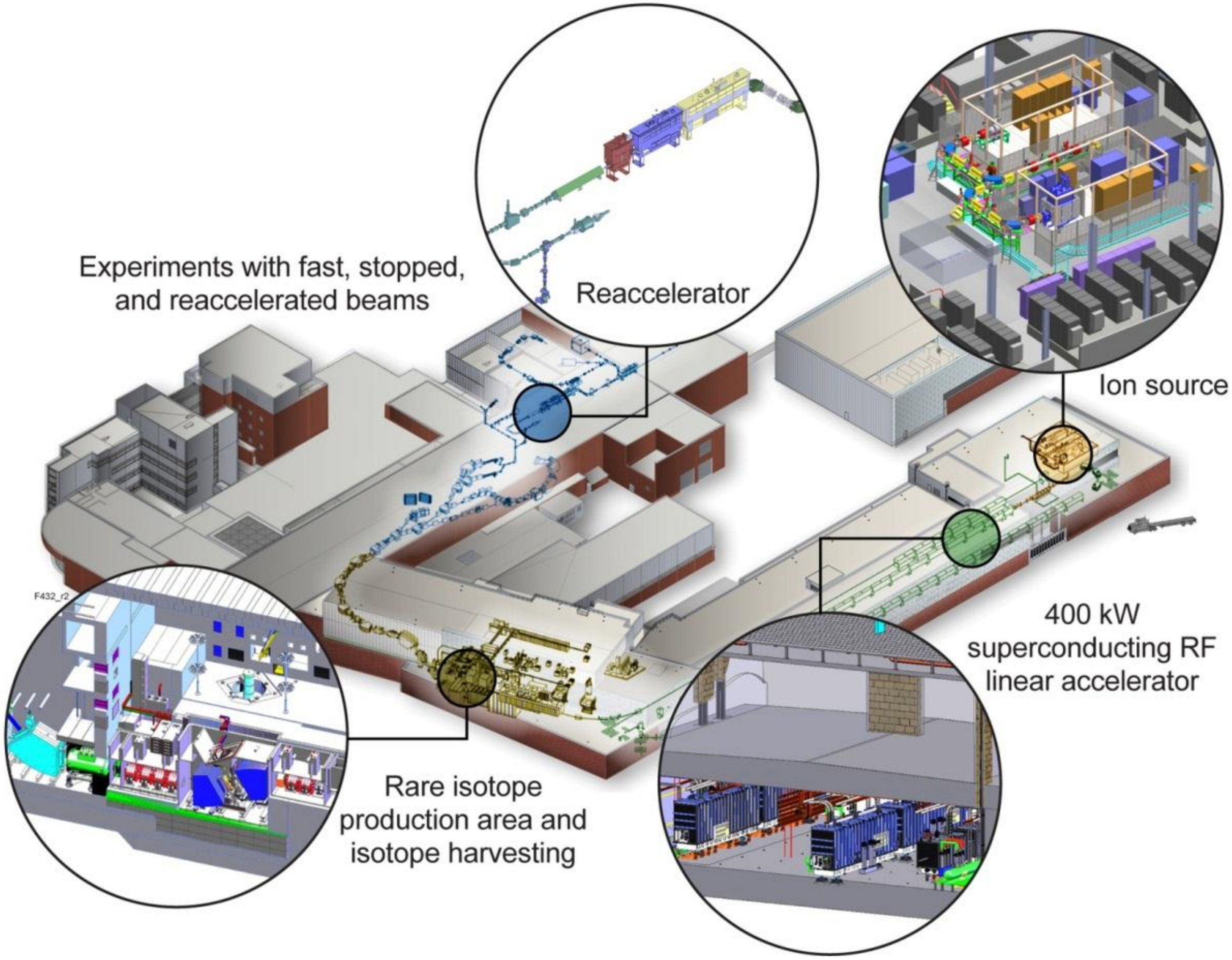
400kW beam power (5 x10[13] ^{238}U/s)

- **Efficient acceleration (multiple charge states)**

Separation of isotopes in-flight:

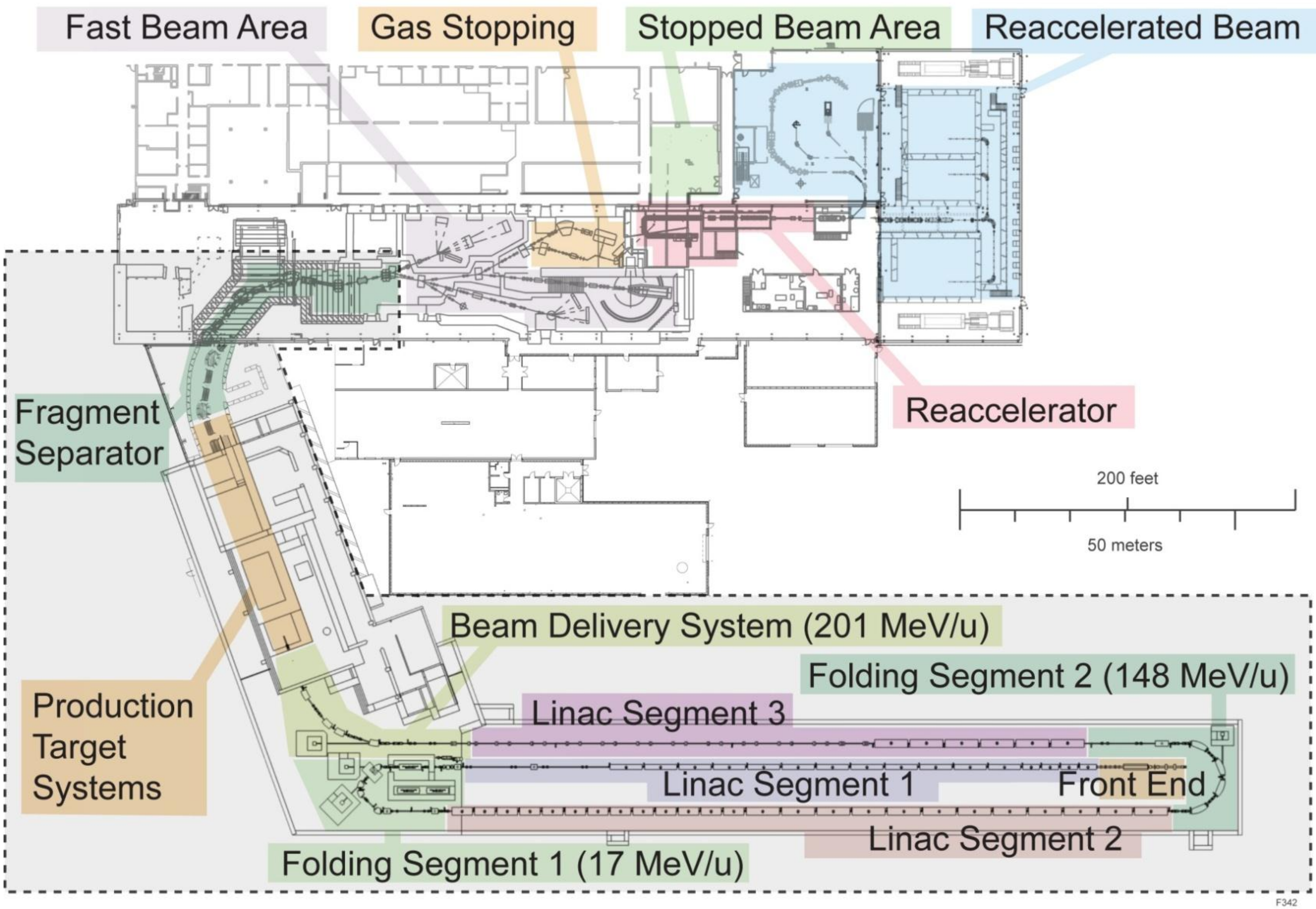
– Fast development time for any isotope

–Suited for all elements and short half-lives

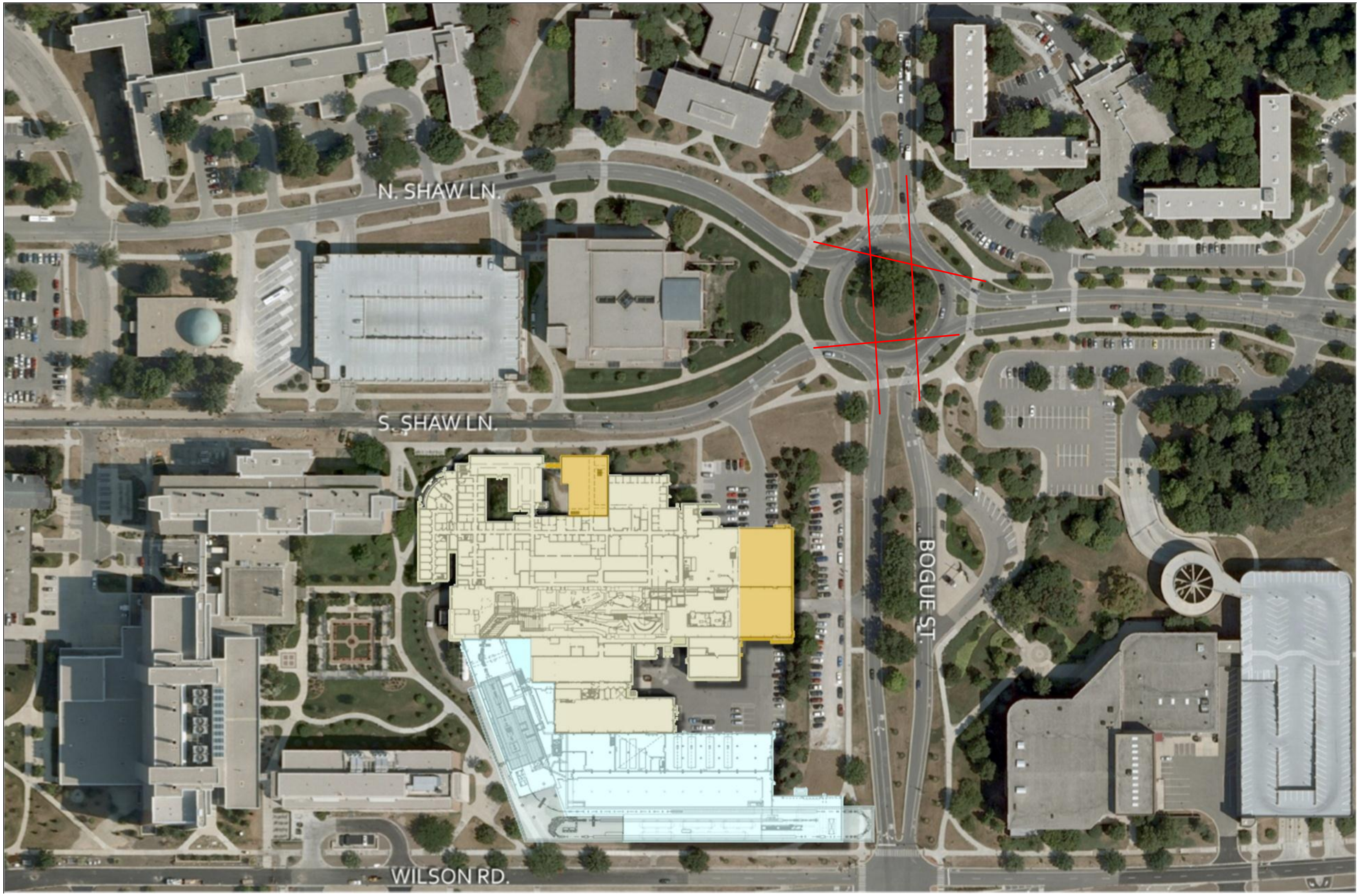


FRIB Facility Layout

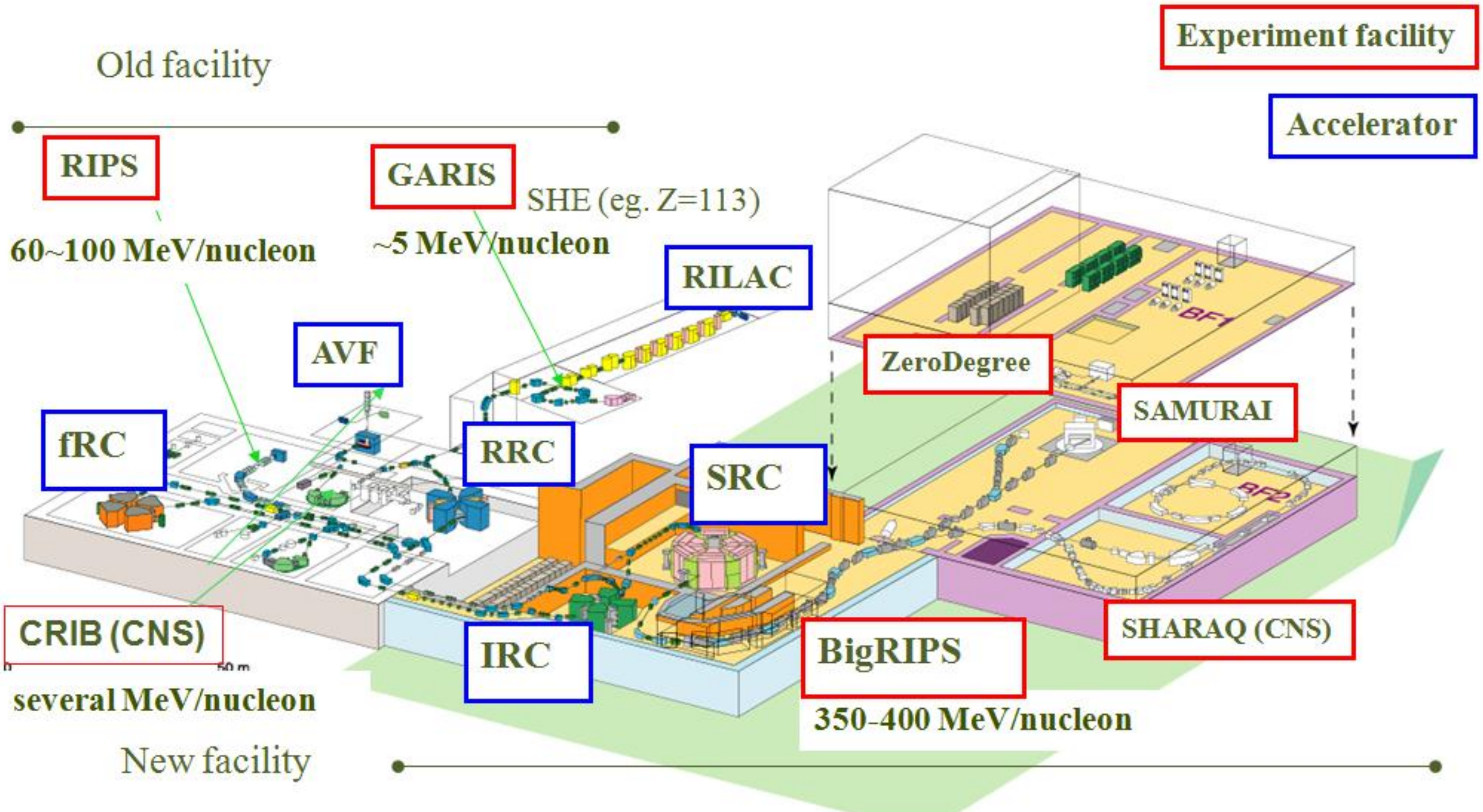
- **Reaccelerated beams, uranium to 12 (15) MeV/u**



The Total Project Cost for FRIB is $730M, of which $635.5M will be provided by DOE and $94.5M will be shared by the community

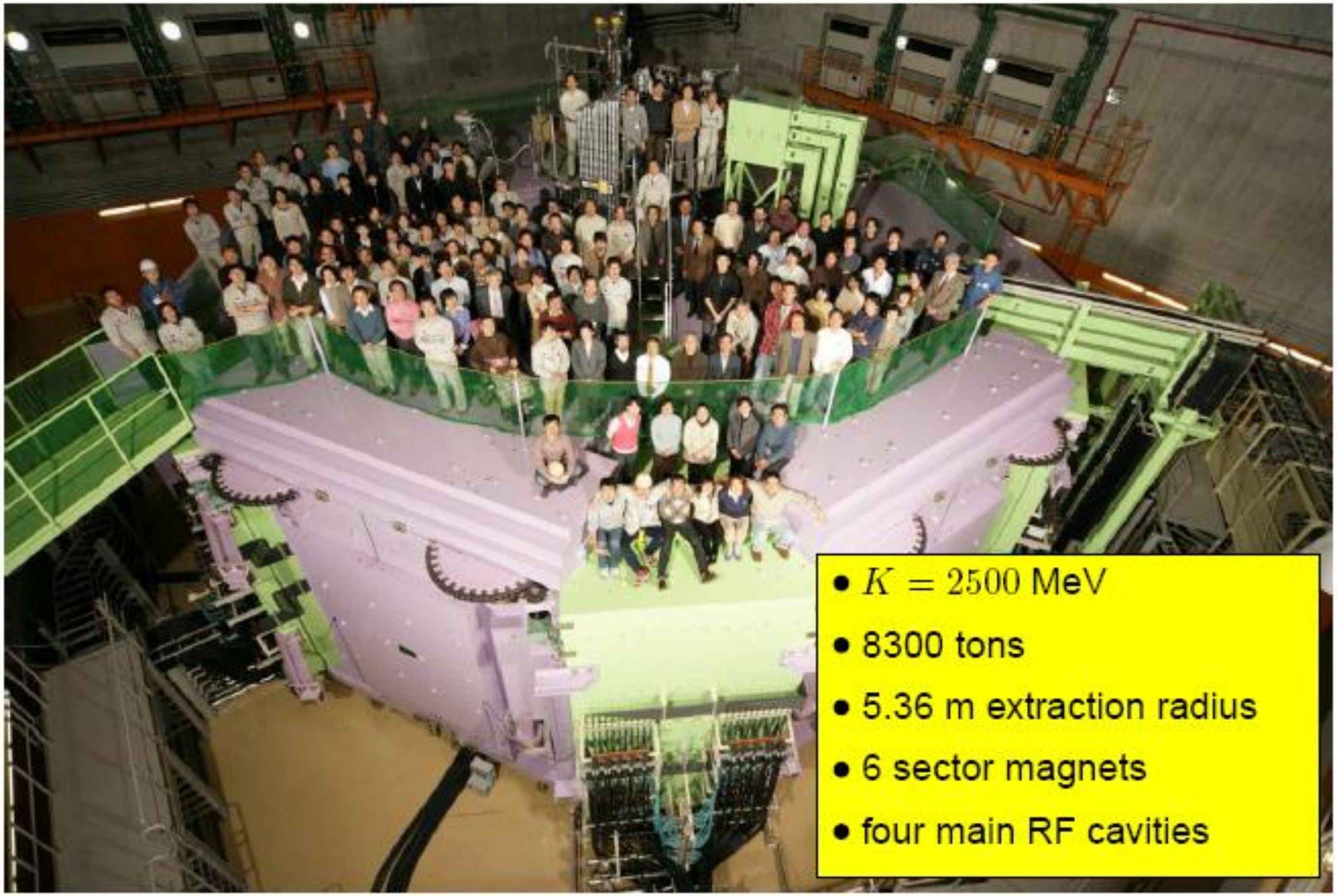


RIKEN RI Beam Factory (RIBF)



Intense Heavy Ion beams (up to U) up to 345*A*MeV at SRC
Fast RI beams by projectile fragmentation and U-fission at BigRIPS
Operation since 2007

SRC: World Largest (Heaviest) Cyclotron

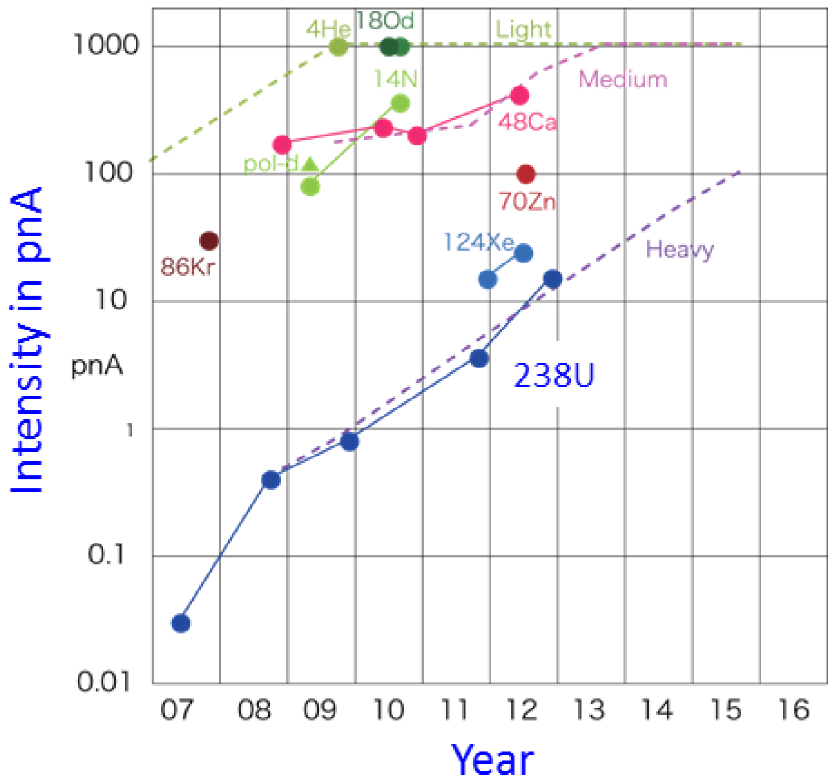


Remind, that "K" is proton energy.
RIBF ^{238}U energy is 345 MeV/u

RIKEN : Summary

- Experimental facilities at RIKEN RIBF, such as BigRIPS, ZeroDegree, SAMURAI, SHARAQ, SLOWRI/PALIS, Rare RI Ring, SCRIT, have been reviewed.
- Outlook of primary beam intensity

Planned schedule of intensity upgrade at RIBF



(From RIKEN accelerator group)

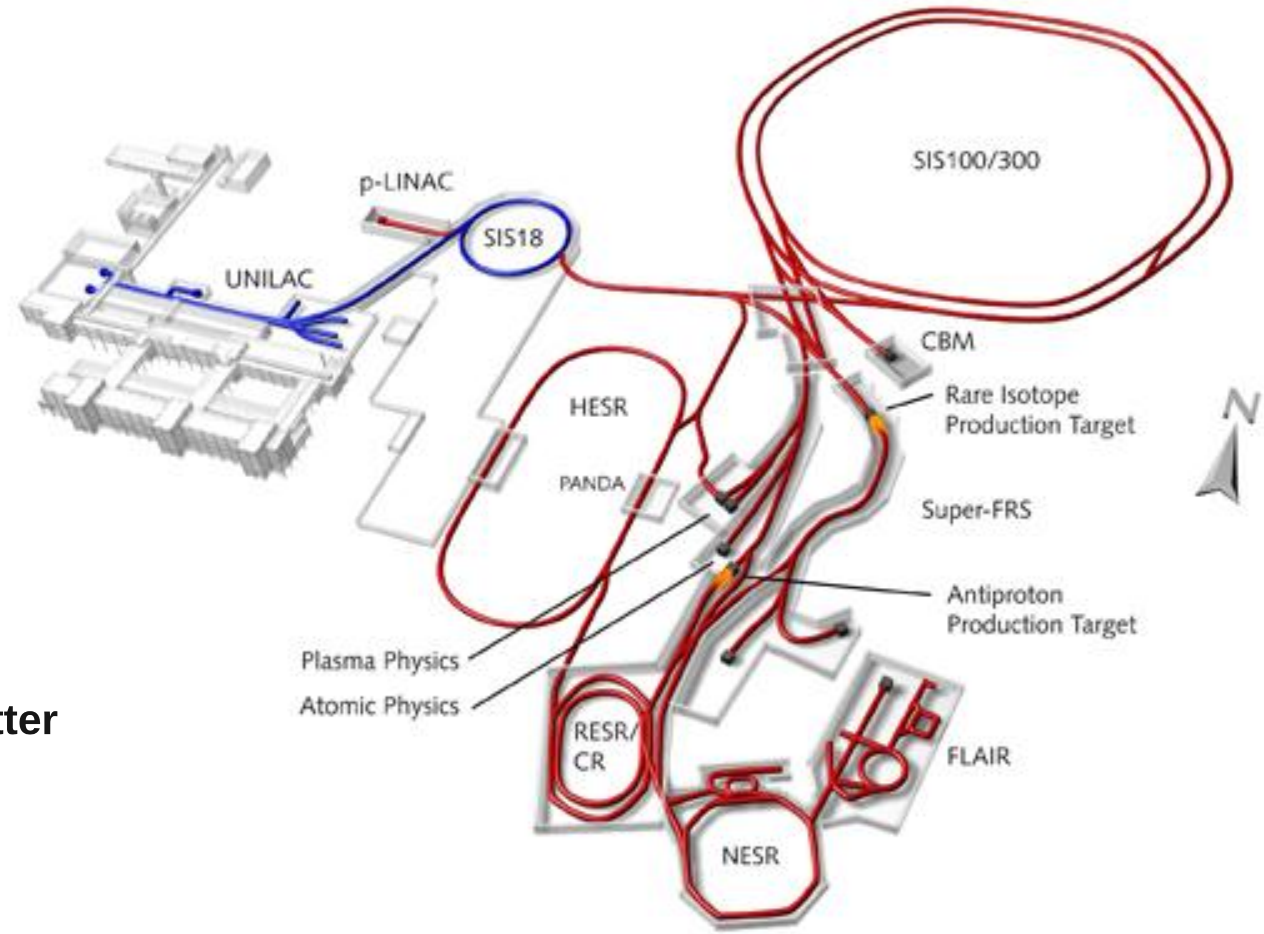
Present status of primary beams

Beam particle	E/A(MeV)	Beam current (pnA): Maximum record	Beam current (pnA): Expected ¶	Injector
d	250	1000	200	AVF
d(pol.)	250	120	30	AVF
^{4}He	320	1000	1000	AVF
^{14}N	250	400	400	RILAC
^{18}O	345	1000	500	RILAC
^{48}Ca	345	415	150	RILAC
^{70}Zn	345	100	75	RILAC
^{76}Ge	345	not tested	N/A	RILAC
^{78}Kr	345	under development	50	RILAC
^{86}Kr	345	30	50	RILAC
^{136}Xe	345	not tested	20	RILAC2
^{124}Xe	345	27	20	RILAC2
^{238}U	345	15.1	10	RILAC2

¶ Some intensities are limited by shielding requirements

Courtesy of T.Kubo

Facility for Antiproton and Ion Research



Beams at 1.5 GeV/u

10^{12}/s Uranium

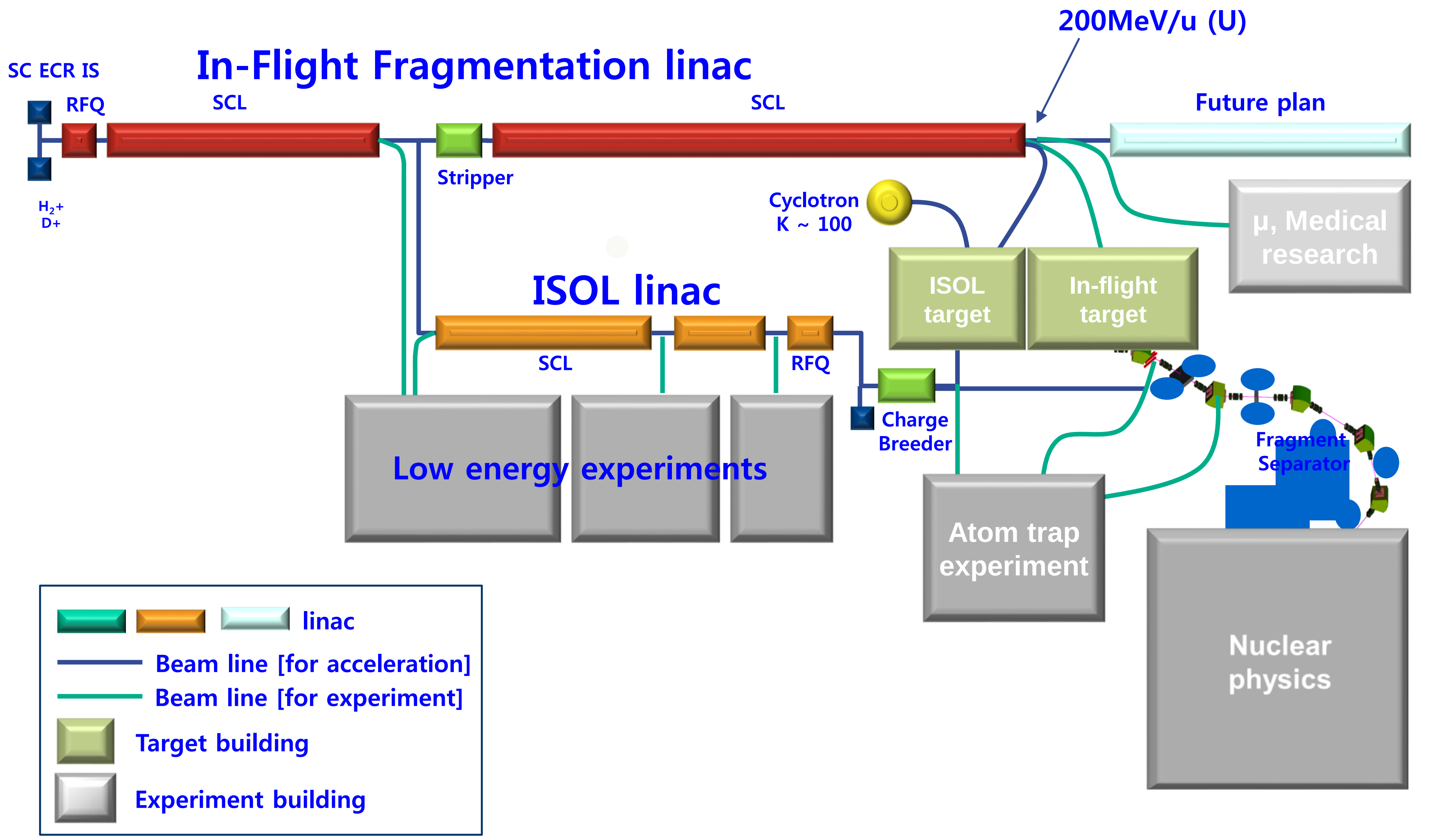
Research

- **Compressed matter**
- **Rare isotopes**
- **Antiproton**
- **Plasma**
- **Atomic physics**

Completion of the first stages are planned around 2018

http://www.fair-center.de/index.php?id=1

KoRIA Schematic Layout



Seung Woo Hong

Brief Summary: The Five-Minute Rap Version

Rare Isotope Rap by Kate McAlpine (also did the LHC Rap)

B.Sherrill