Workshop "Advanced Ideas and Experiments for DNS-IV"
6 – 8 December, 2018, Dubna

Exotic Nuclei

A.G. Popeko

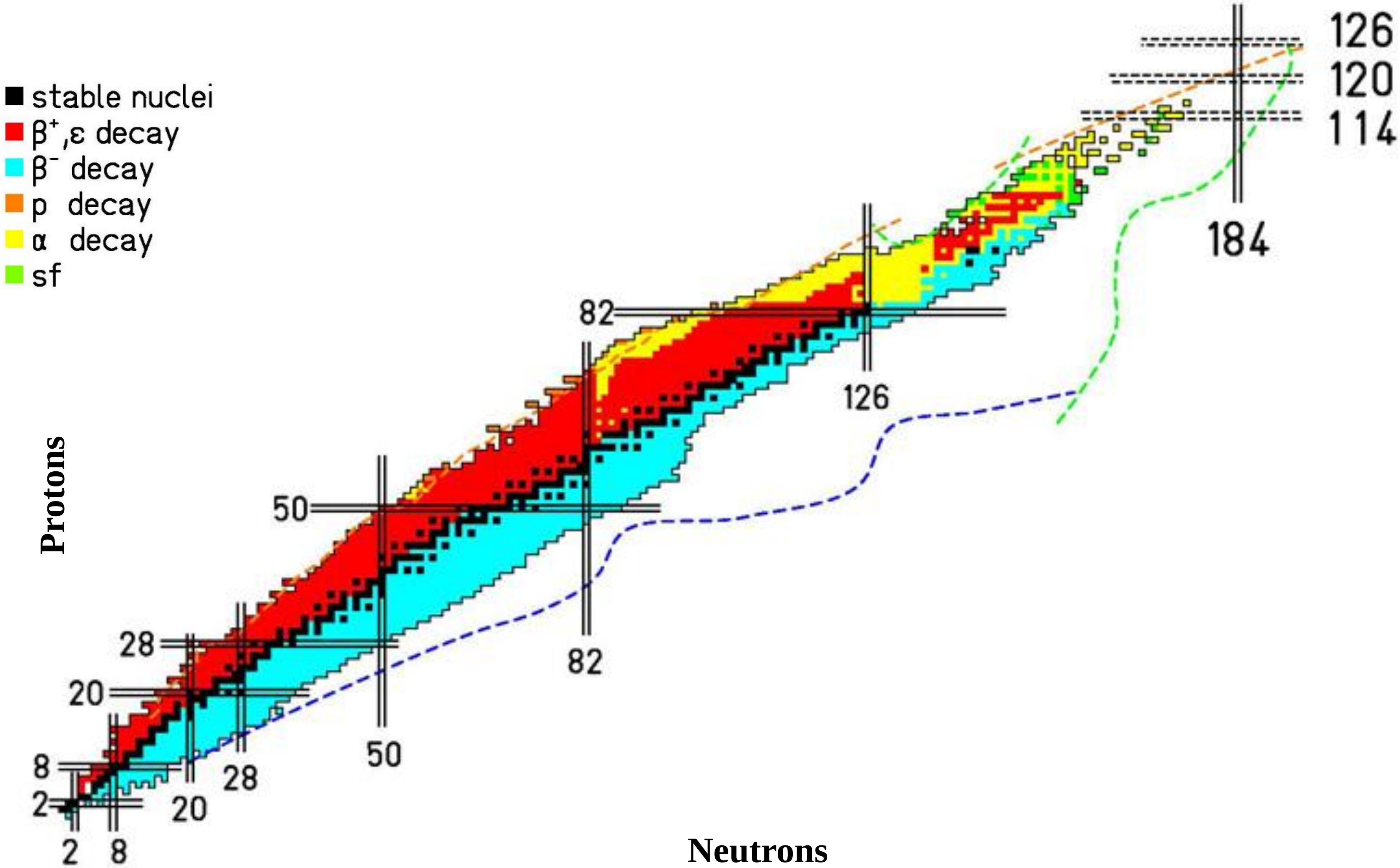
Flerov Laboratory of Nuclear Reactions
Joint Institute for Nuclear Researc

OUTLINES

- **What are exotic nuclei?**
- **Why are they interesting?**
- **Production mechanisms.**
- **Accelerators.**
- **Targets.**
- **How to separate?**
- **How to identify?**
- **Summary.**

What are exotic nuclei?

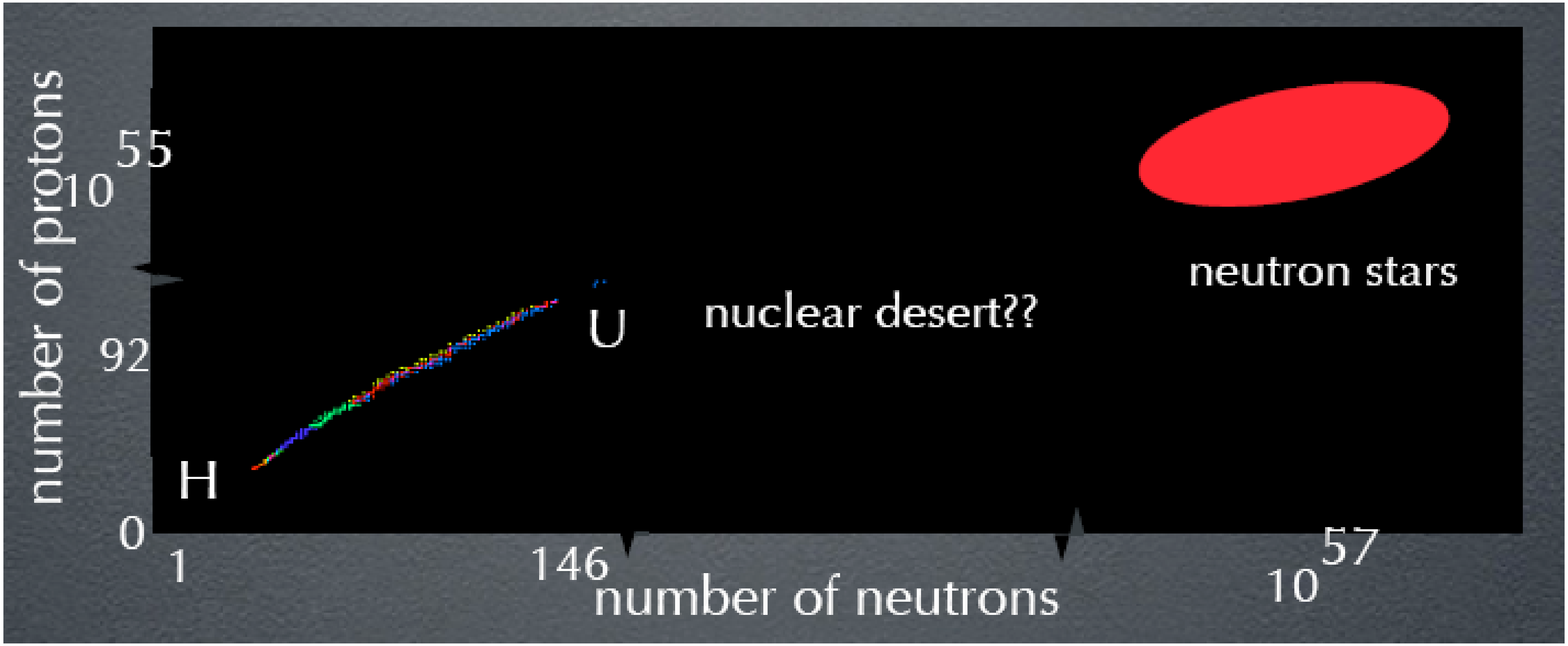
Chart of the Nuclides (decay modes)



What are exotic nuclei?

- Nuclei far from the β-stability valley;
- Nuclei at the border of nucleon stability;
- Nuclei (resonances) beyond the border of stability;
- Superhaevy nuclei;
- Nuclei with unusual form – superdeformed;
- Nuclei with n- or p-”halo” or “skin”;
- Nuclei with unusual structure – nuclear fullerene;
- Nuclei with unusual density distribution – bubble nuclei
- …

Extended Chart of the Nuclides



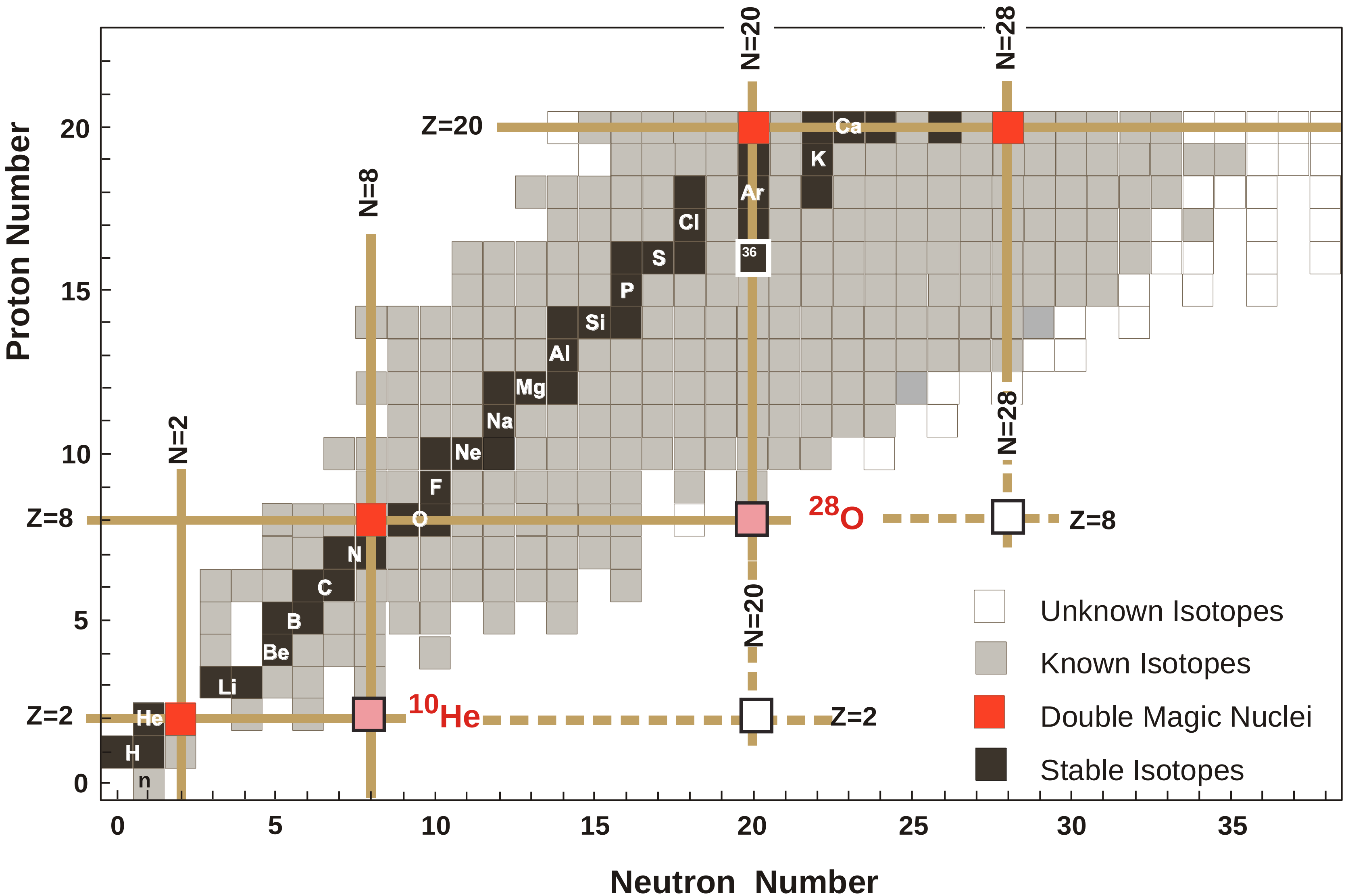
Andrew Westphal, Space Sciences Laboratory U. C. Berkeley

Why are they interesting?

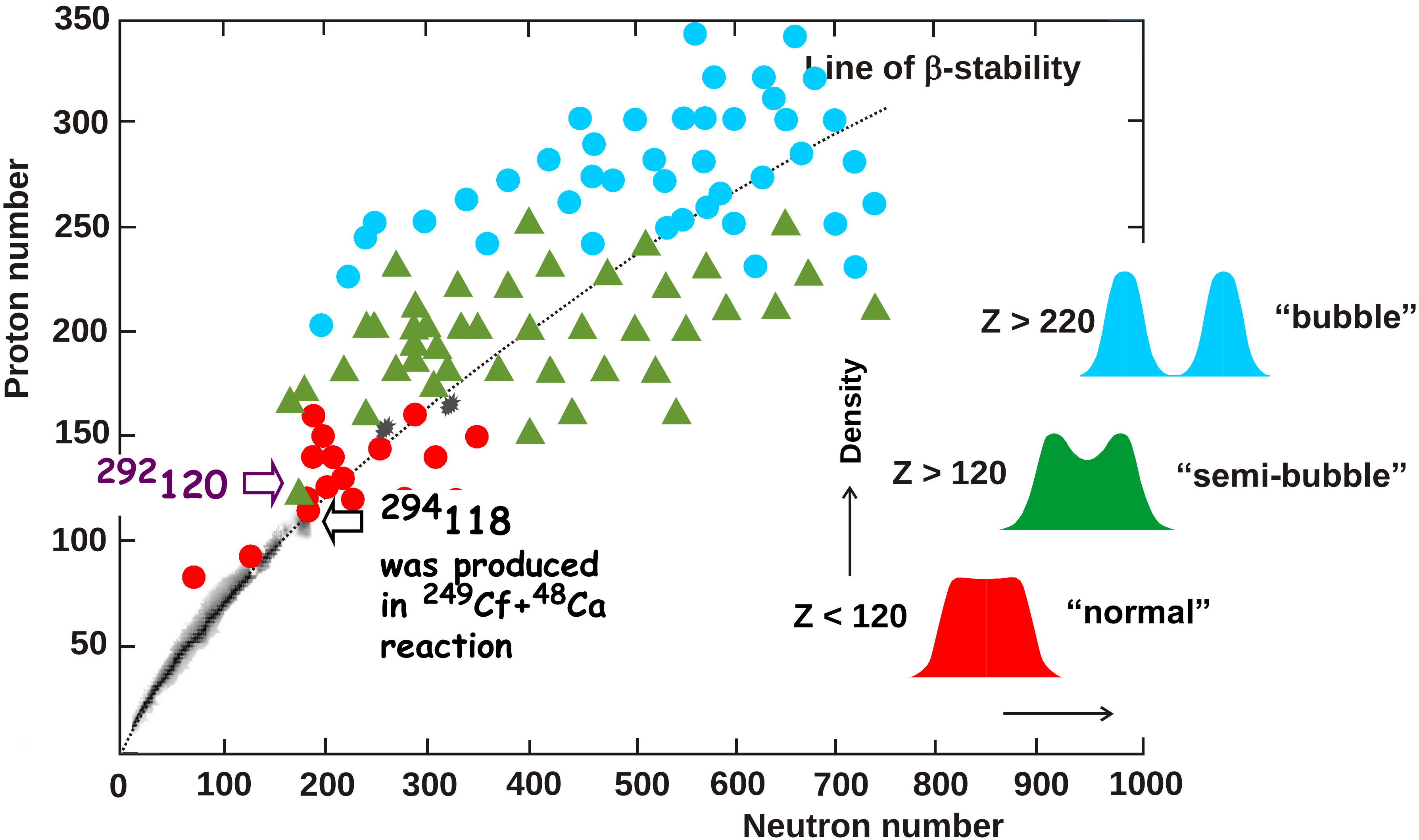
Why are they interesting?

- The borders of nuclear stability: $B_n = 0$; $B_p = 0$;
- How heavy can be the nuclei?
- Properties of exotic nuclei – spectroscopy, masses;
- Astrophysics;
- New decay modes;
- Unusual structures of nuclei;
- Mechanisms of reactions with exotic nuclei;
- Synthesis of even more exotic;
- Resonances beyond stability lines;
- Fundamental interactions;
- Electrodynamics of extreme fields;
- β–beams;
- Applications;
- ……

Collective effects and nuclear shells

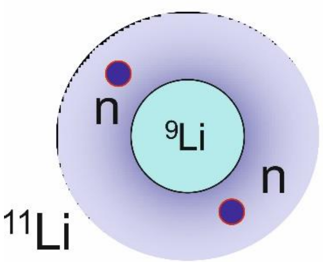


Nuclei with unusual density distribution – bubble nuclei



Nuclei with unusual structure

Neutron halo, Borromean nuclei



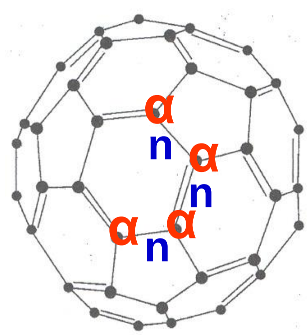
^{9}Li + n Barely Unbound

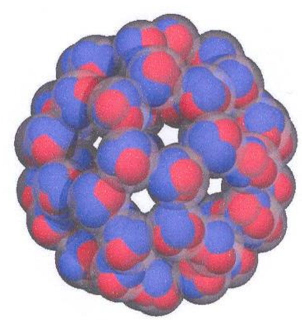
n + n Barely Unbound

^{9}Li + n+n Bound

Nuclear fullerene

Z=120, A=298-300
60 α-particles
+ 60 neutrons





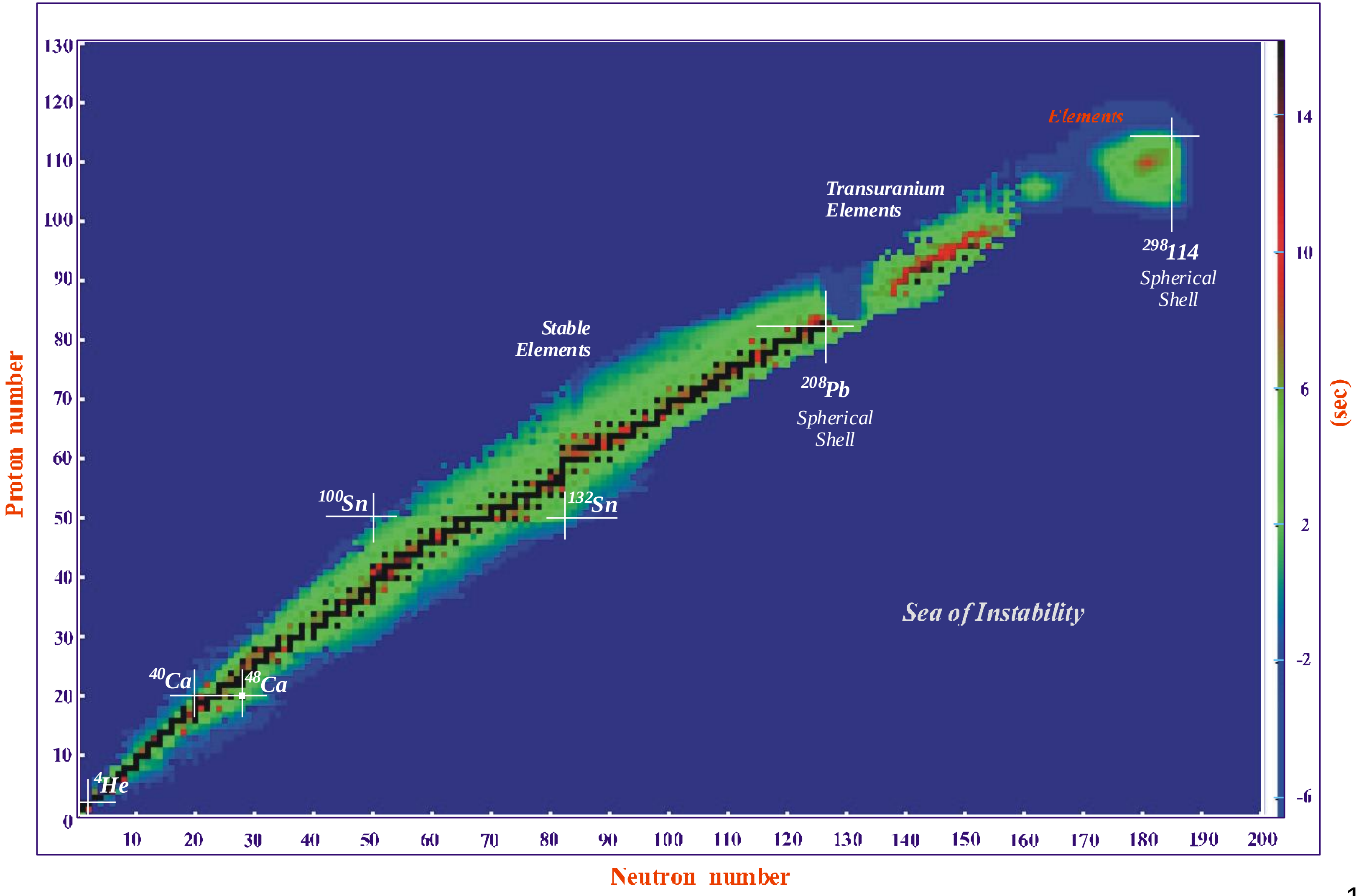
Superheavy nuclei

- **1966: A. Sobiczewski, F.A. Gareev, B.N. Kalinkin: next "magic numbers" are Z=114, N=184;**
- **1966: V.M. Strutinsky; "shell correction" method;**
- **1967: H.B. Meldner: next "magic numbers" are Z=114, N=184.**

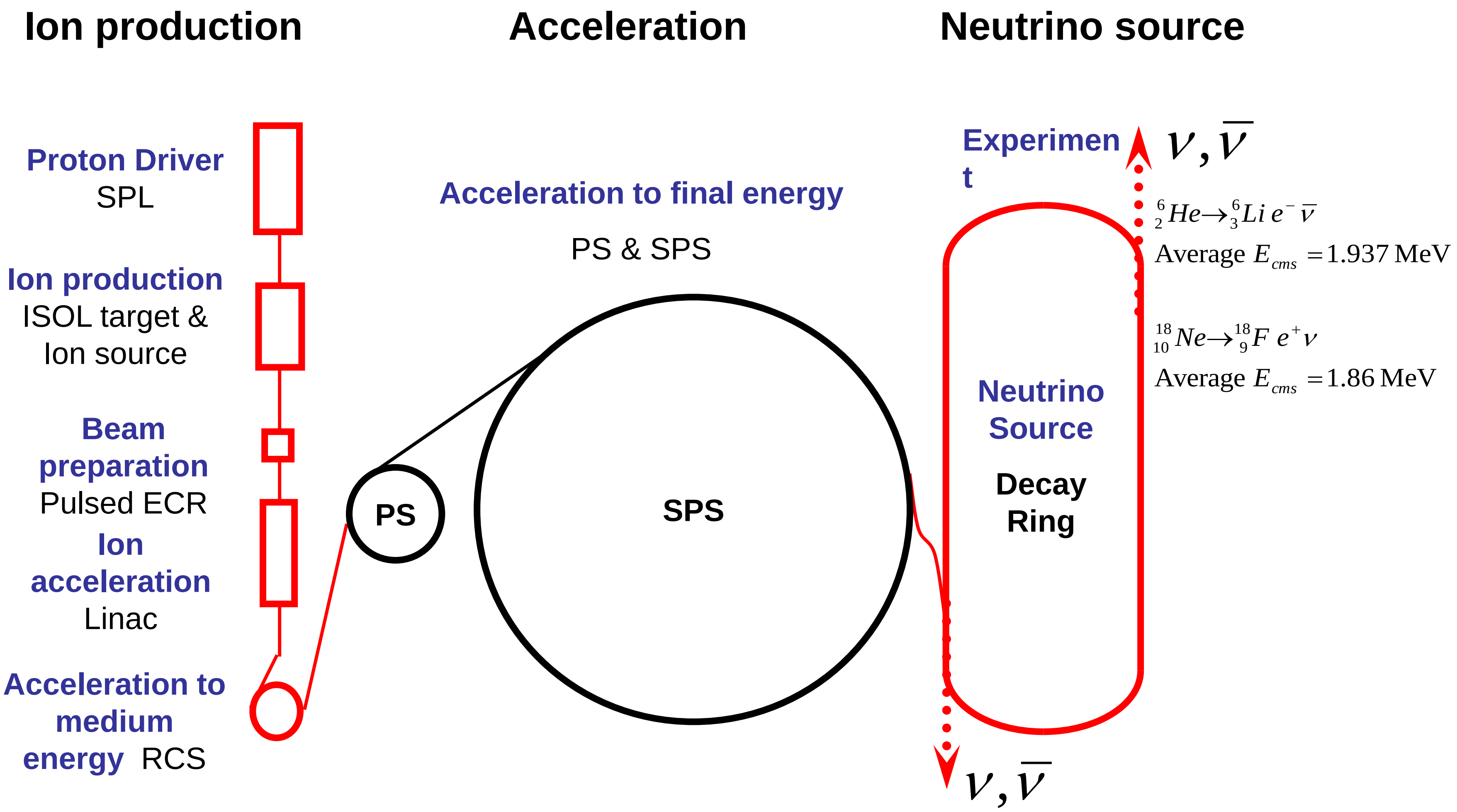
Accuracy of predictions:

- **Spontaneous fission half-life: $T_{1/2} * 10^{\pm 10}$!!**
- **α-decay: $T_{1/2} * 10^{\pm 10}$!!**

Chart of the Nuclides (life-times) SuperHeavy Elements

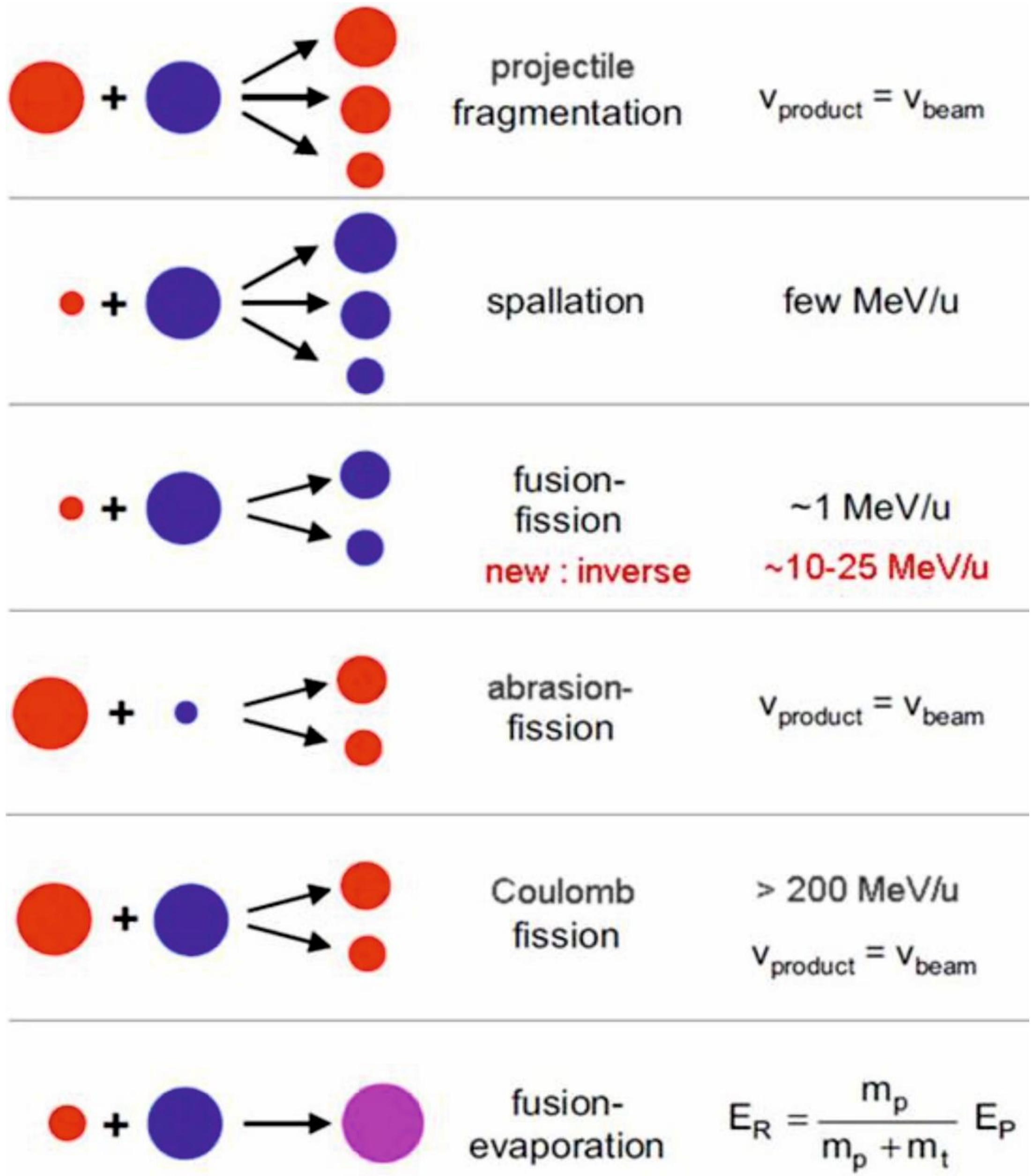


β-пучки (^6He, ^{18}Ne)

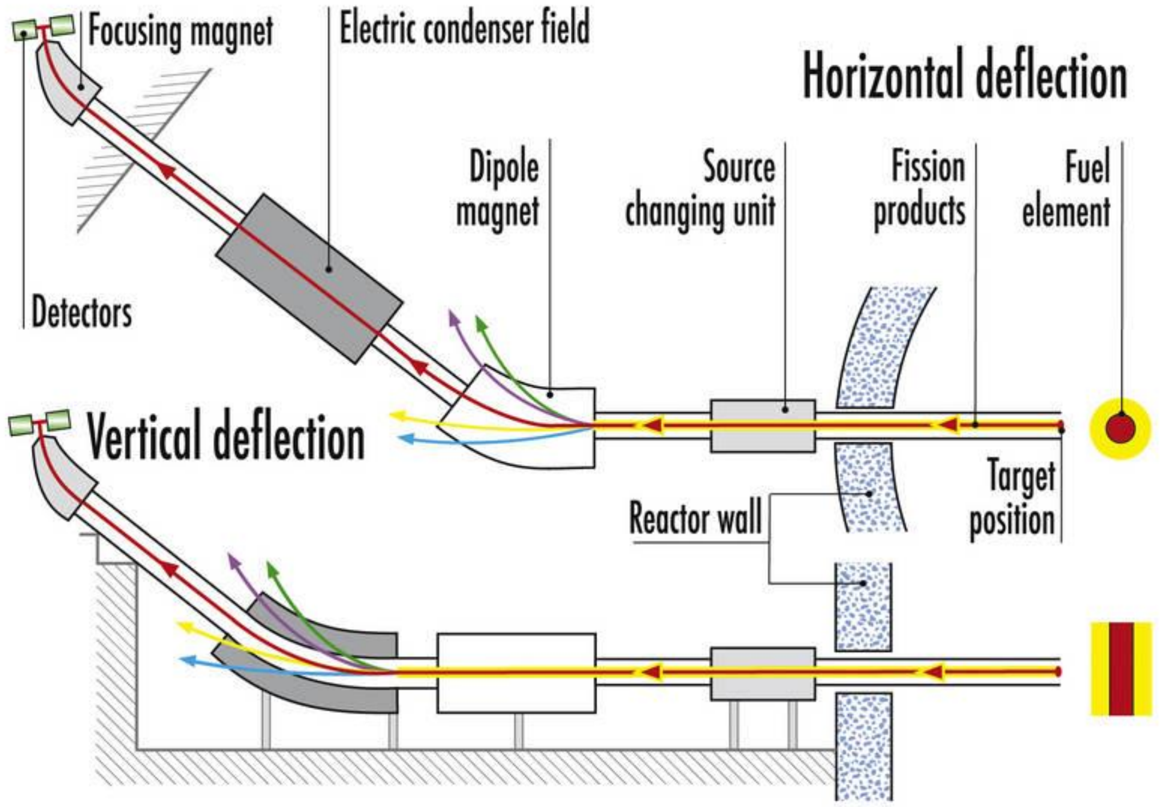


Production mechanisms

Exotic isotope production mechanisms

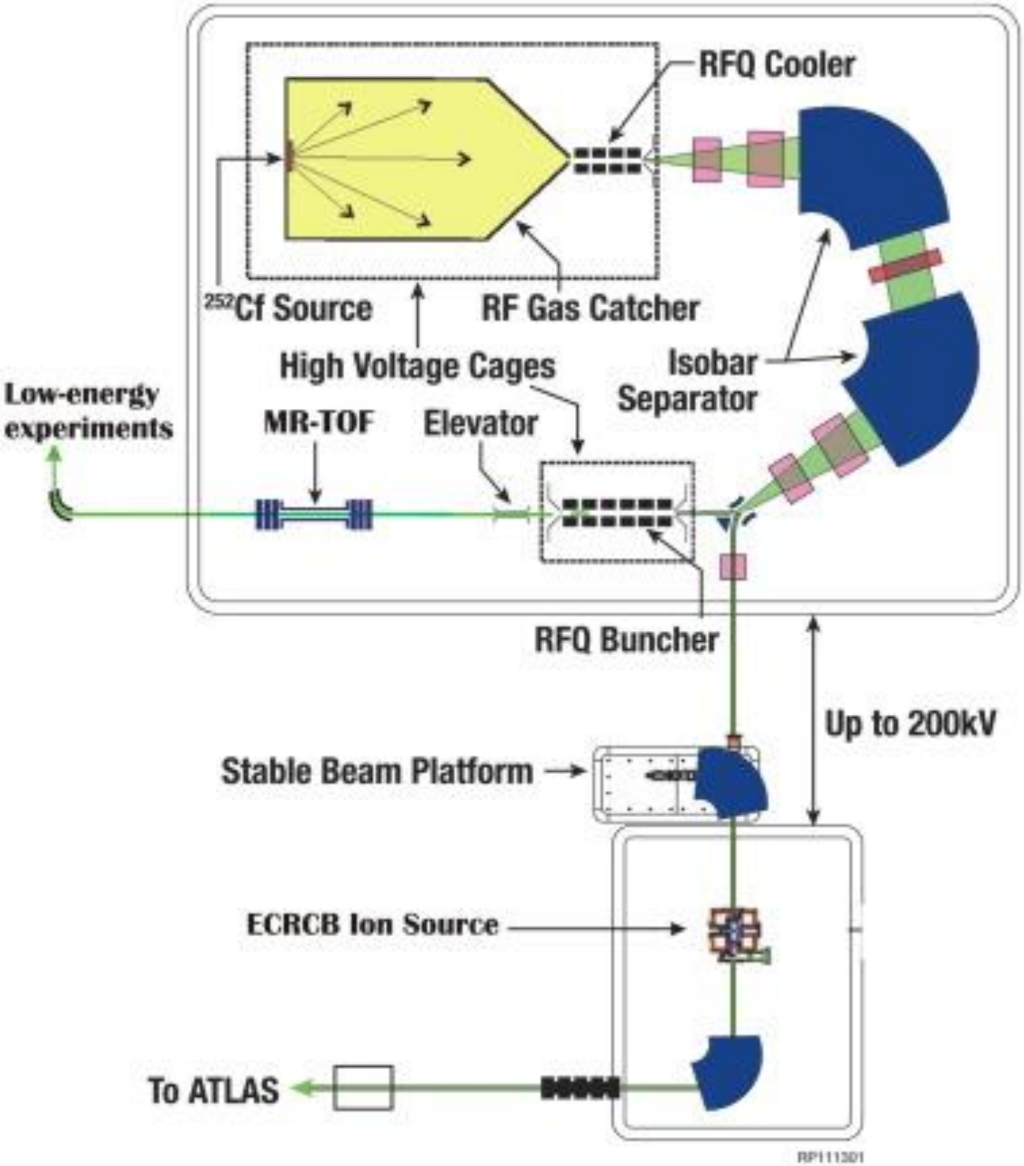


Сепаратор PN1 (Lohengrin)
ILL, Grenoble, France

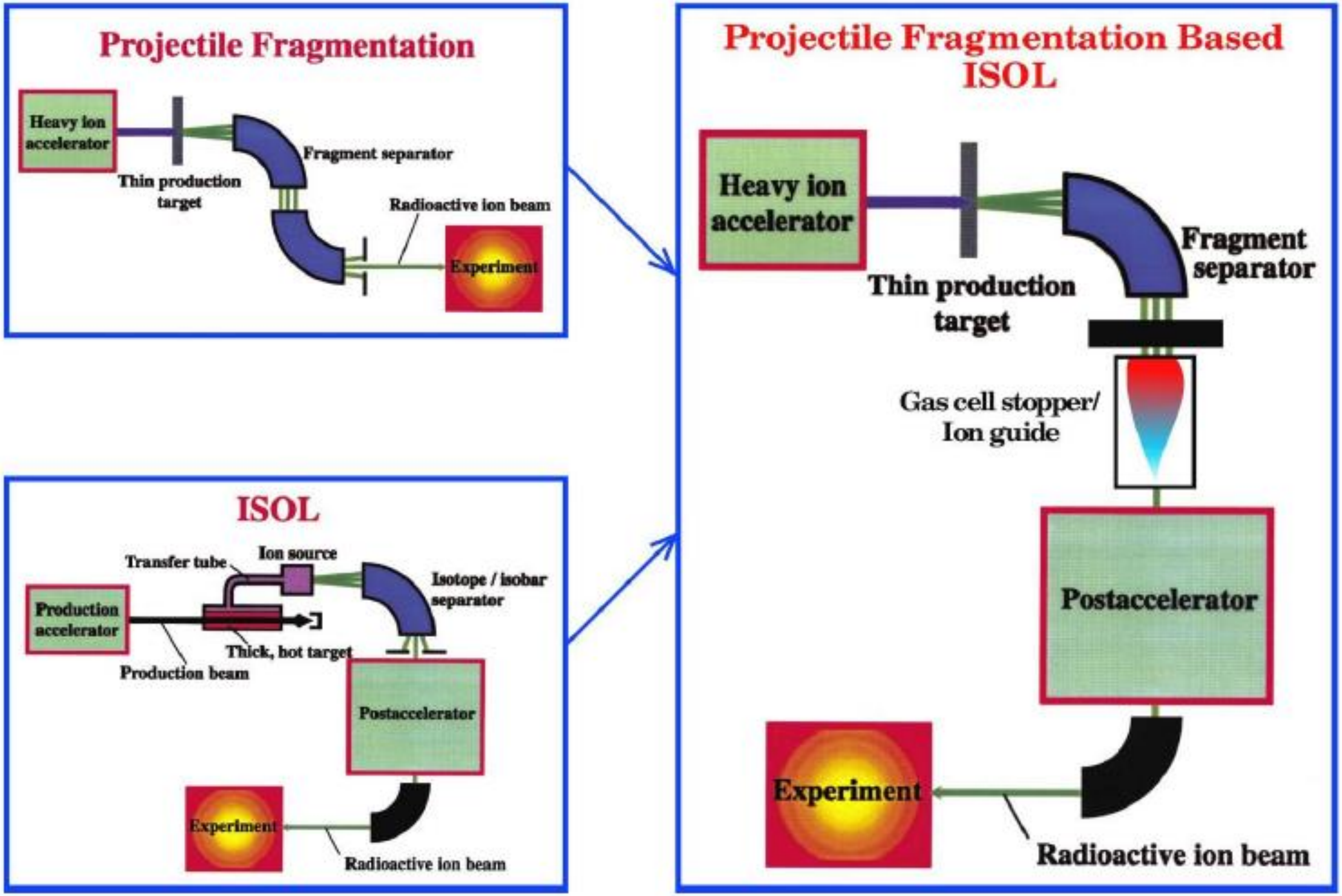


- $\Phi_n \approx 5 \cdot 10^{14}$ n/cm^2/s $\rightarrow$ 1 mg ^{235}U$\rightarrow$ 10^{12} fission/s;
- Изучение экзотических ядер;
- Изучение деления ядер.

CARIBU (2 mg ^{252}Cf → 10^9 fiss/s)



ISOL or In-flight production



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

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

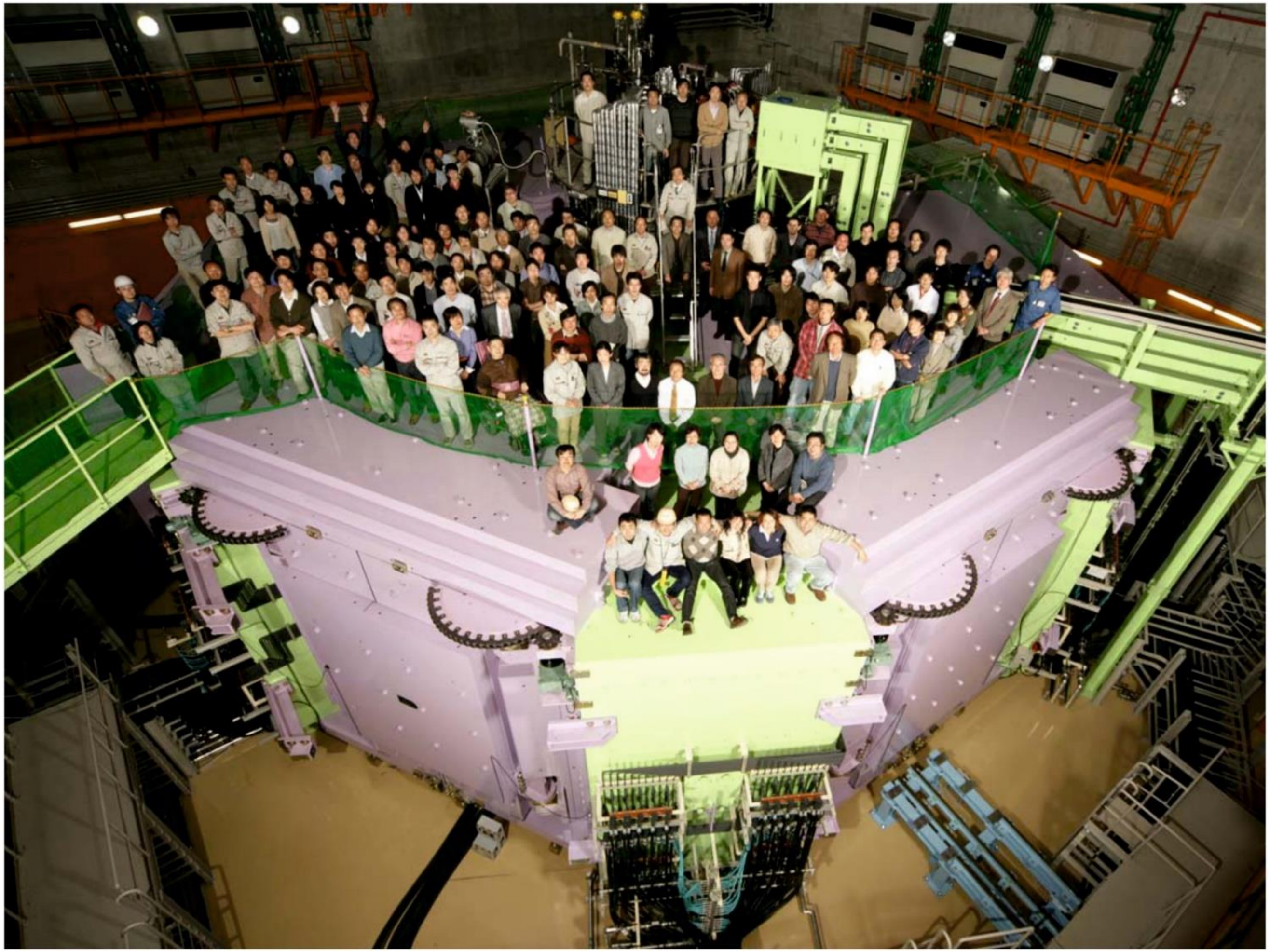
ISOL:

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

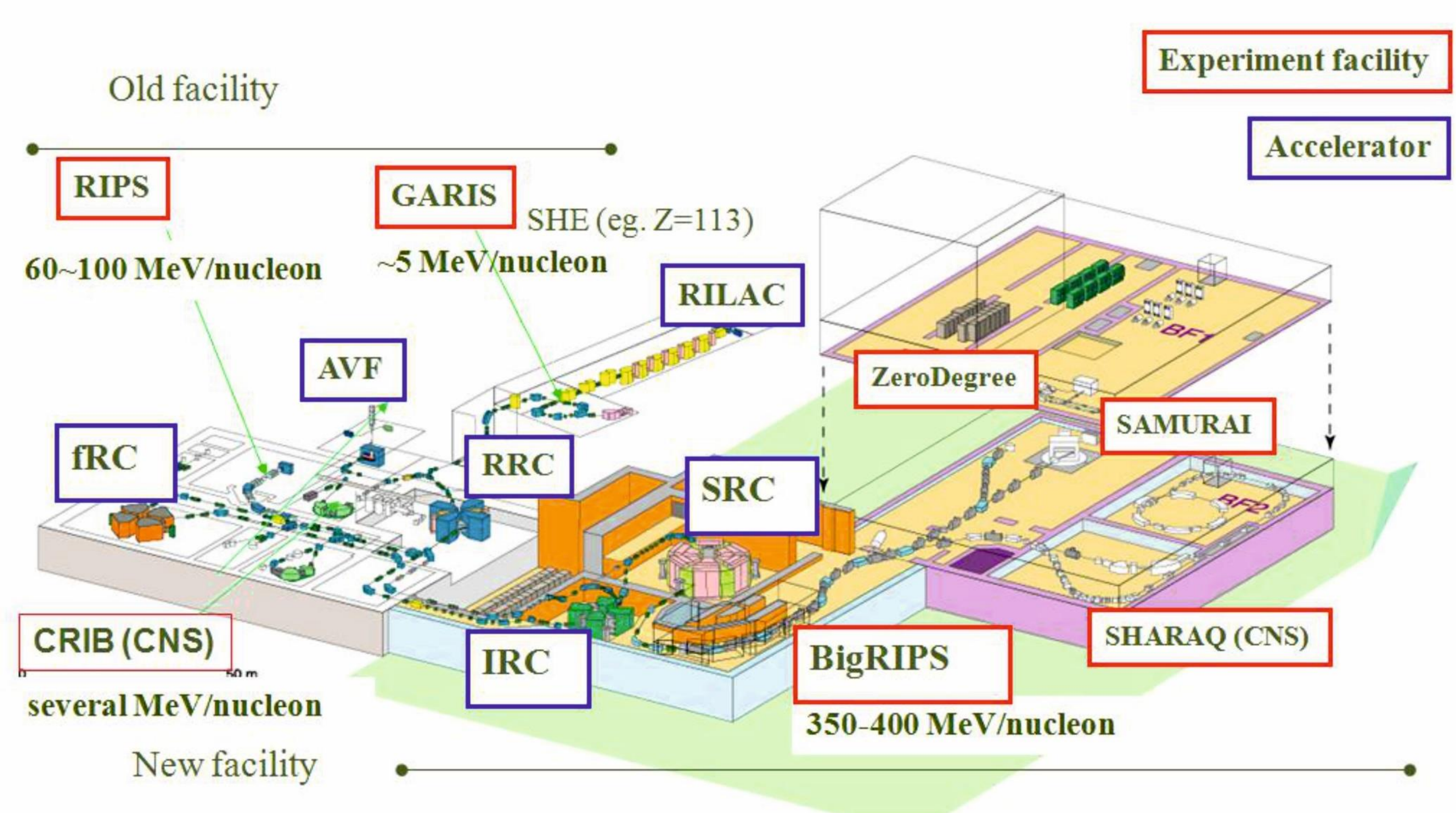
Accelerators

Superconducting Ring Cyclotron K=2600
RIKEN, Japan



July 2018: ^{49}S, ^{52}Cl, ^{59}Ca, ^{60}Ca

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

Facility for Rare Isotope Beams, FRIB

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

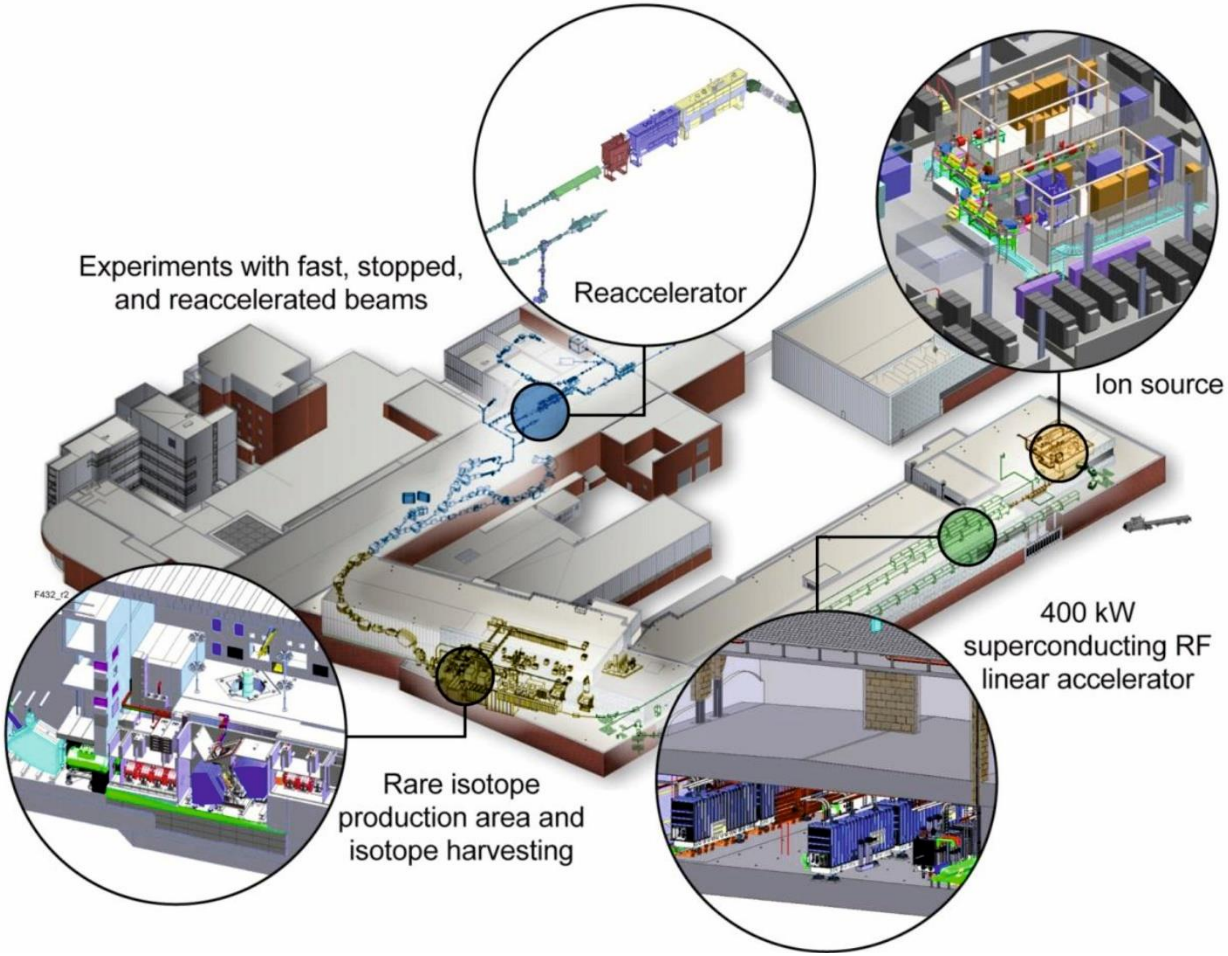
Key Features:

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

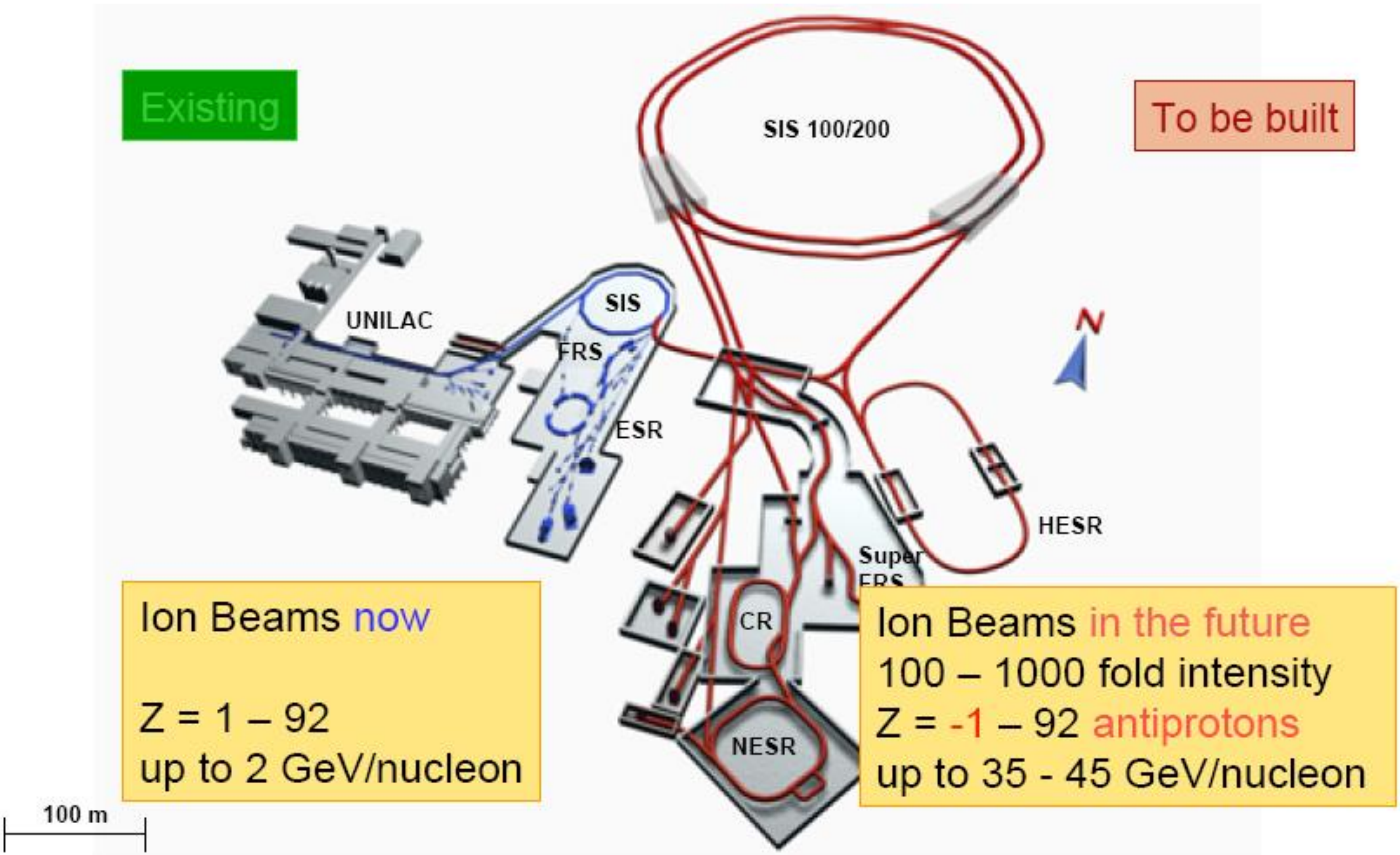
- Efficient acceleration (multiple charge states)

Separation of isotopes in-flight:

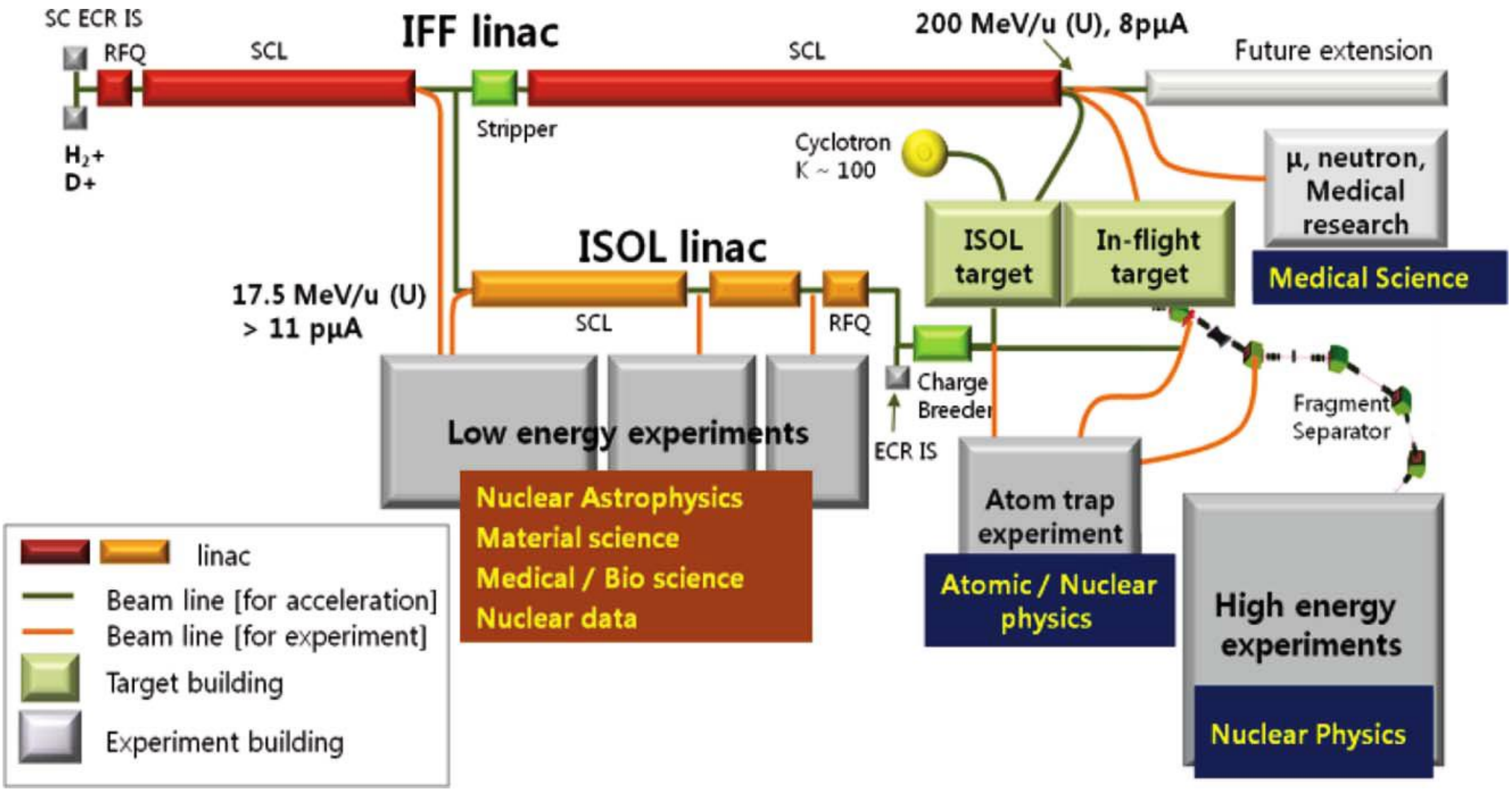
– Fast development time for any isotope
–Suited for all elements and short half-lives



FAIR, Germany

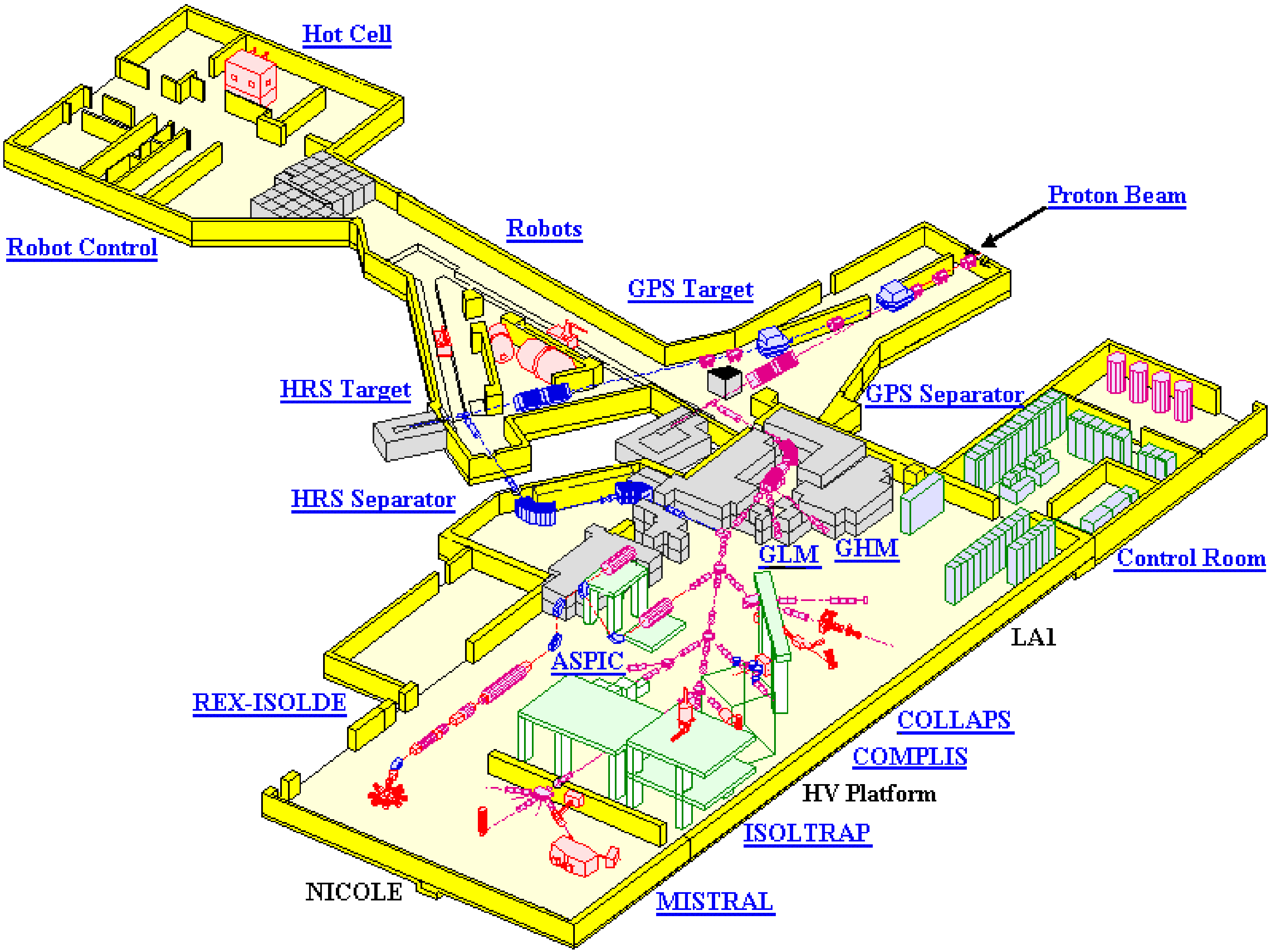


KoRIA



Beam power: 400 kW; protons – 600 MeV; U – 200MeV/A

REX – ISOLDE, CERN

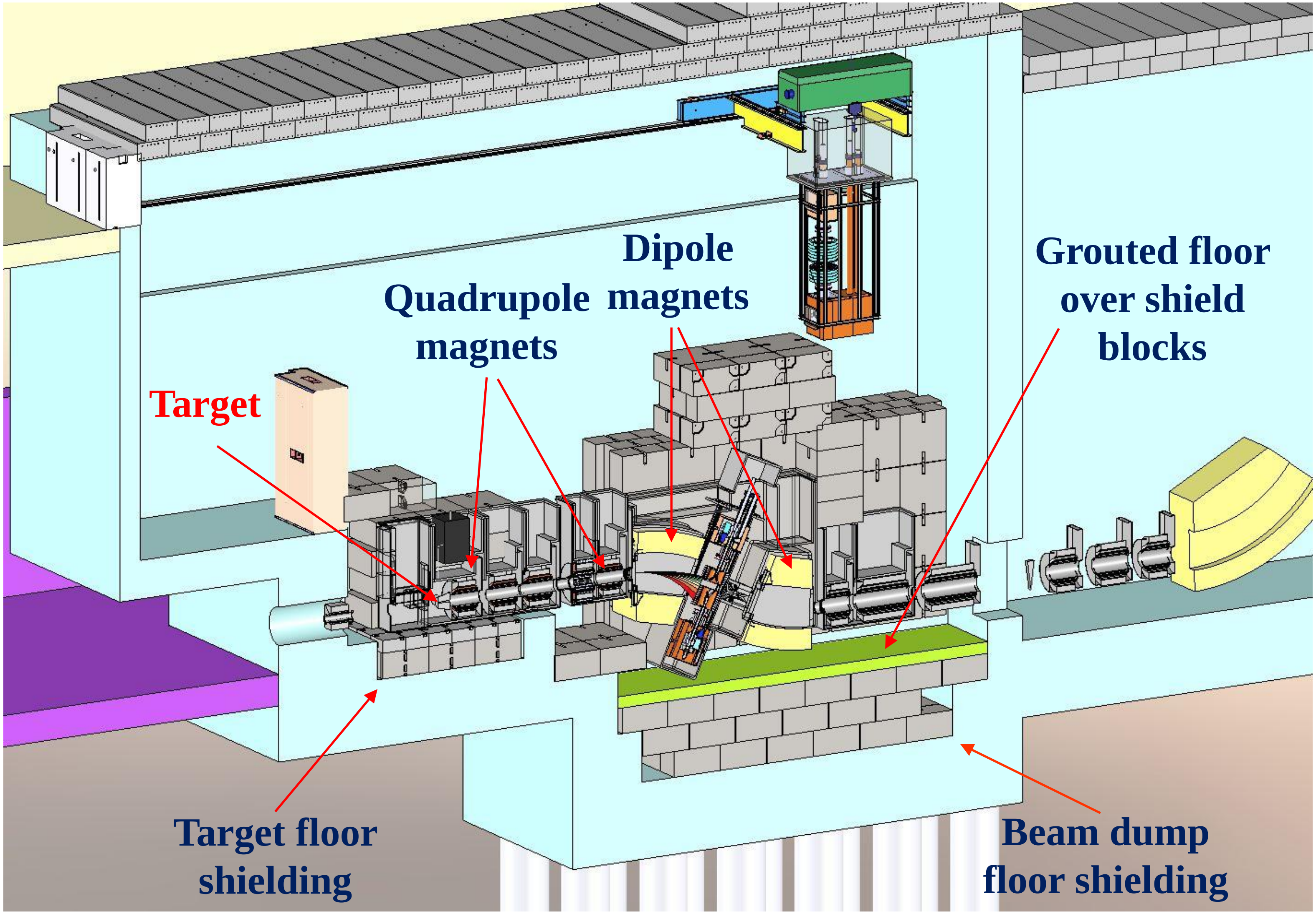


Targets

FRIB Production Target and Beam Dump Area

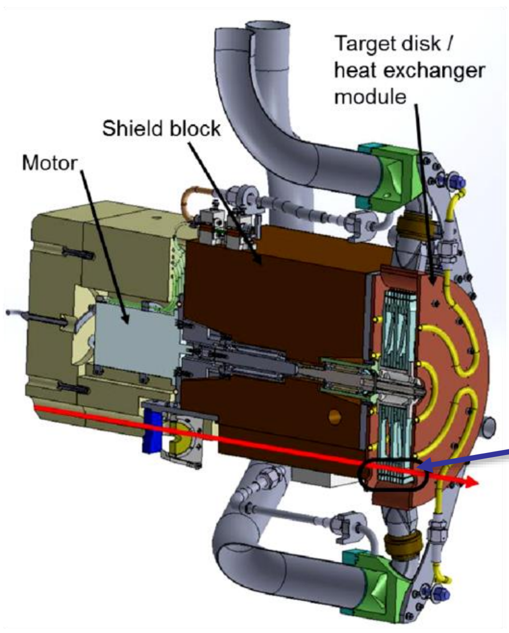
Rare isotope beam production with beam power of 400 kW at 200 MeV/u from C to U

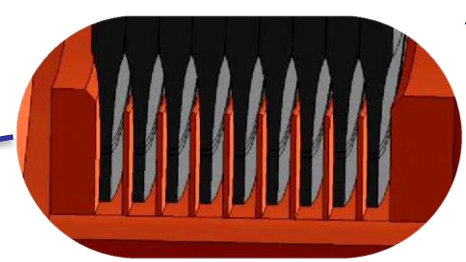
Technical Risk: High power density: ~ 20 - 60 MW/cm^3



Multi-slice Target Concept FRIB

Cooled by thermal radiation
T ≈ 1800 - 1900◦C



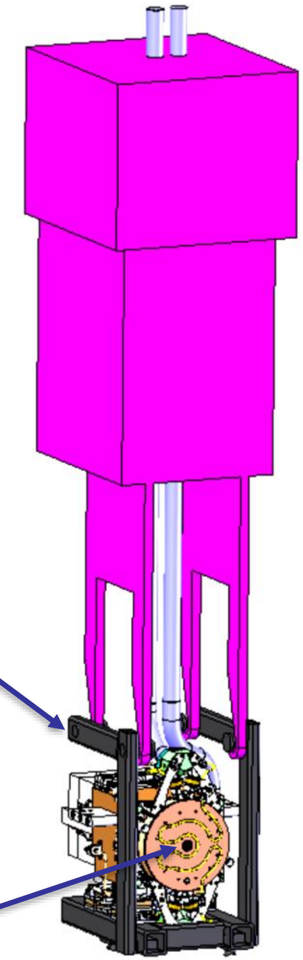


Multi-slice target heat exchanger

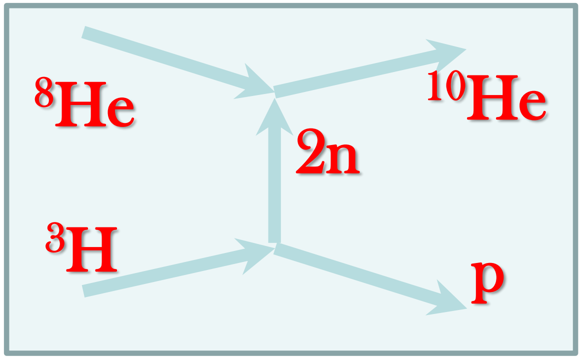
Shielding

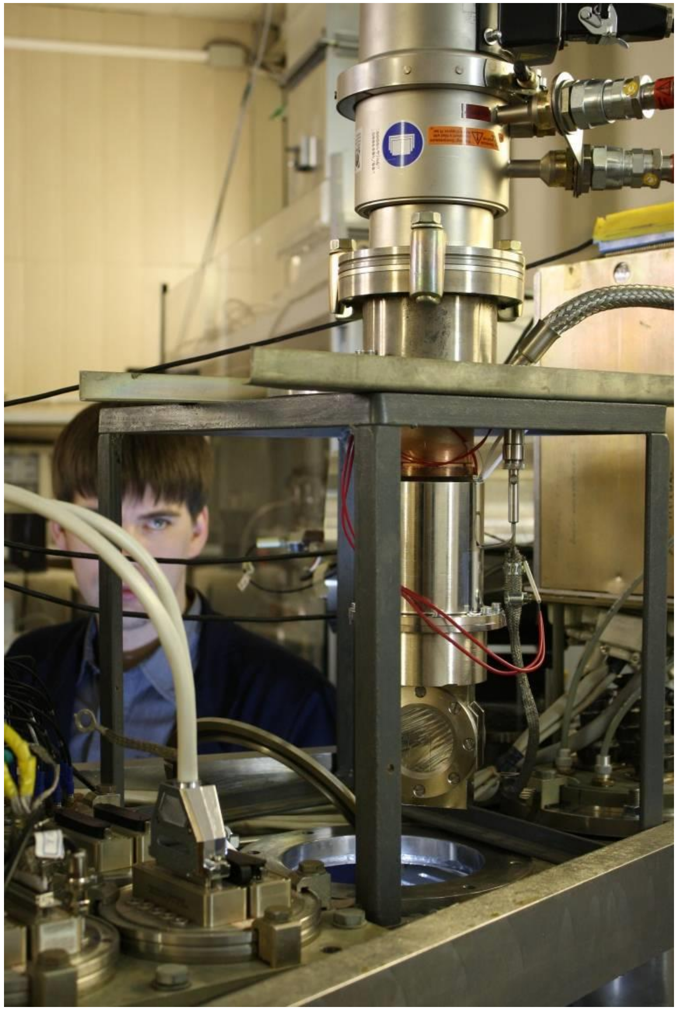
Lifting frame

Target



Tritium target: ^{10}He: 2n-transfer



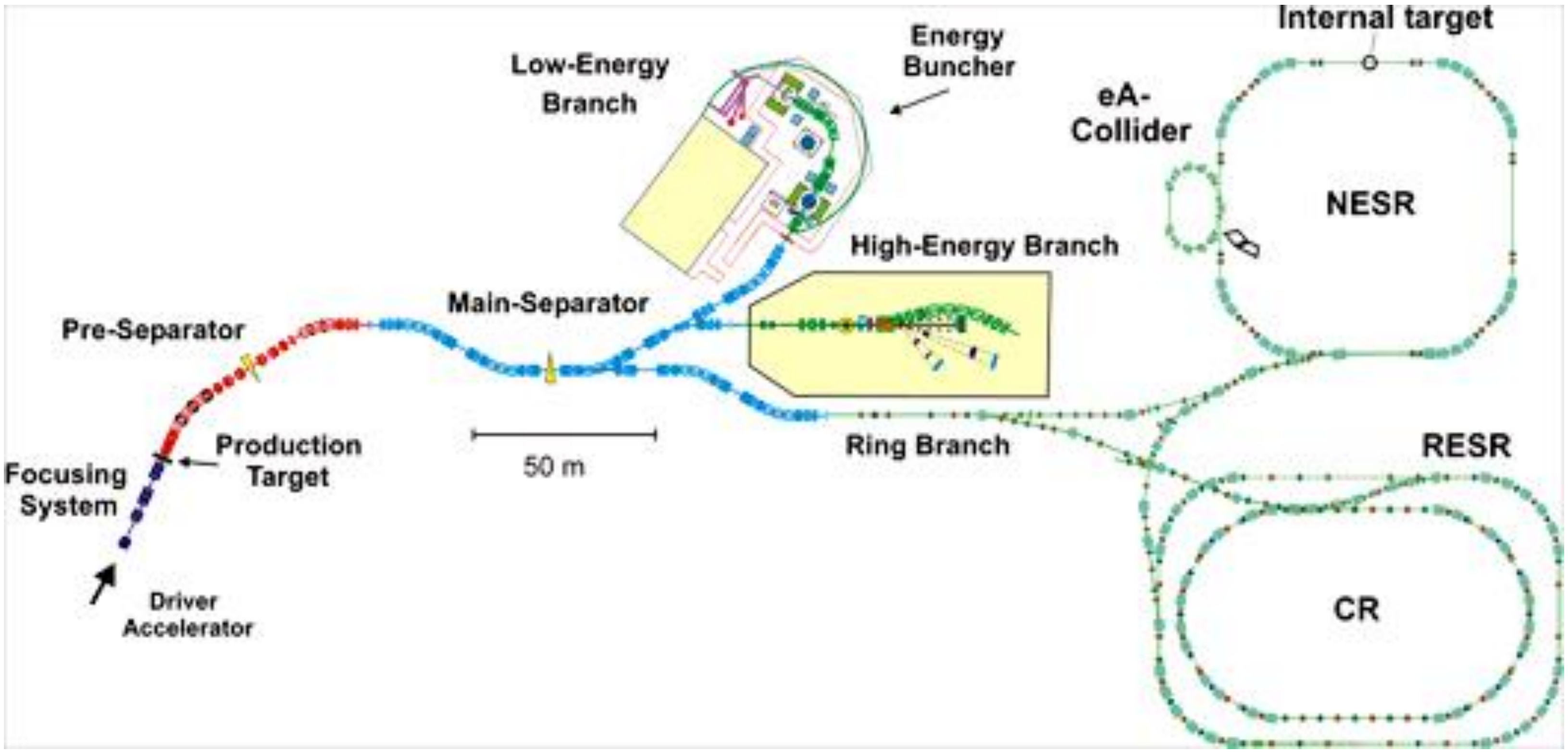


How to separate?

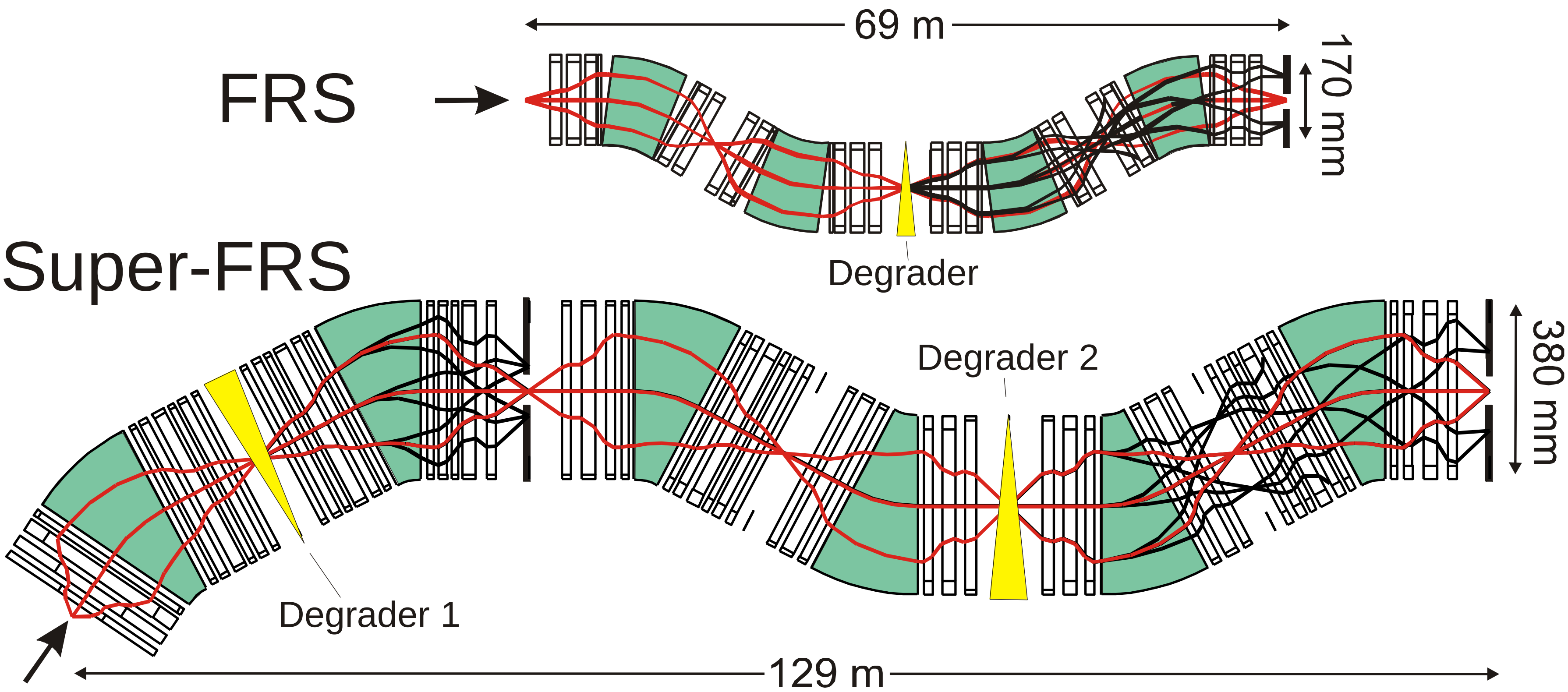
Background

- **Primary beam;**
- **Scattered beam;**
- **Transfer (target-like) products;**
- **Neutrons;**
- **High-energy protons or alphas.**

Super-FRS
FAIR, Germany

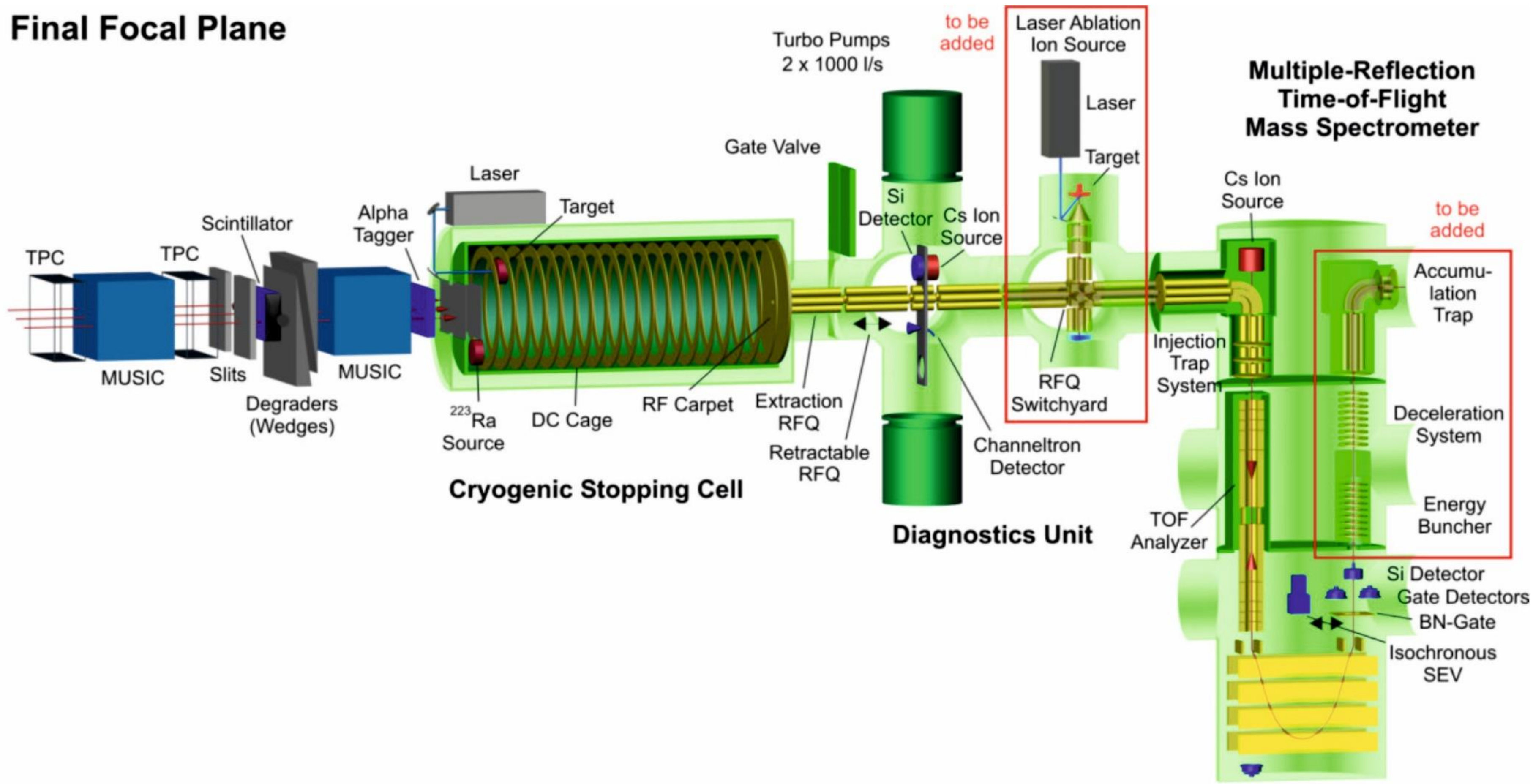


Comparison of FRS and Super-FRS

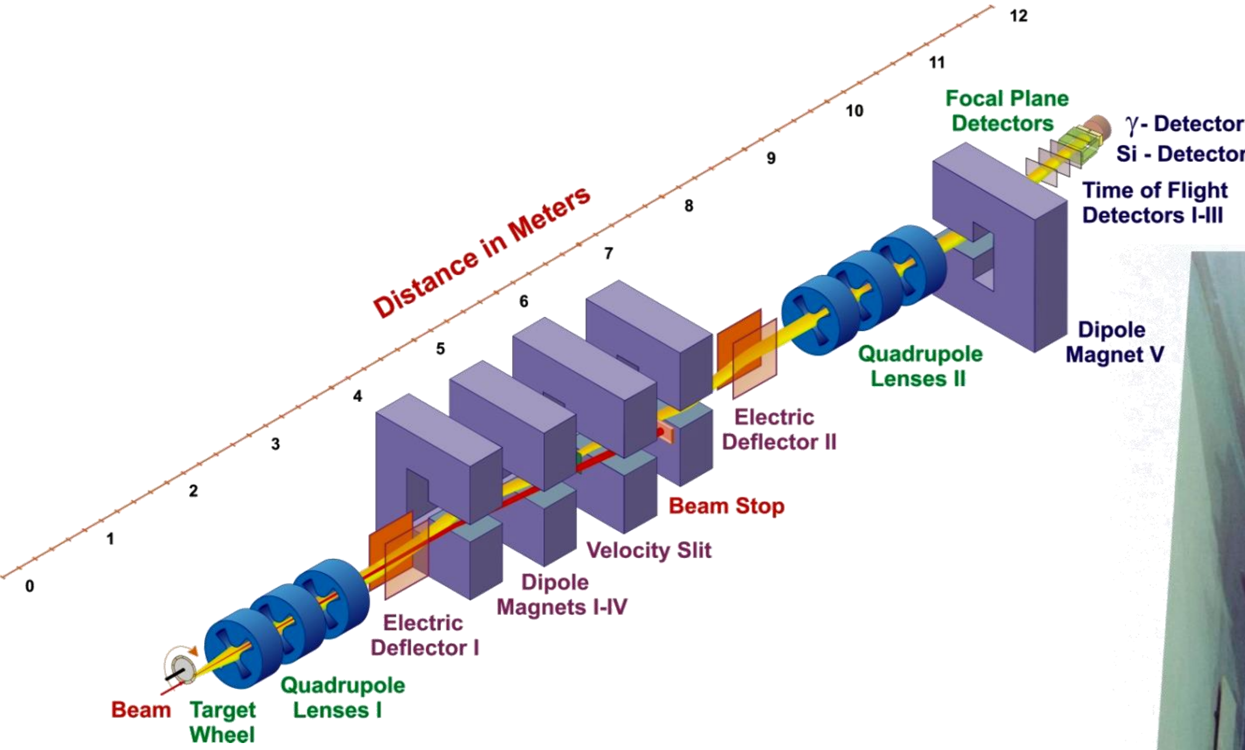


Fragment-separator ACCULINNA-2:
assembling and testing.

Cryogenic Stopping Cell for MR-ToF mass spectrometry



Velocity Filter “SHIP”

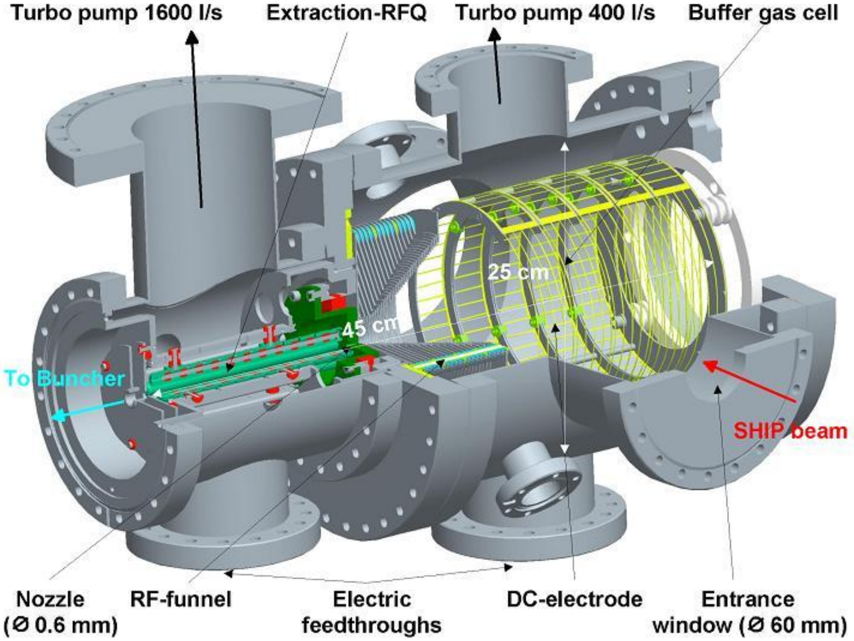


The gas-filled separator GFS-II

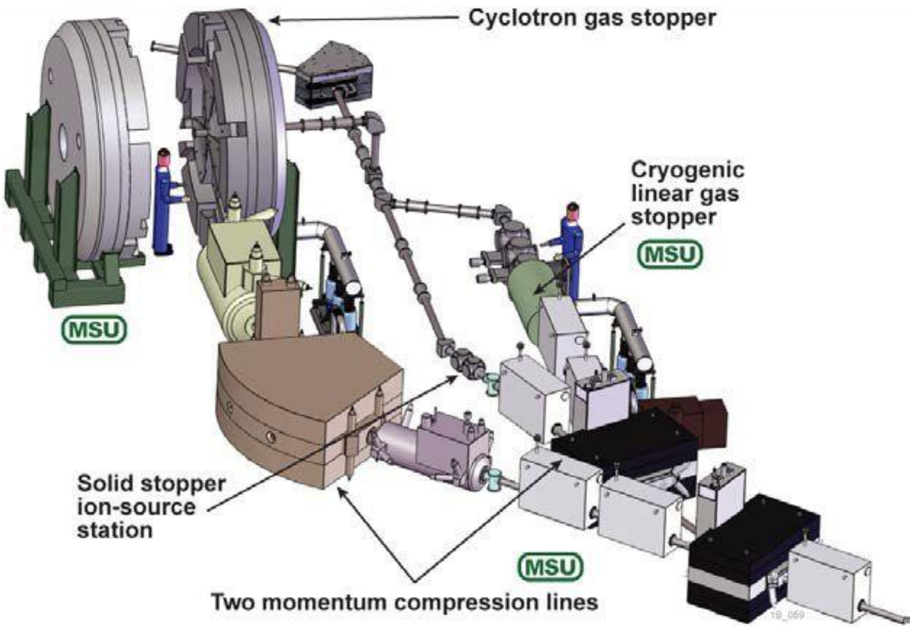
New gas-filled separator GFS-II: assembling

Gas-Catcher

Linear gas stopper

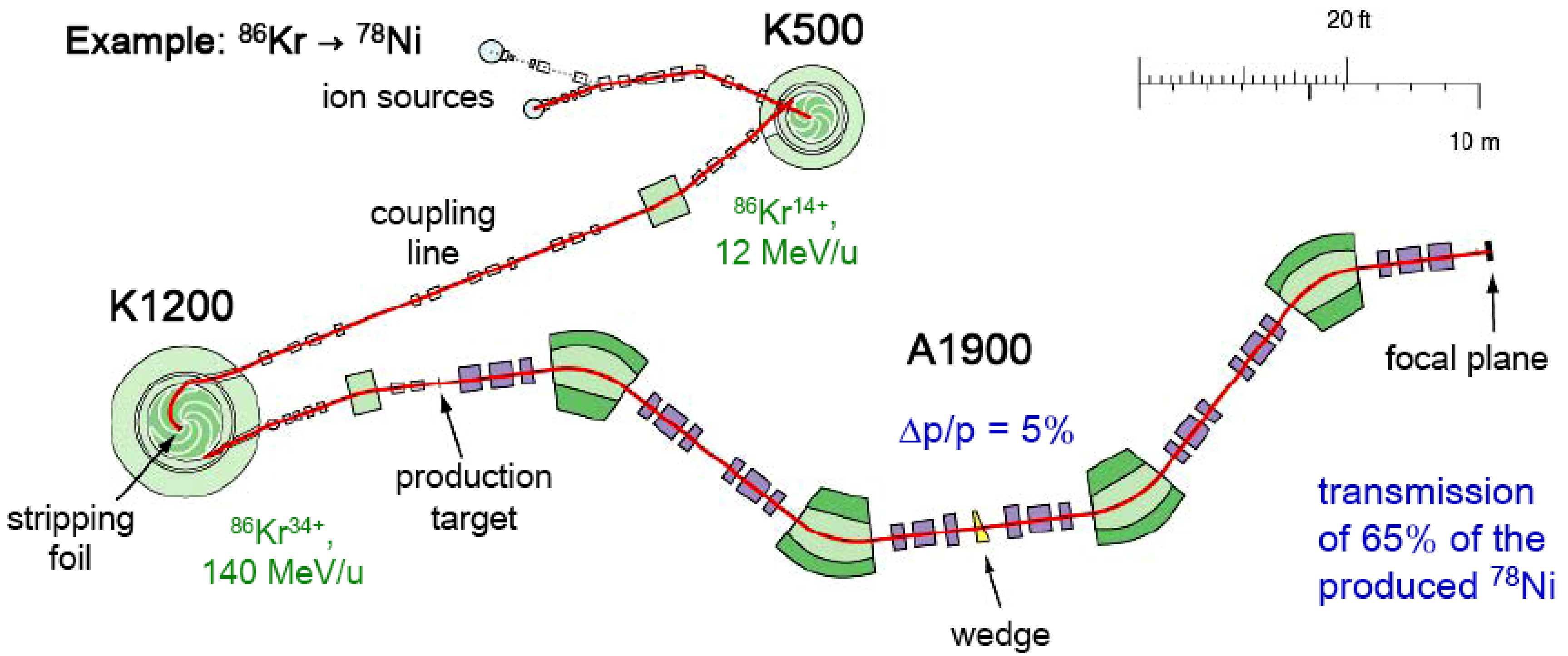


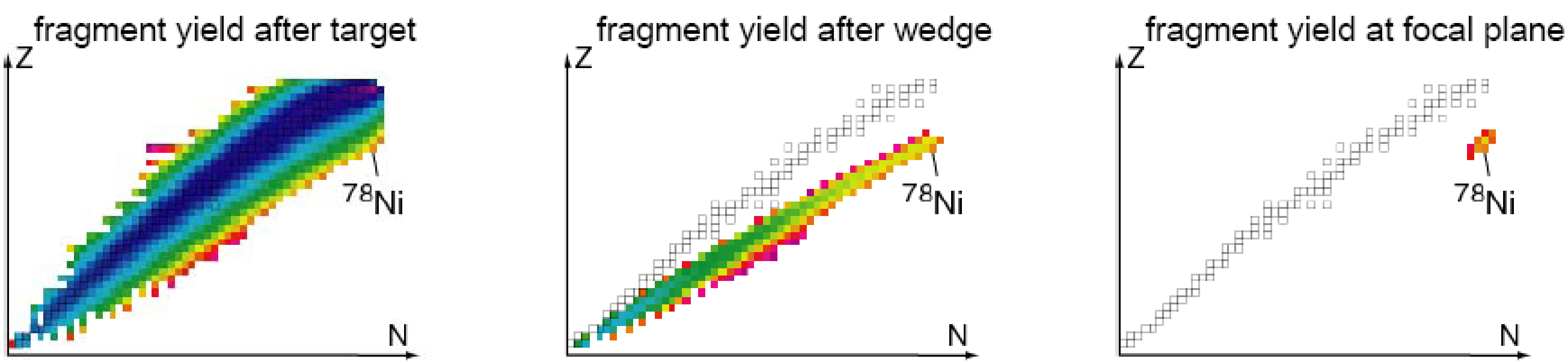
Cyclotron gas stopper



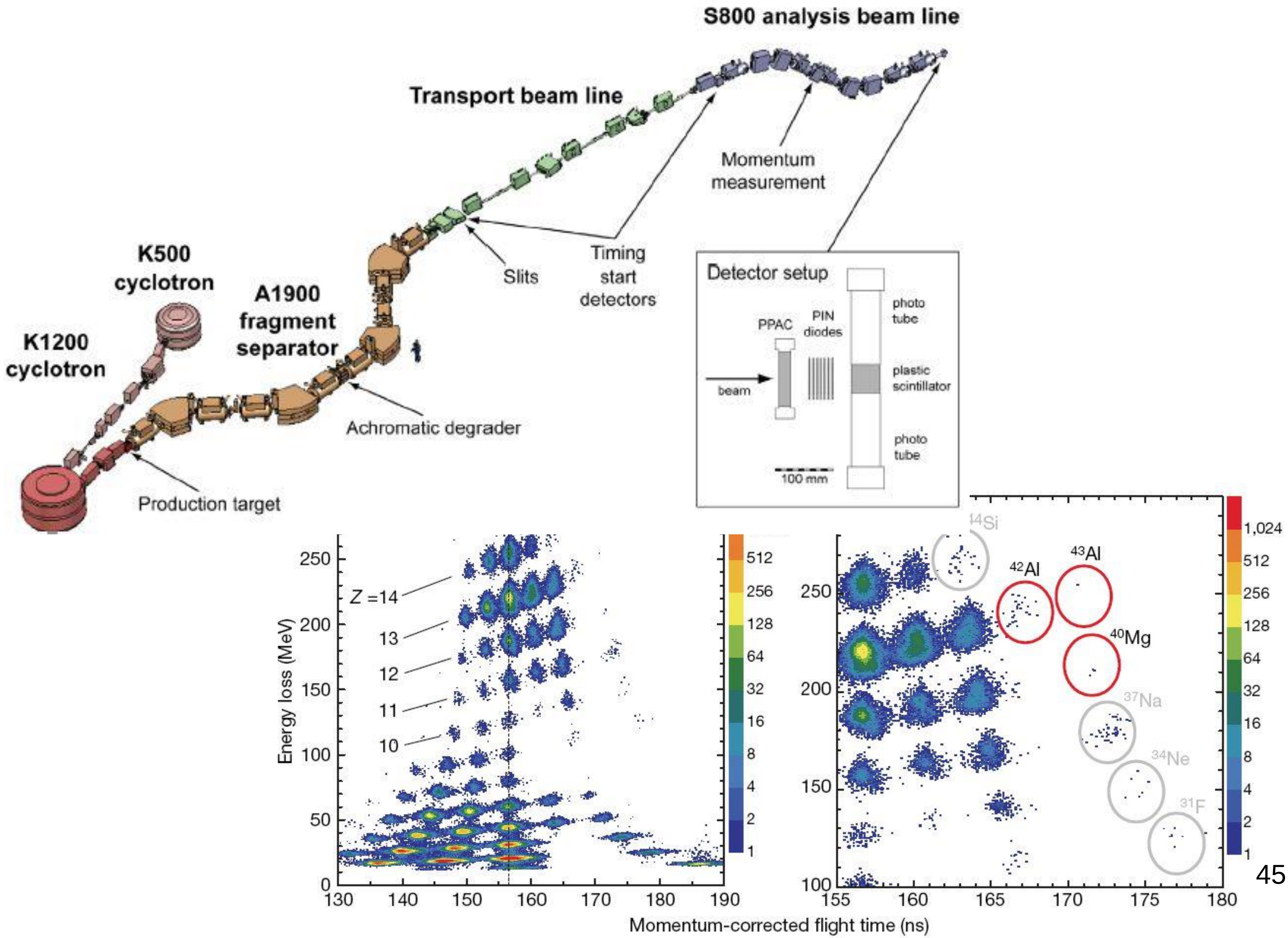
How to identify?

Michigan State University (USA)

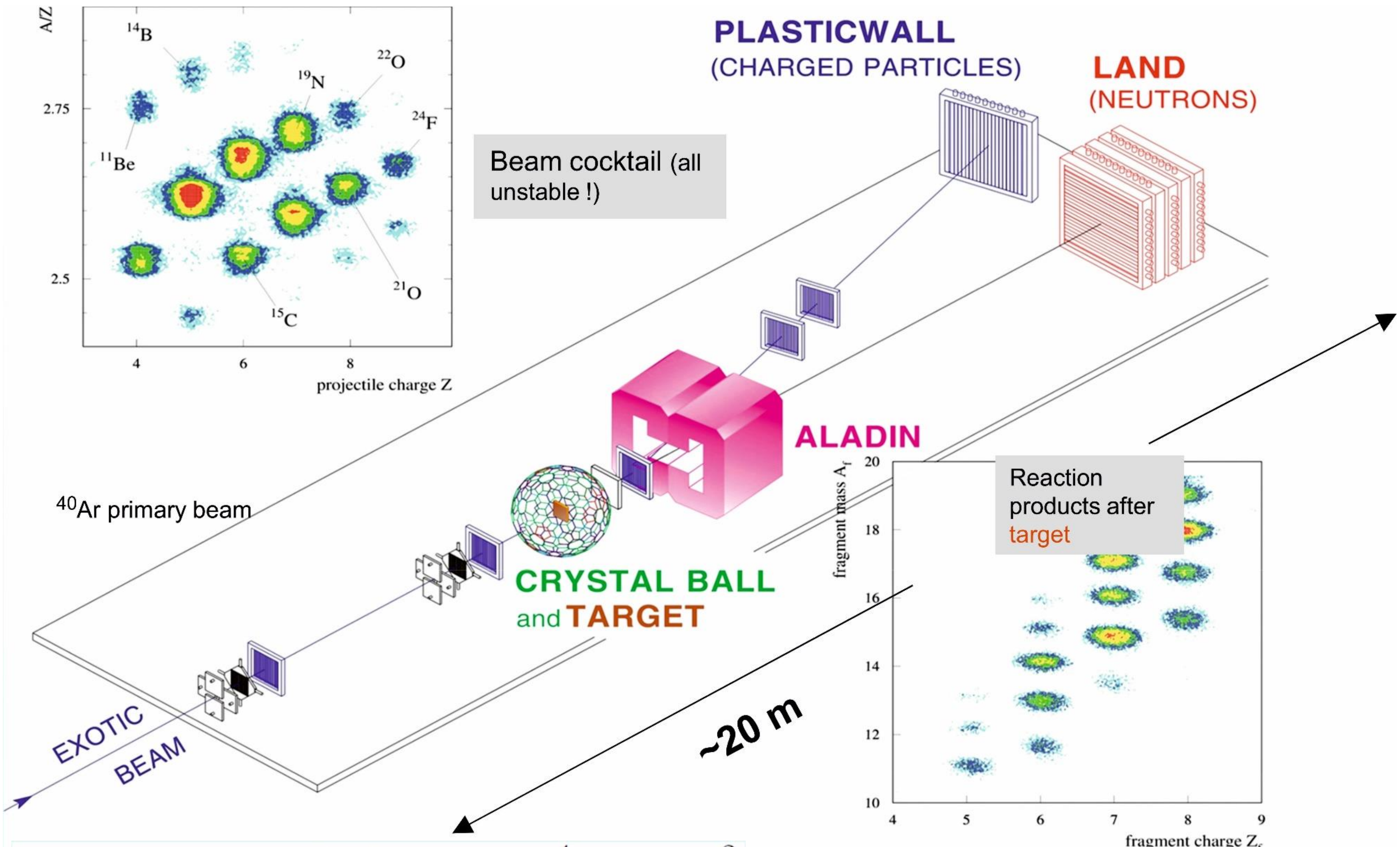




Example: ^{40}Mg Production, 120 pnA ^{48}Ca 140 MeV/u

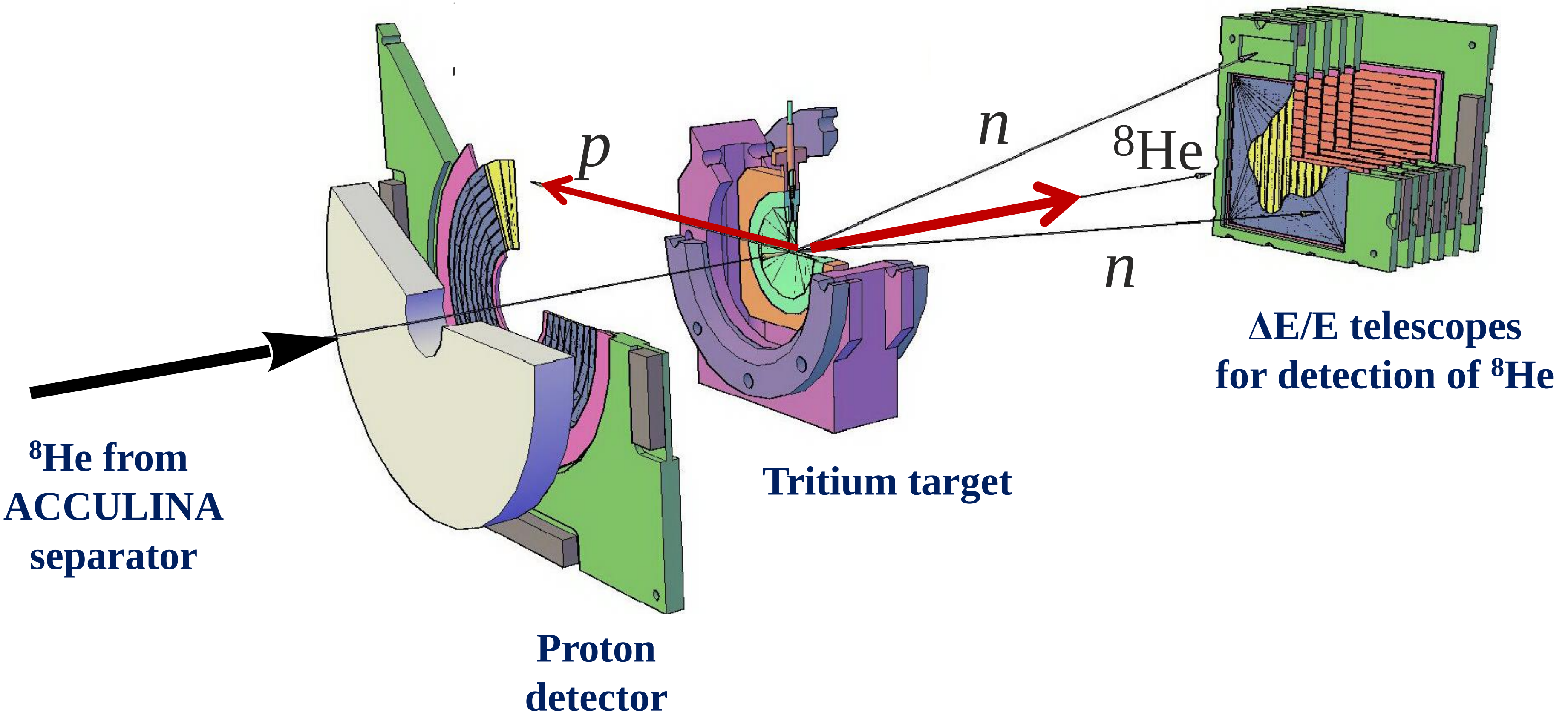


Kinematical complete experiments

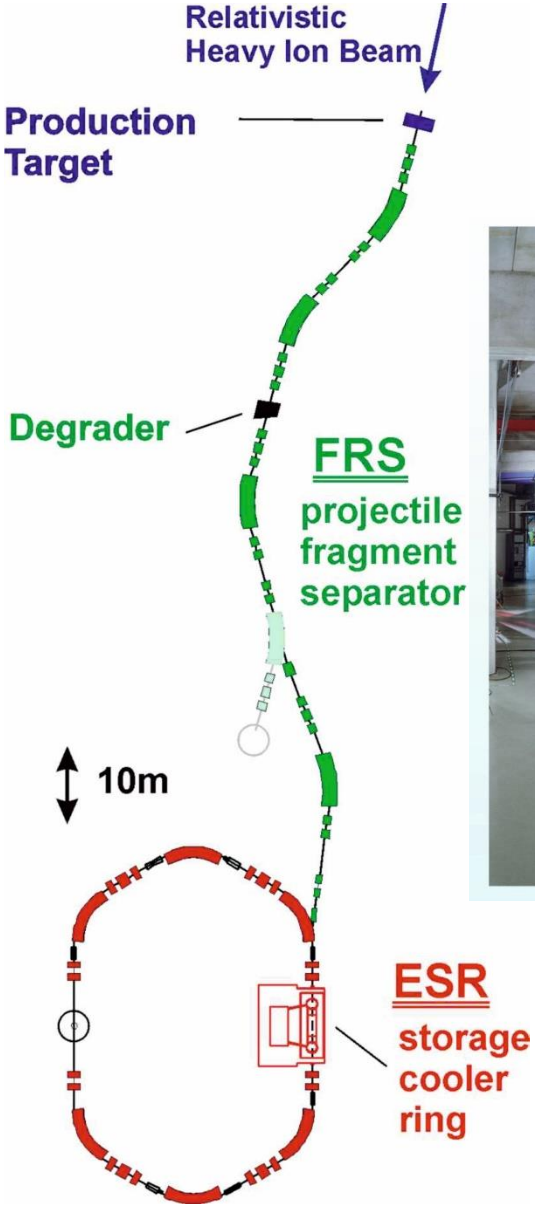


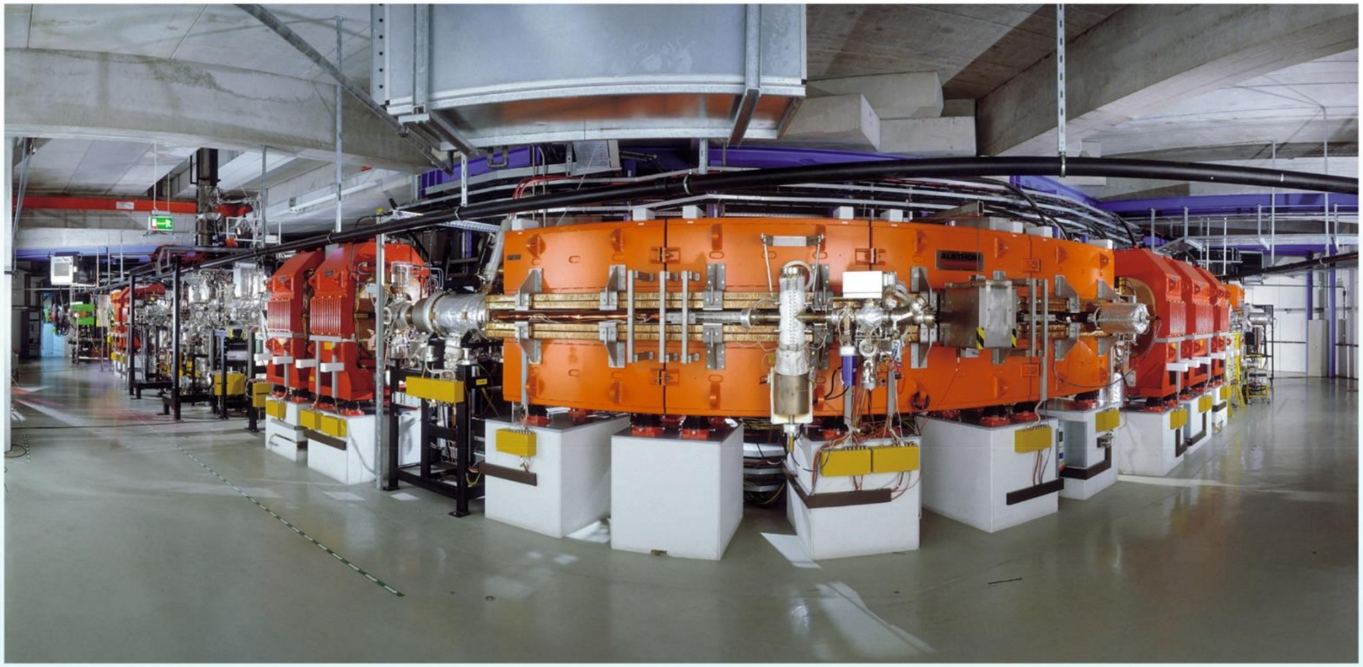
$$m^* - M = \sum_{i<j} \frac{E_i E_j - m_i m_j c^4 - \boldsymbol{p}_i \boldsymbol{p}_j c^2}{M c^4}$$

Detector system for identification of ^{10}He produced in reaction $^{8}He(t,p)$

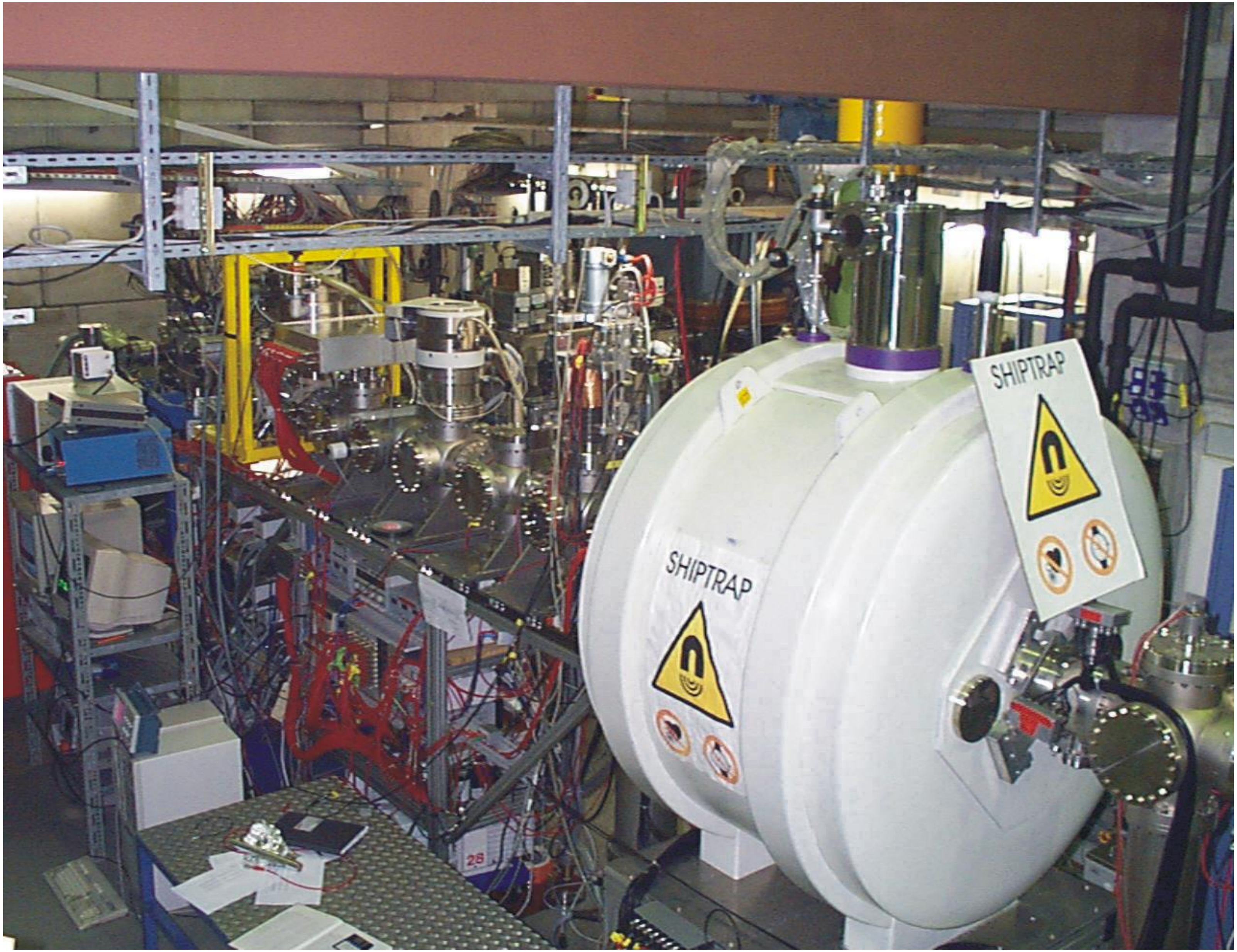


Storage-ring mass spectrometry





SHIP-trap

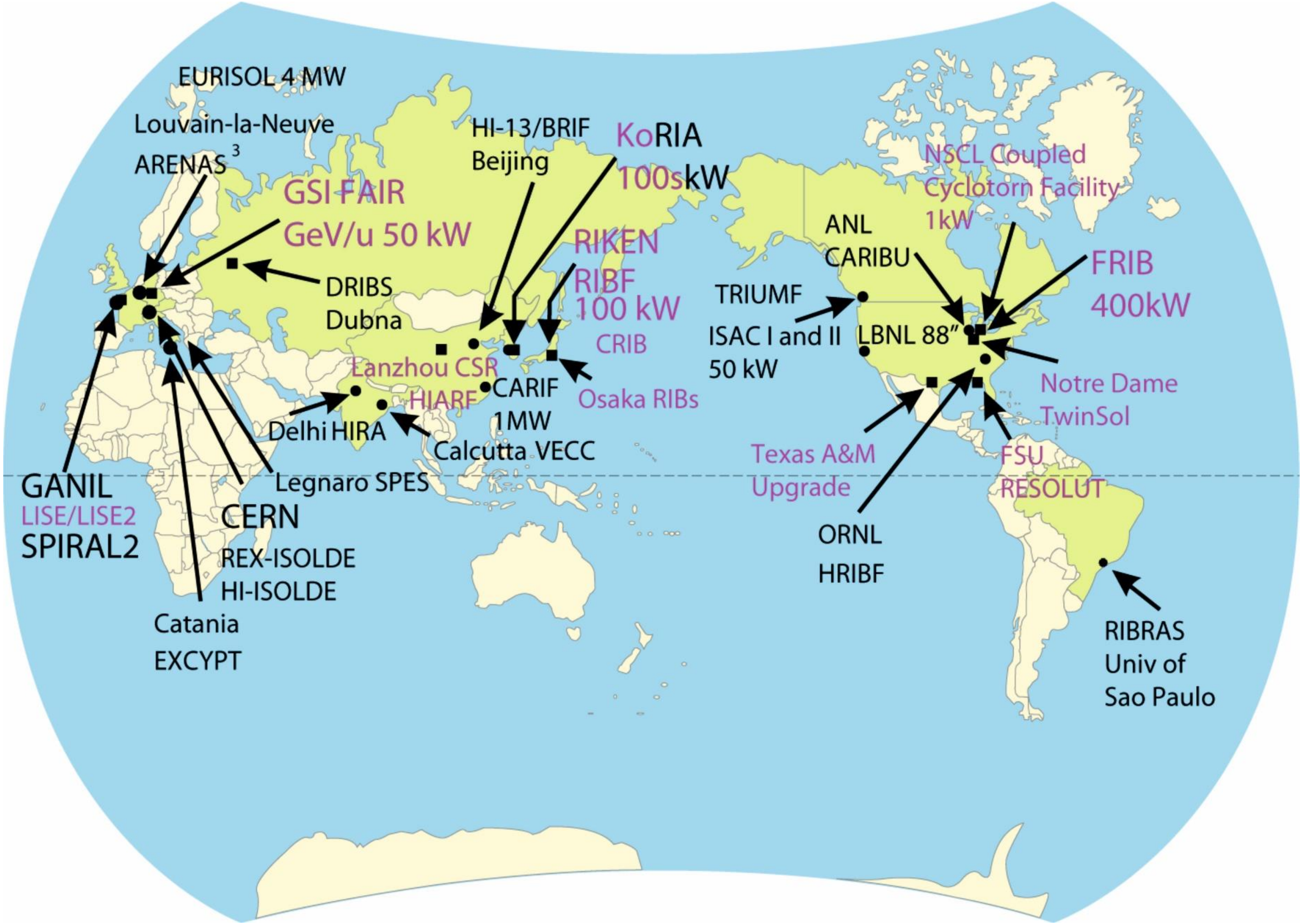


New focal plane detector GABRIELA

GABRIELA - Gamma Alpha Beta Recoil Investigation with the Electromagnetic Analyser

Summary

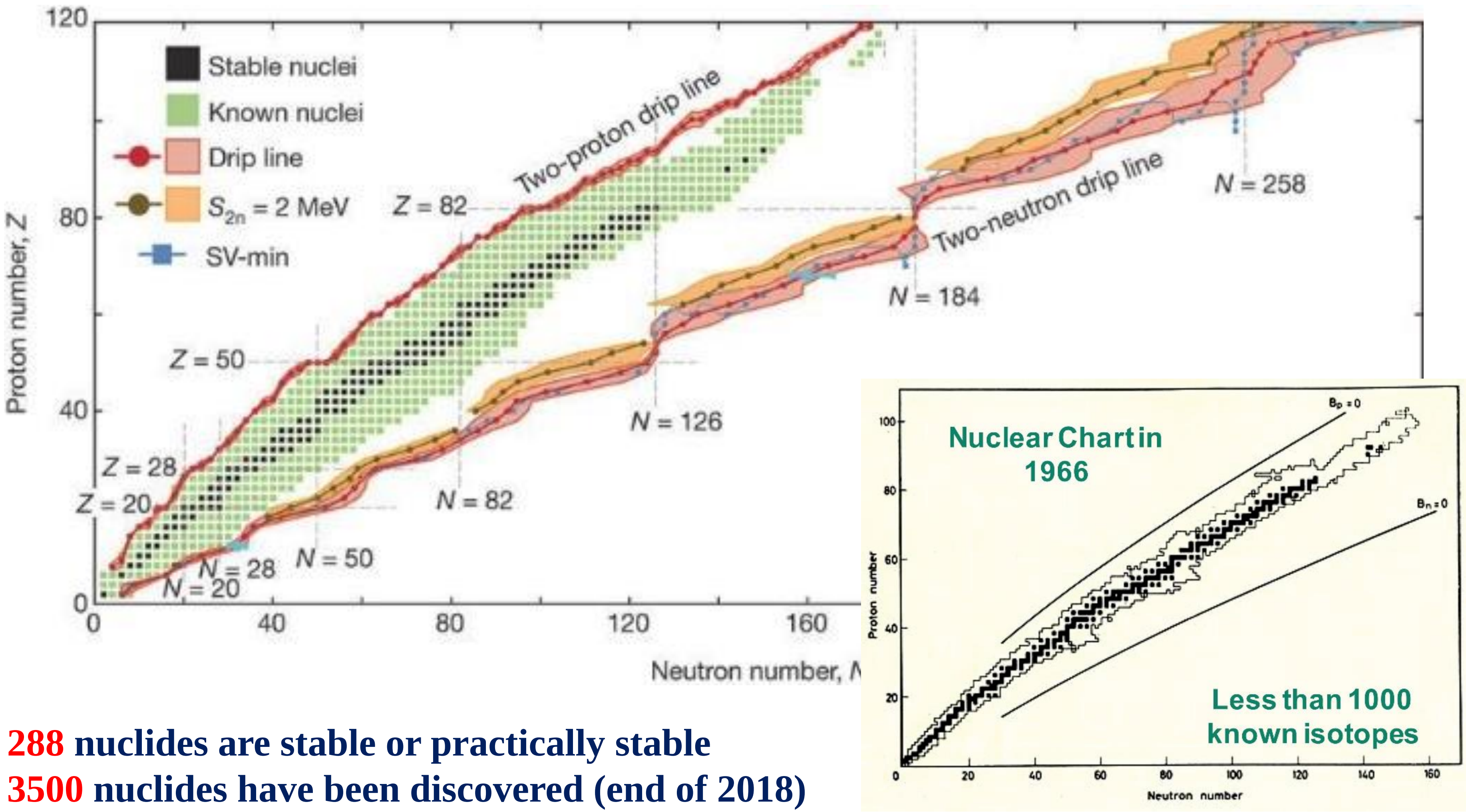
World view of rare isotope facilities



In-flight production, **in target production**

The limits of the nuclear landscape

J. Erler, et al., doi:10.1038/nature11188



288 nuclides are stable or practically stable
3500 nuclides have been discovered (end of 2018)
9035 nuclides with 2≤ Z≤ 120 are predicted to be bound

Summary

- **More than 3000 new nuclides have been discovered, more than 6000 of most exotic nuclei are awaiting to be discovered.**

- **The studies of exotic nuclei are especially important for nuclear structure, fundamental interactions and astro-physics.**

- **The next–generation facilities will provide excellent possibilities for research and education.**

- **There are many extremely technical problems on the way to new nuclei which must be solved by the next-generation scientists.**

THANK YOU FOR YOUR ATTENTION !