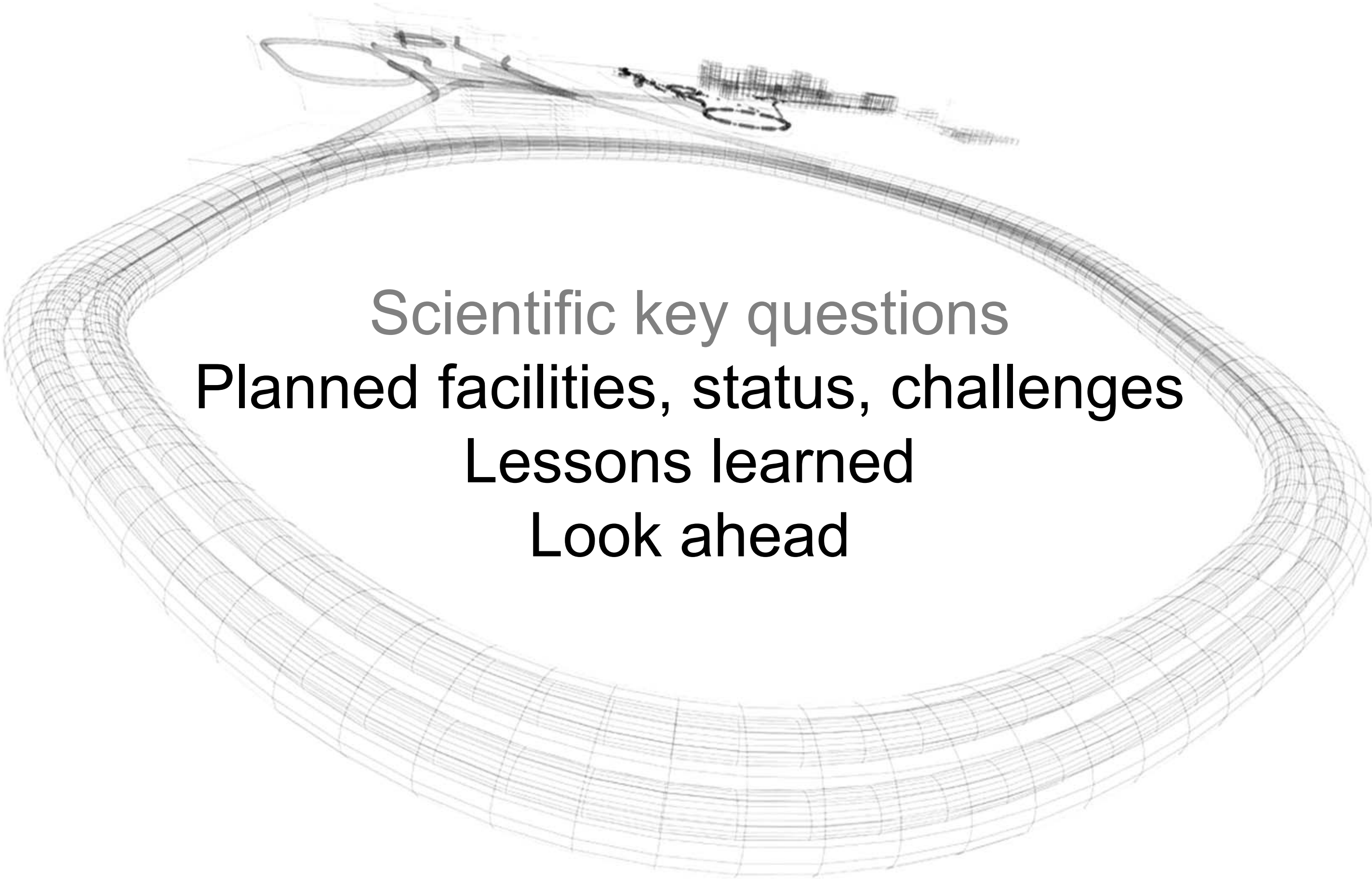
Next-generation facilities for research with exotic nuclei

Christoph Scheidenberger

GSI and FAIR



Scientific key questions

Planned facilities, status, challenges

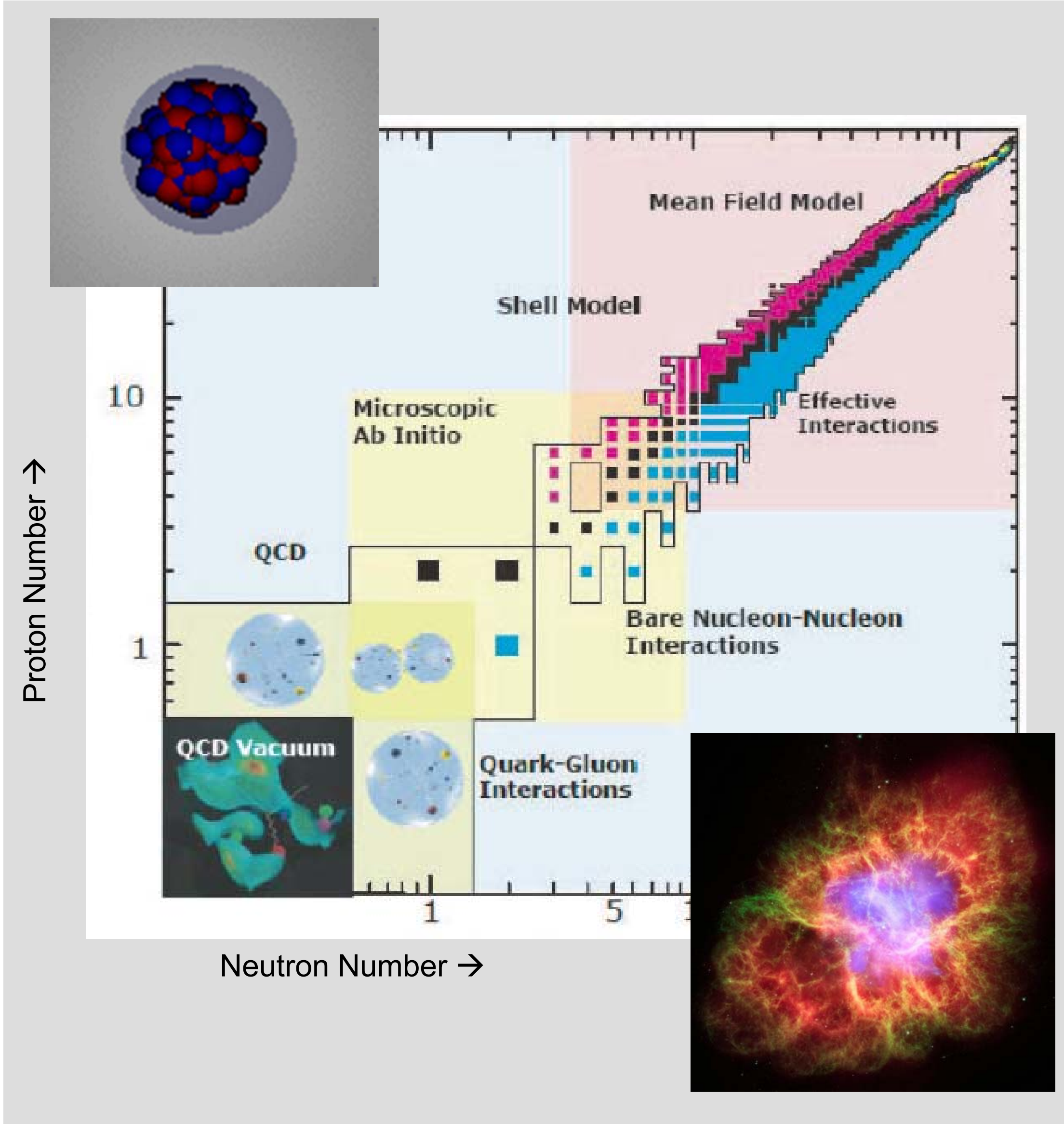
Lessons learned

Look ahead

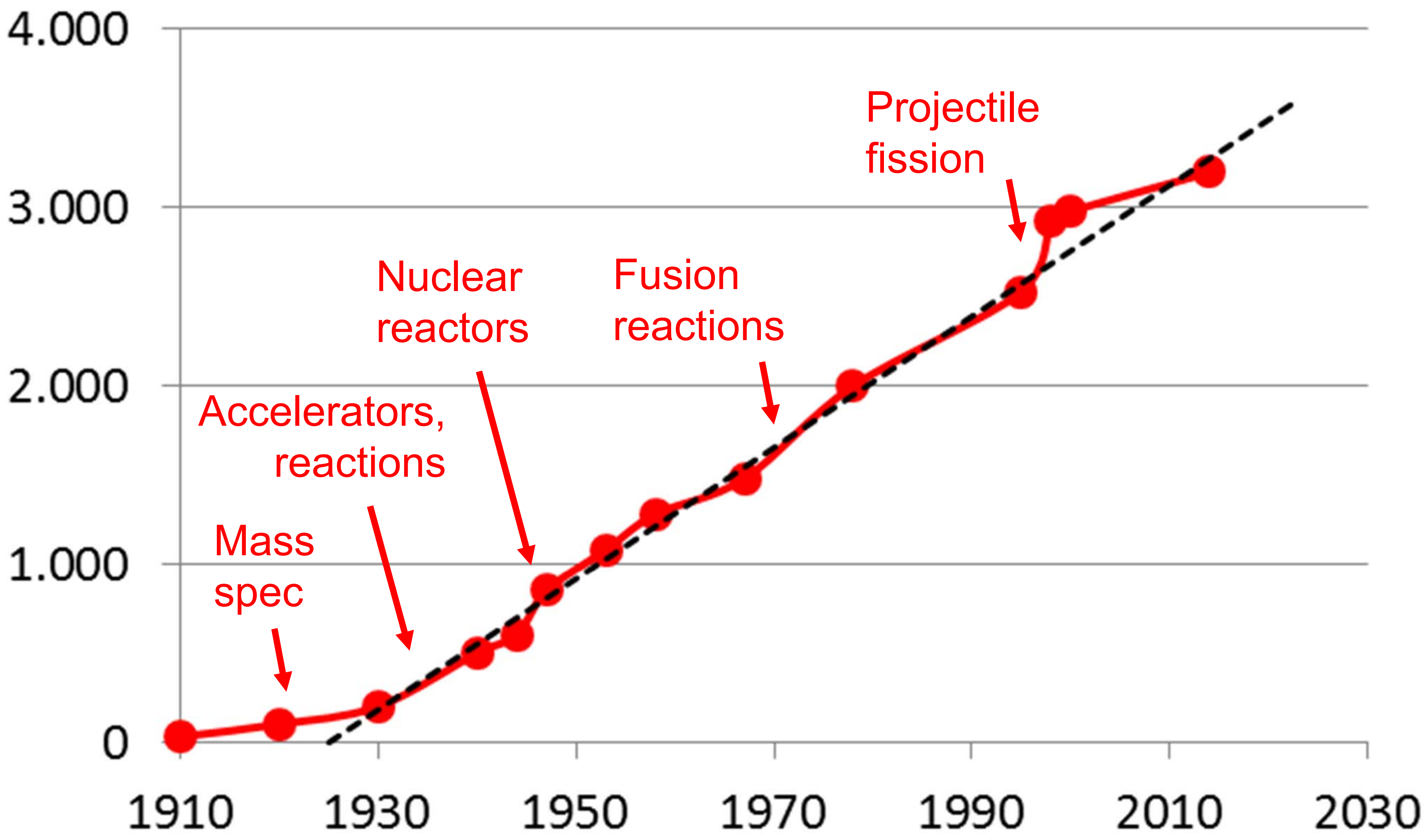
Exotic nuclei, nuclear astrophysics, superheavy elements

- Mission
  - Unified picture of the nucleus
  - Limits of nuclear existence
  - Origin of chemical elements

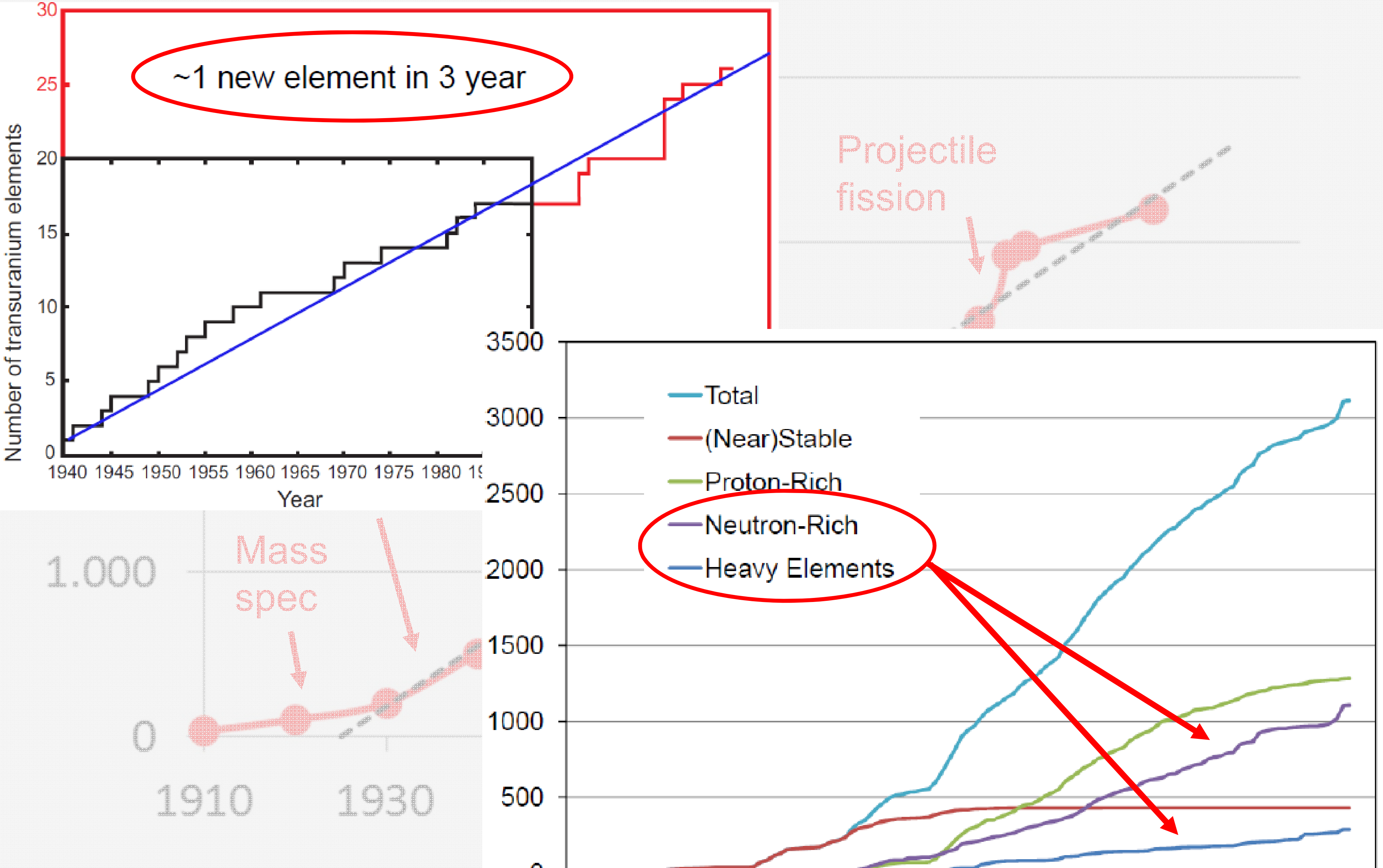
- Approach
  - Explore unknown territory
  - Intense exotic nuclear beams
  - Cutting-edge instruments



Isotope and element discoveries

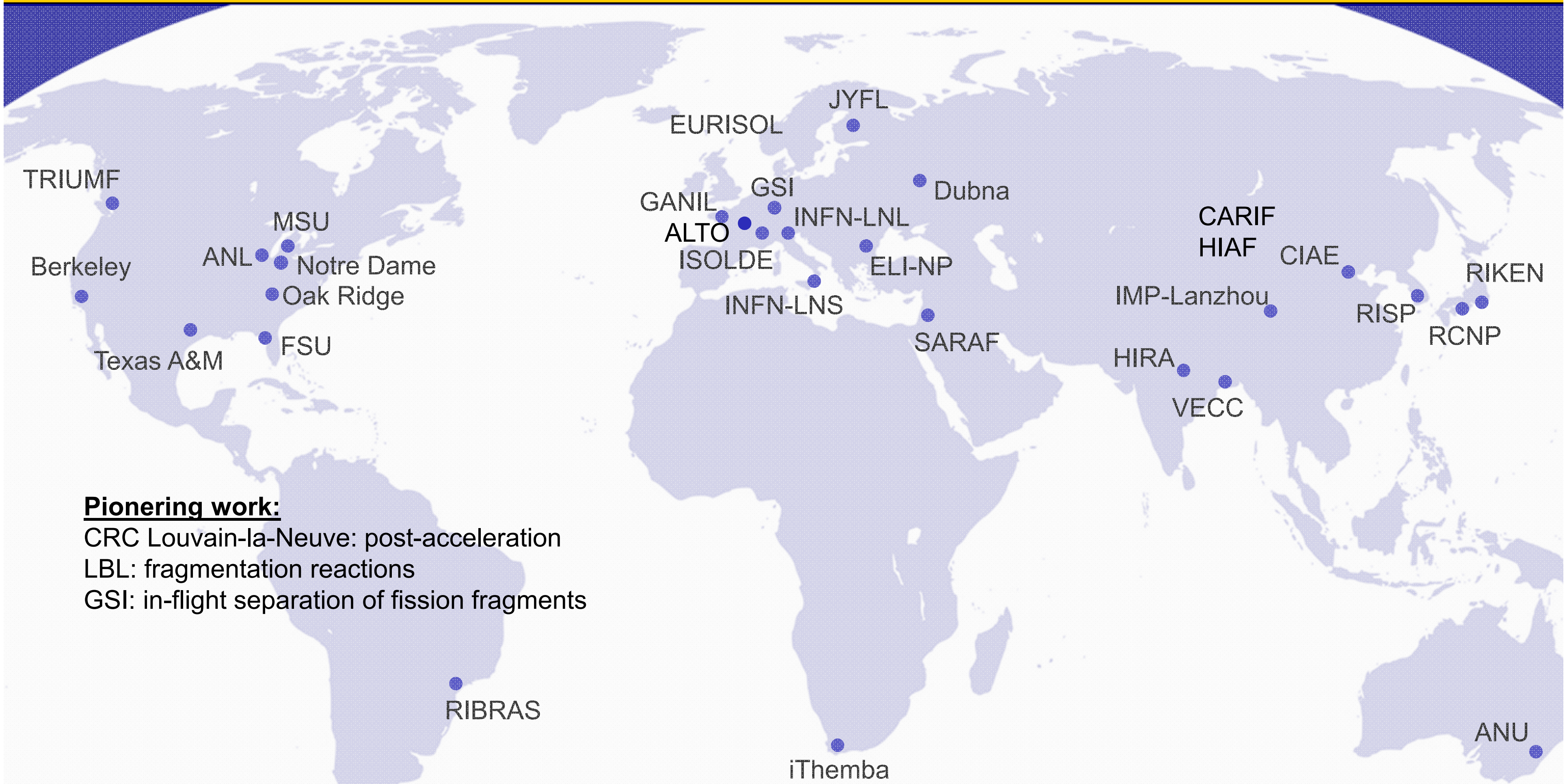


Isotope and element discoveries



Courtesy: M. Thoennessen

Facilities worldwide



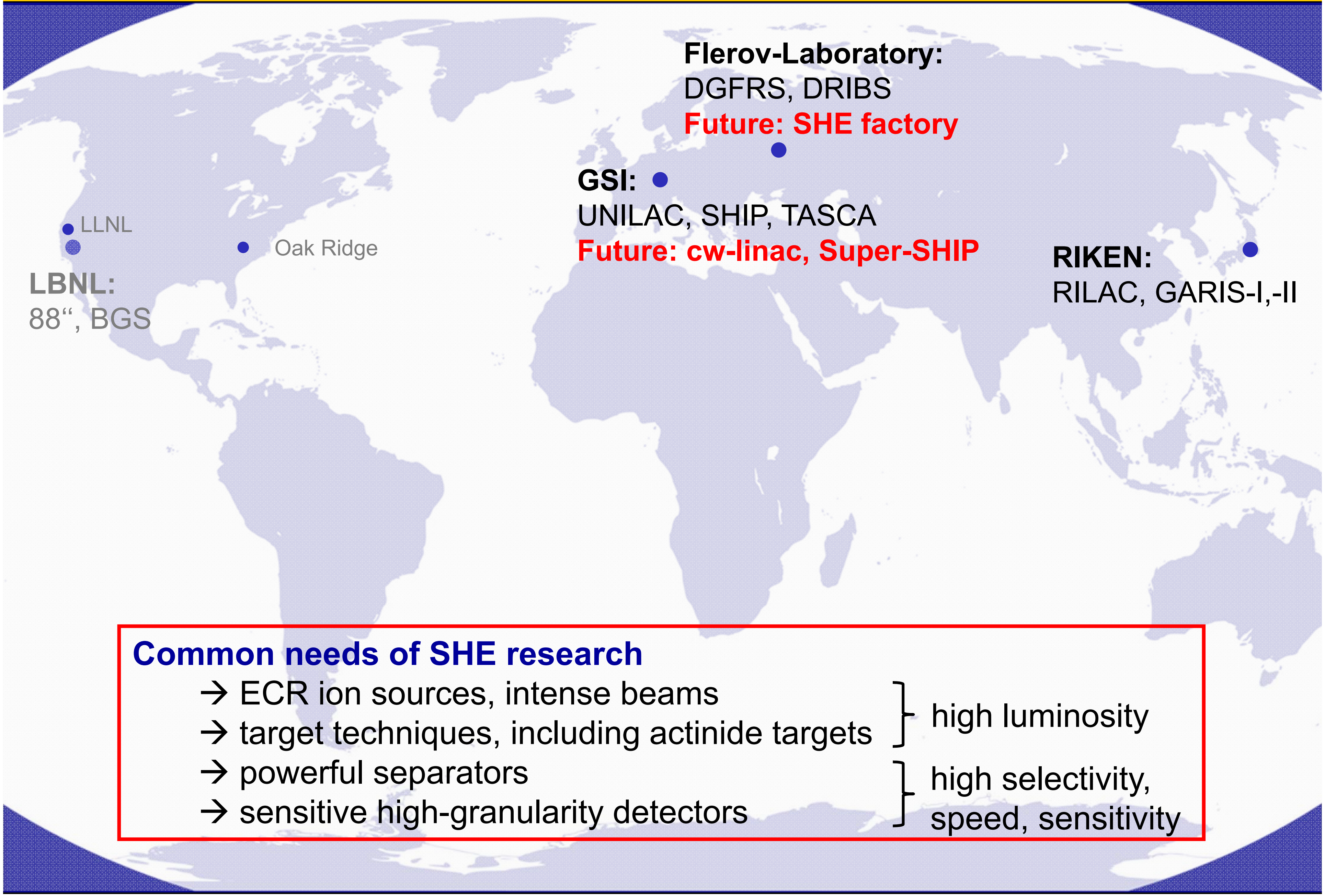
Pionering work:

CRC Louvain-la-Neuve: post-acceleration
LBL: fragmentation reactions
GSI: in-flight separation of fission fragments

It is the goal common to all existing and future facilities to

→ increase the number of known isotopes
→ extend the scientific reach
→ elaborate refined instrumentation
→ develop new ideas and applications

Stable beam facilities for SHE research



Common needs of SHE research

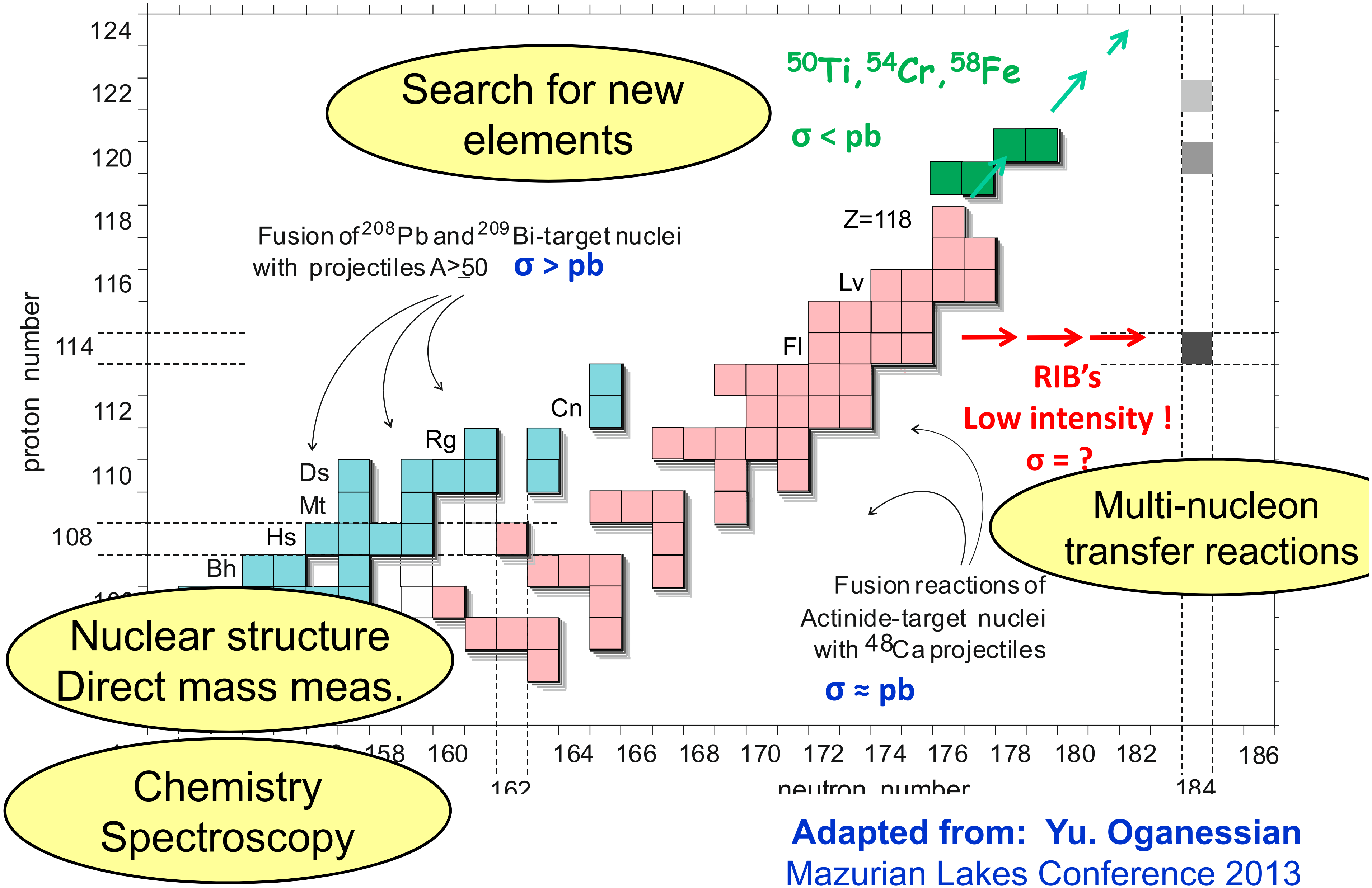
- → ECR ion sources, intense beams
- → target techniques, including actinide targets

} high luminosity

- → powerful separators
- → sensitive high-granularity detectors

} high selectivity, speed, sensitivity

SHE future perspectives and strategy



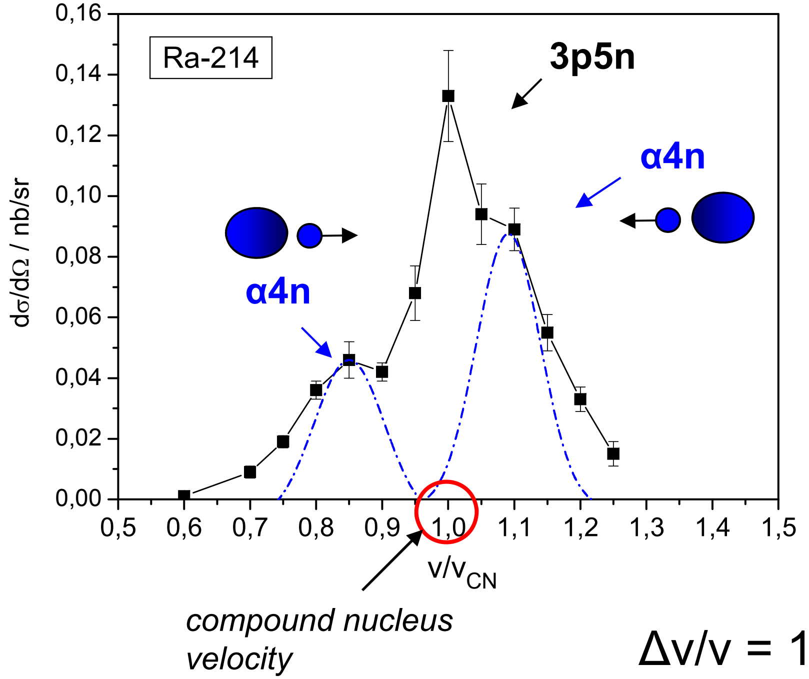
Adapted from: Yu. Oganessian
Mazurian Lakes Conference 2013

Challenge: new reactions for SHE research

1) Kinematical studies for multi-nucleon transfer reactions:

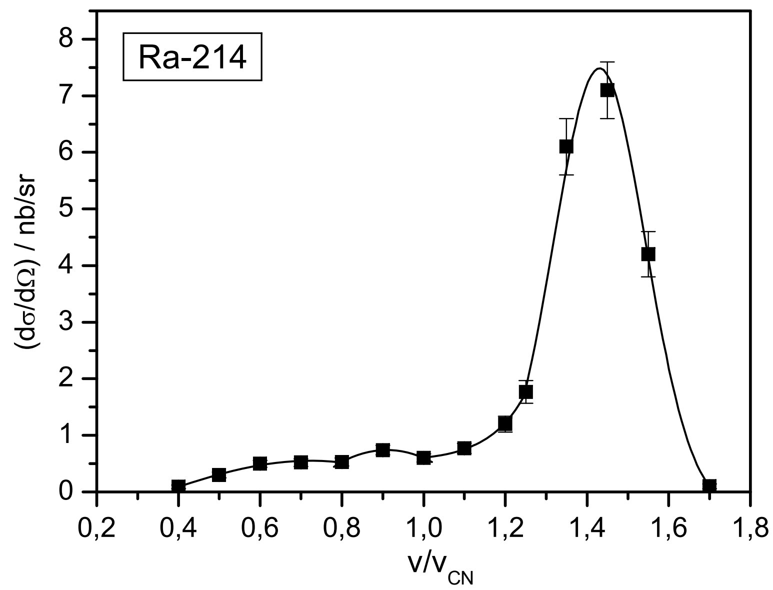
example for fusion-evaporation

$^{25}Mg + ^{197}Au \rightarrow ^{222}Pa^*$ (E^*=64 MeV)



example for a transfer channel:

$^{25}Mg + ^{206}Pb \rightarrow ^{13}C + ^{218}Ra$



$\Delta v/v$ = 10% (FWHM)

Courtesy of S. Heinz

2) Reaction studies with radioactive beams

E.g.: study of di-nuclear systems $^{A}Rb + ^{209}Bi$ ($Z_1 + Z_2 = 120$) at HIE-ISOLDE

(approved proposal, Dubna-GSI collaboration)

Beamtime budgets at SHE laboratories (*)

	FLNR Dubna	RIKEN	GSI
Beam on target (days/ year)	~ 120	~ 300	~ 100
Duty factor	100% (DC)	100% (DC)	25% (pulsed beam)
Beam intensity on target	≈ 1.0 pμA (^{48}Ca) ≈ 0.5 pμA (^{58}Fe)	≈ 0.7 pμA (^{48}Ca, ^{58}Fe, ^{70}Zn)	≈ 1.2 pμA (^{48}Ca) ≈ 0.8 pμA (^{50}Ti)
projectiles / year (as of today)	**≈ 0.5x10^{20} (^{48}Ca, ^{58}Fe)**	**≈ 1.1x10^{20} (^{48}Ca, ^{64}Ni, ^{70}Zn)**	**≈ 0.6x10^{20} (^{48}Ca) ≈ 0.4x10^{20} (^{50}Ti)**
Future: projectiles / year	**SHE factory: ≈ 1x10^{21} (^{48}Ca)**	**upgrade!**	**sc cw-linac: ≈ 3x10^{21} (^{48}Ca)**

(*) all numbers represent typical average values !

SHE future projects

→ dedicated linear accelerators needed!

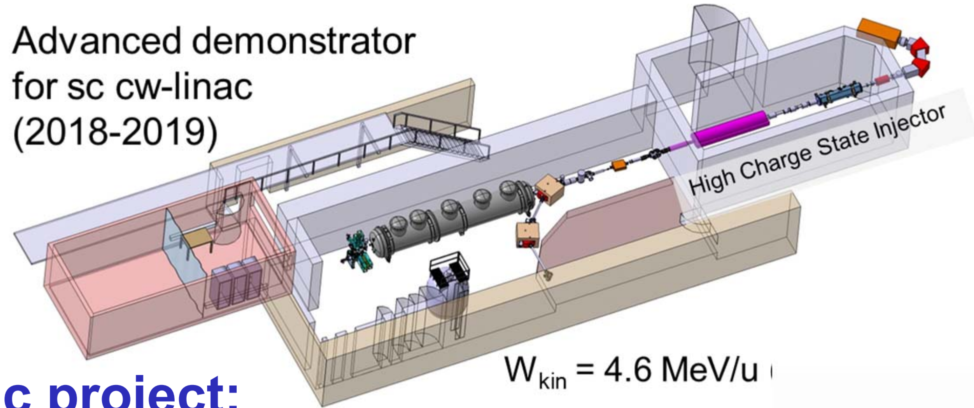
Dubna

SHE factory:

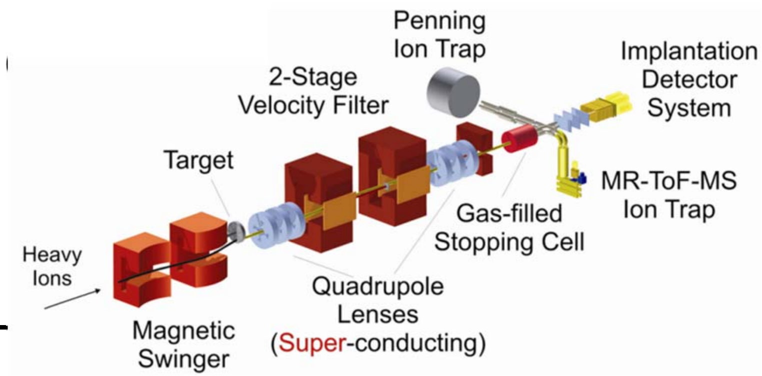
- **Primary beams: x10...30**
  (e.g. Ca-48, Ti-50, Ni-64)
- **Isotope production: x10**
  (e.g. Cm-248, Bk-249, Cf-251)
- **Improved setups: x2...5**

GSI / HIM

Advanced demonstrator
for sc cw-linac
(2018-2019)



sc velocity filter

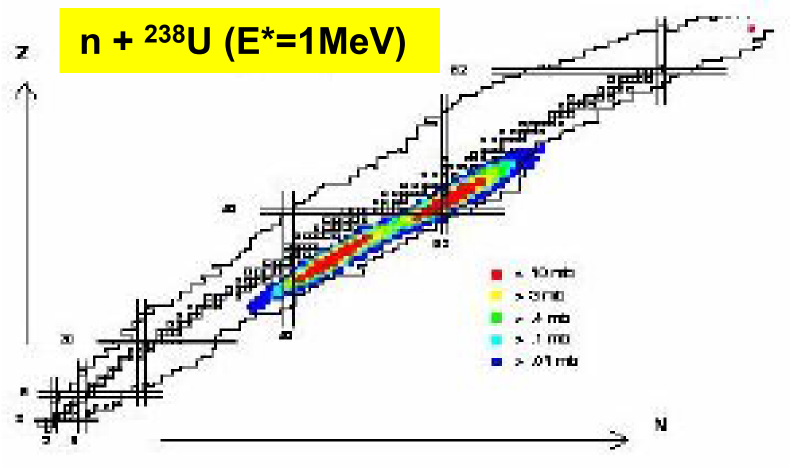


cw-linac project:

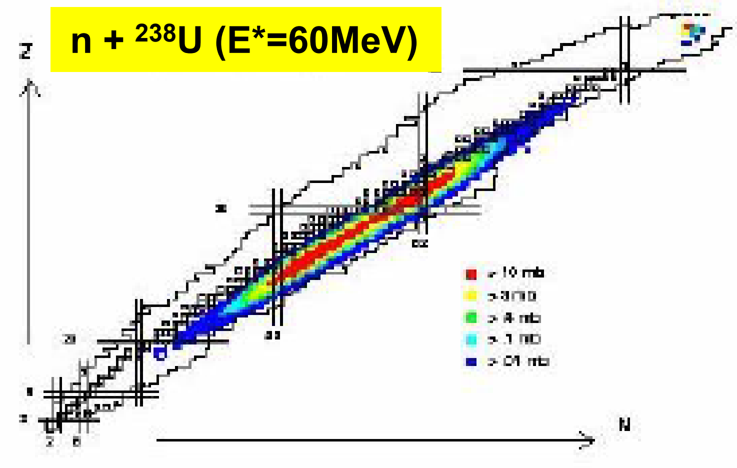
*** sc ECR: x5**
*** duty cycle: x4**
*** Super-SHIP: x2**

Production of n-rich isotopes: different approaches

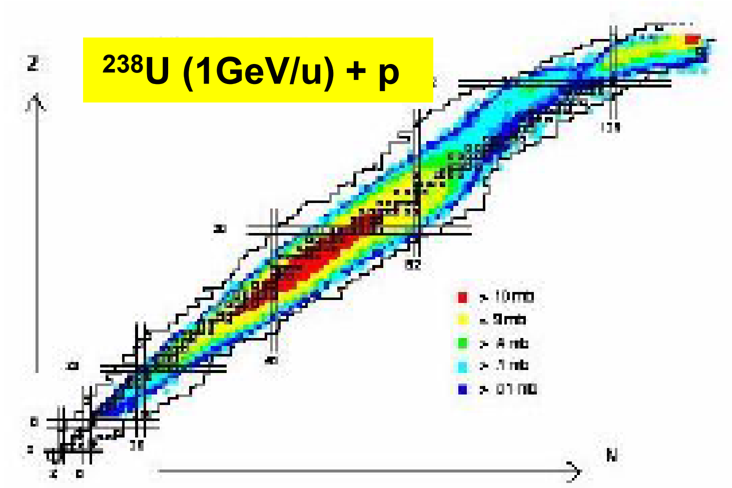
Reactor/Bremsstrahlung



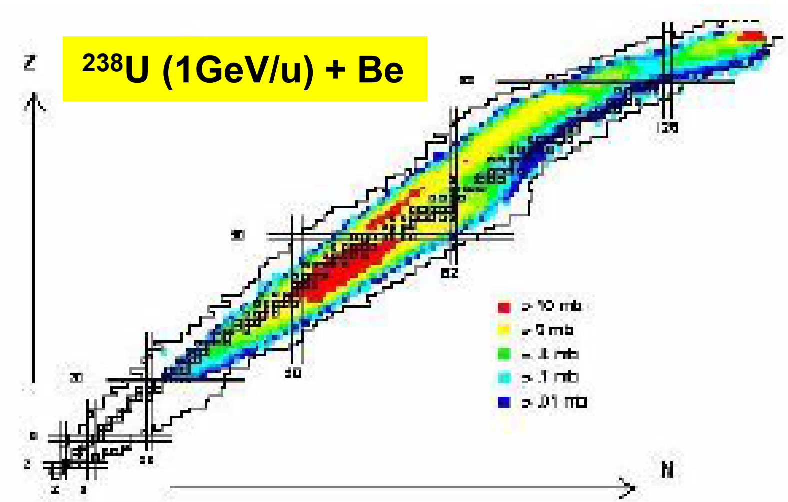
Converter(d→n)



Proton induced spallation



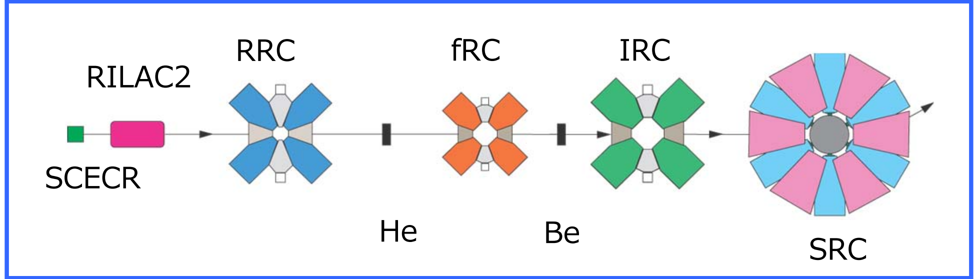
In-flight fragmentation



Courtesy: J. Benlliure

The EXAMPLE: RIKEN-RIBF

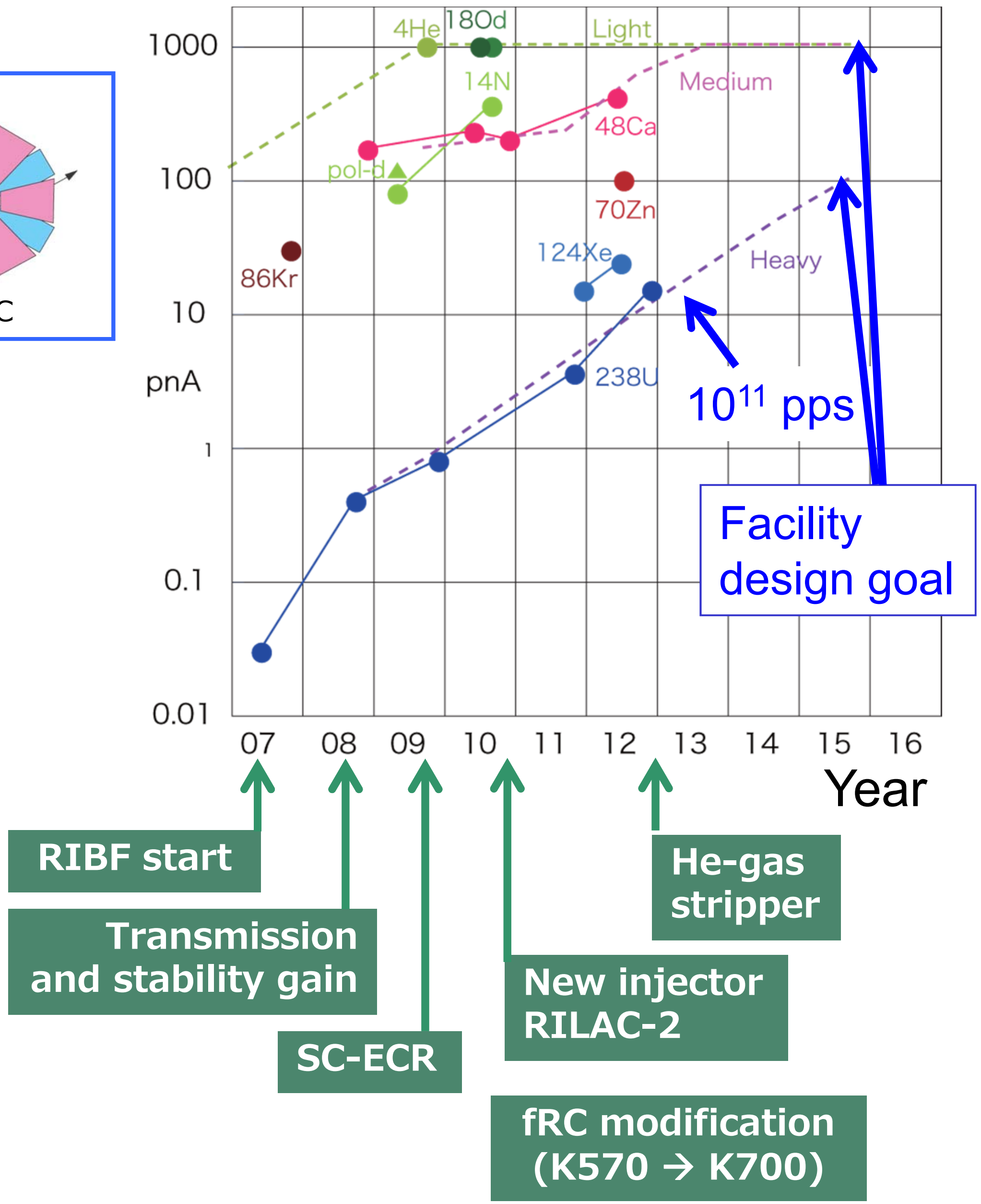
Configuration of accelerator chain



see Okuno, Fukunishi, Kamigaito, Prog. Theor. Exp. Phys. 03C002 (2012)

Design goal for light beams reached!
Max. beam power:
6 kW (^{18}O – 345 MeV/u)
7 kW (^{48}Ca) → ~20 kW by 2015

Design goal for uranium beams:
100 pnA → reached in 2015 (?)



BigRIPS

- ZeroDegree spectrometer

  Forward spectrometer fixed at 0 deg.

- SAMURAI spectrometer

  Kinematical complete measurement

- SHARAQ spectrometer (by CNS)

  High-resolution measurement

- SLOWRI & PALIS: gas catchers

  See contribution by M. Wada

  Combine in-flight and ISOL schemes

- Rare RI ring: isochronous ring

  For TOF mass measurement

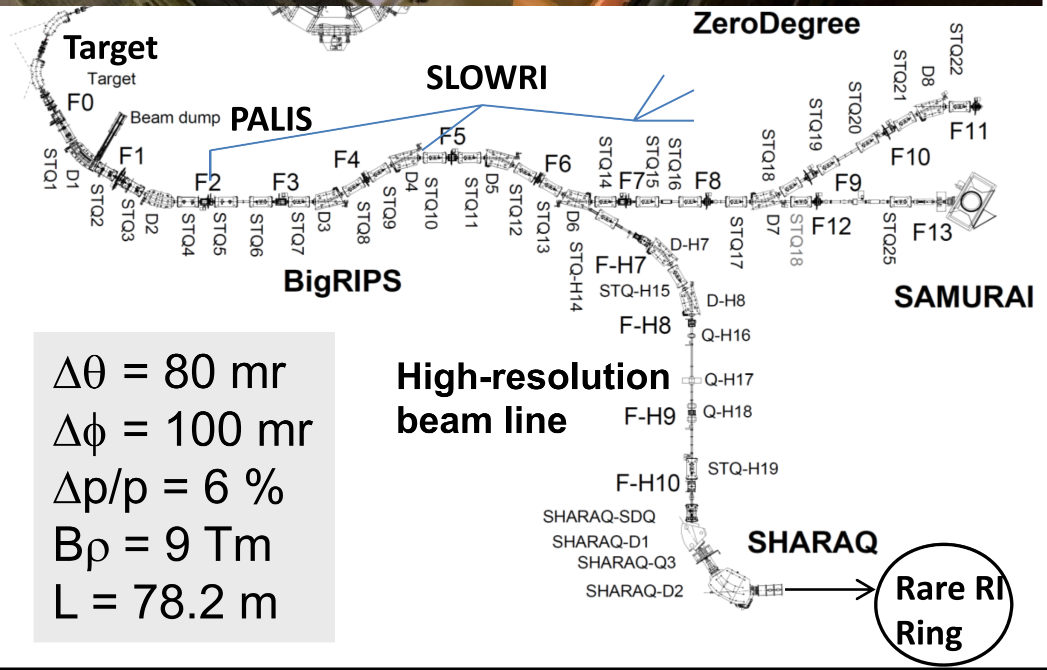
- SCRIT (Self-Confining RI target)

  Electron-RI scattering

- γ-ray array detectors (DALI2, ...)

  Gamma-ray spectroscopy

Courtesy of T. Kubo



$\Delta\theta$ = 80 mr

$\Delta\phi$ = 100 mr

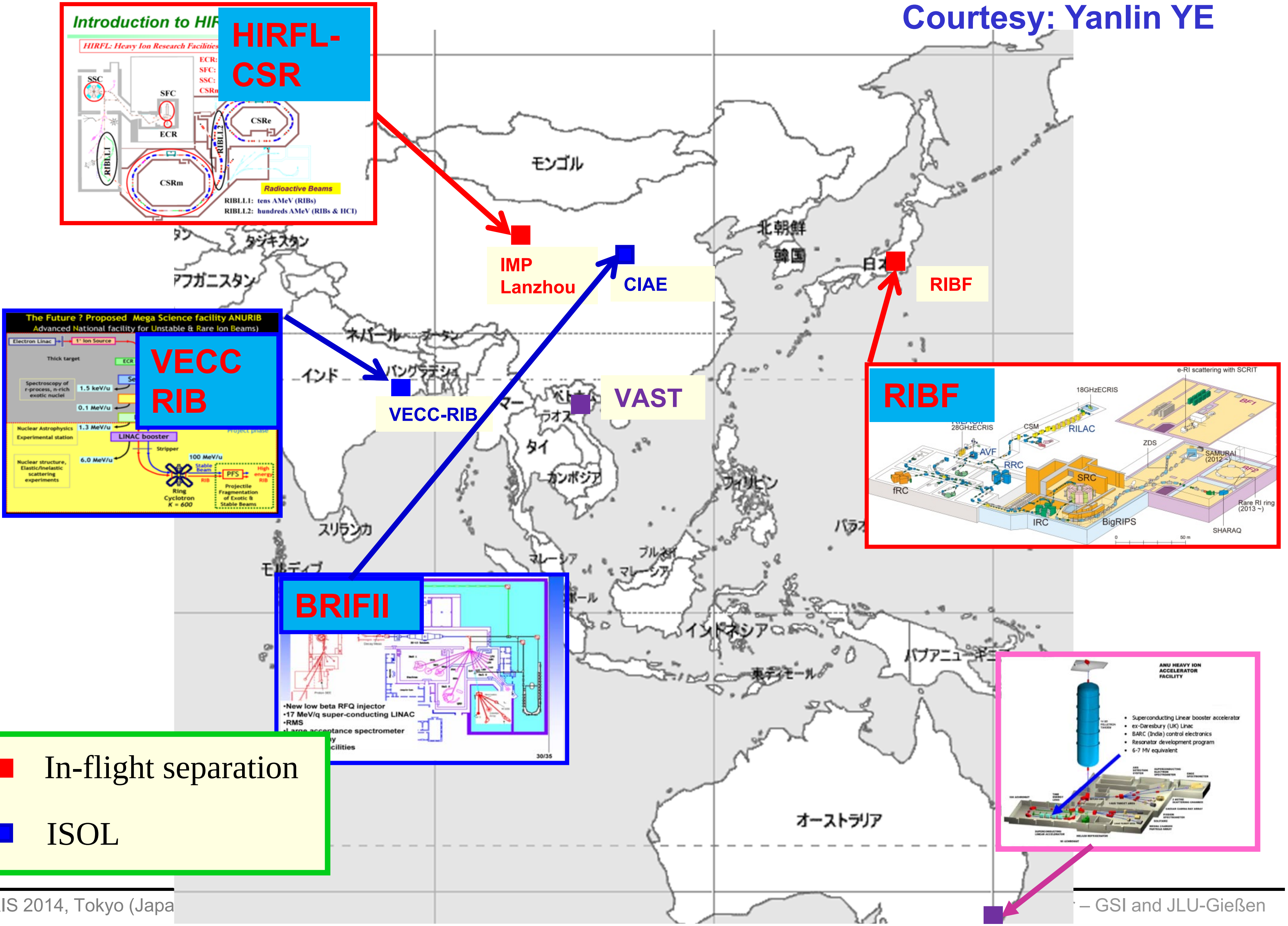
$\Delta p/p$ = 6 %

$B\rho$ = 9 Tm

L = 78.2 m

Exisiting RIB facilities in Asia and Australia

Courtesy: Yanlin YE



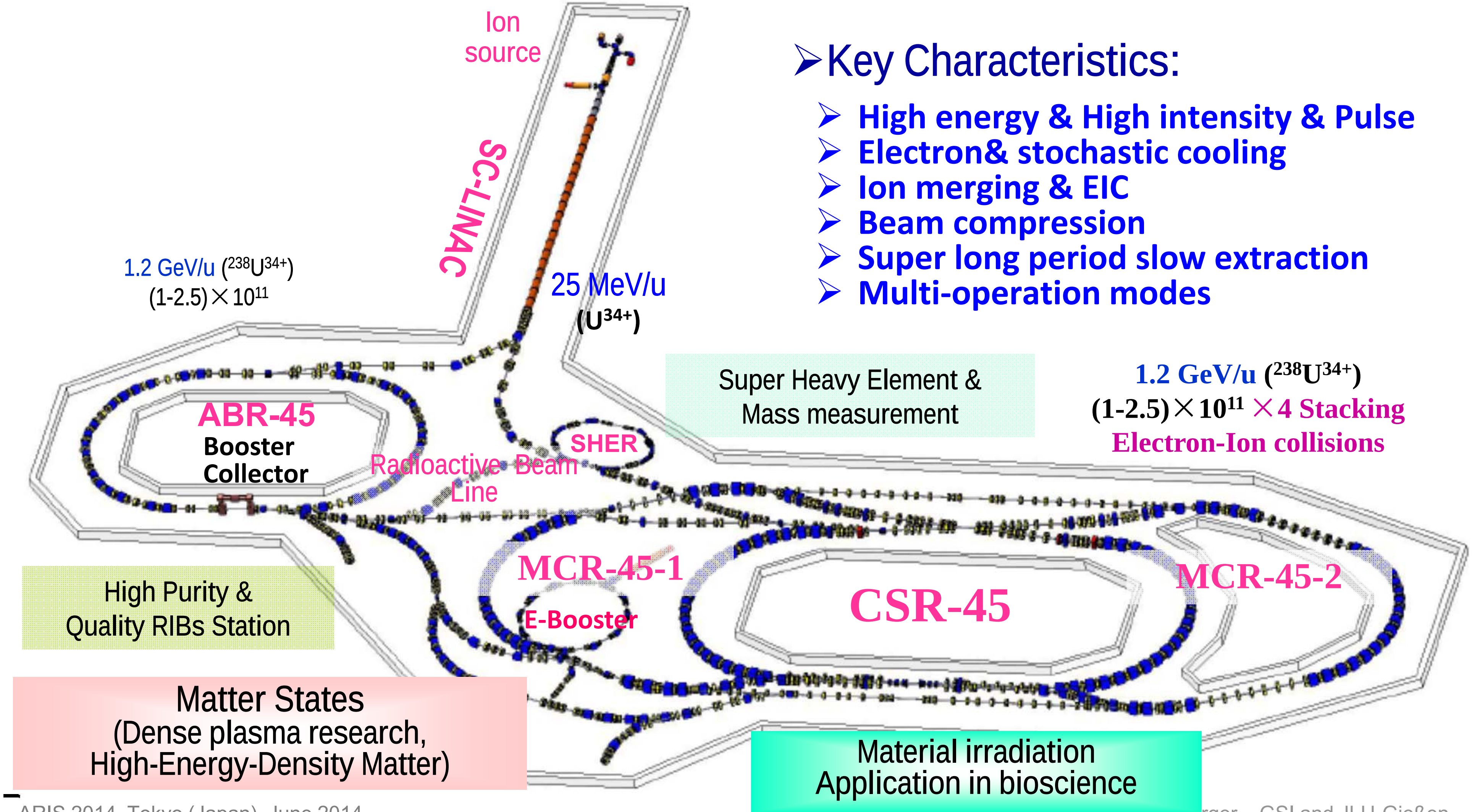
■ In-flight separation

■ ISOL

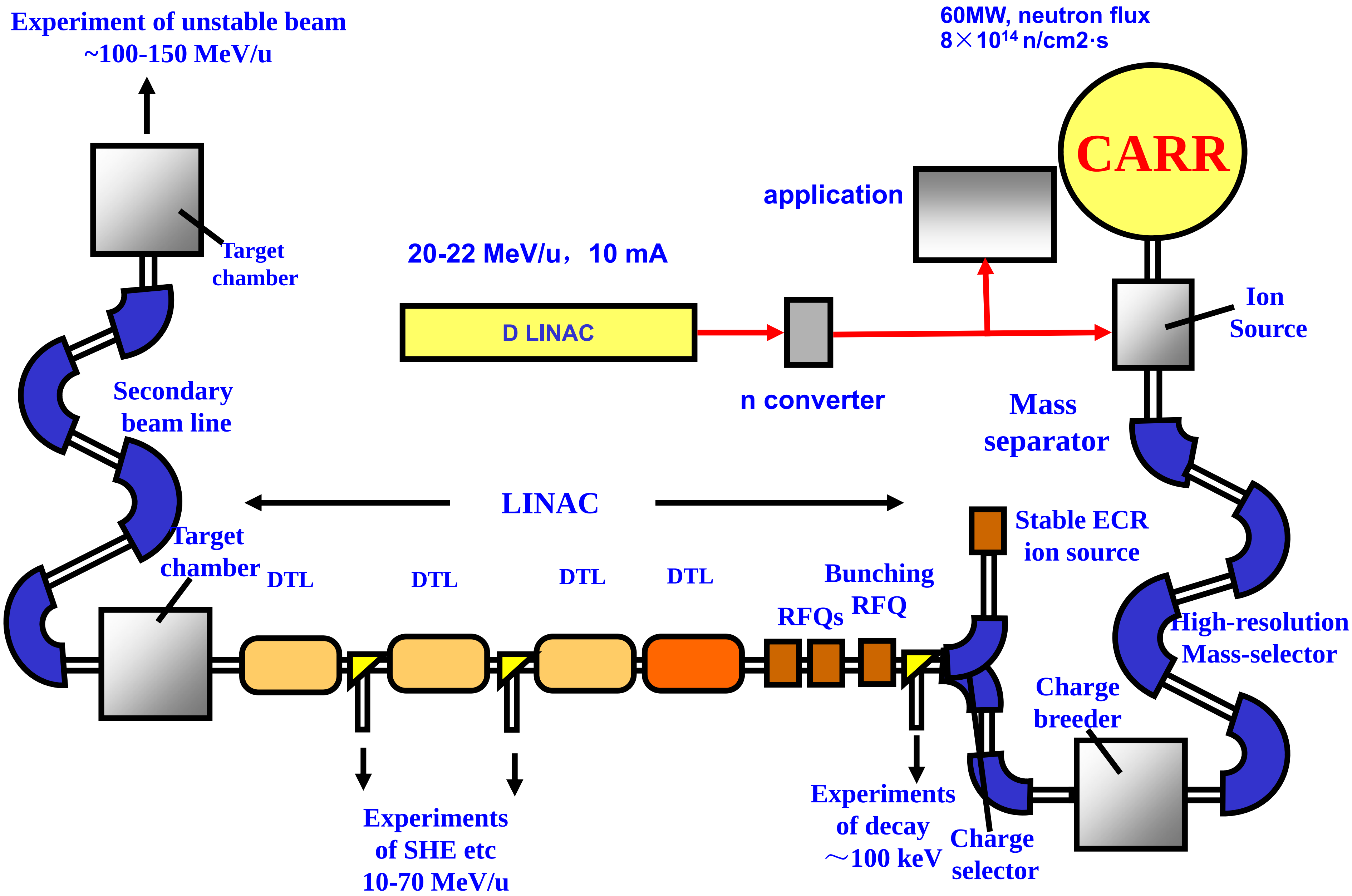
Lanzhou: HIAF(High-Intensity heavy ion Accelerator Facility)

- Accelerator Components:
  - High intensity ion source
  - High intensity pulse SC-Linac
  - Multi-function synchrotron
  - Unique shape storage ring system
  - Large acceptance radioactive beam line
  - Electron booster and storage ring

- Key Characteristics:
  - **High energy & High intensity & Pulse**
  - **Electron& stochastic cooling**
  - **Ion merging & EIC**
  - **Beam compression**
  - **Super long period slow extraction**
  - **Multi-operation modes**



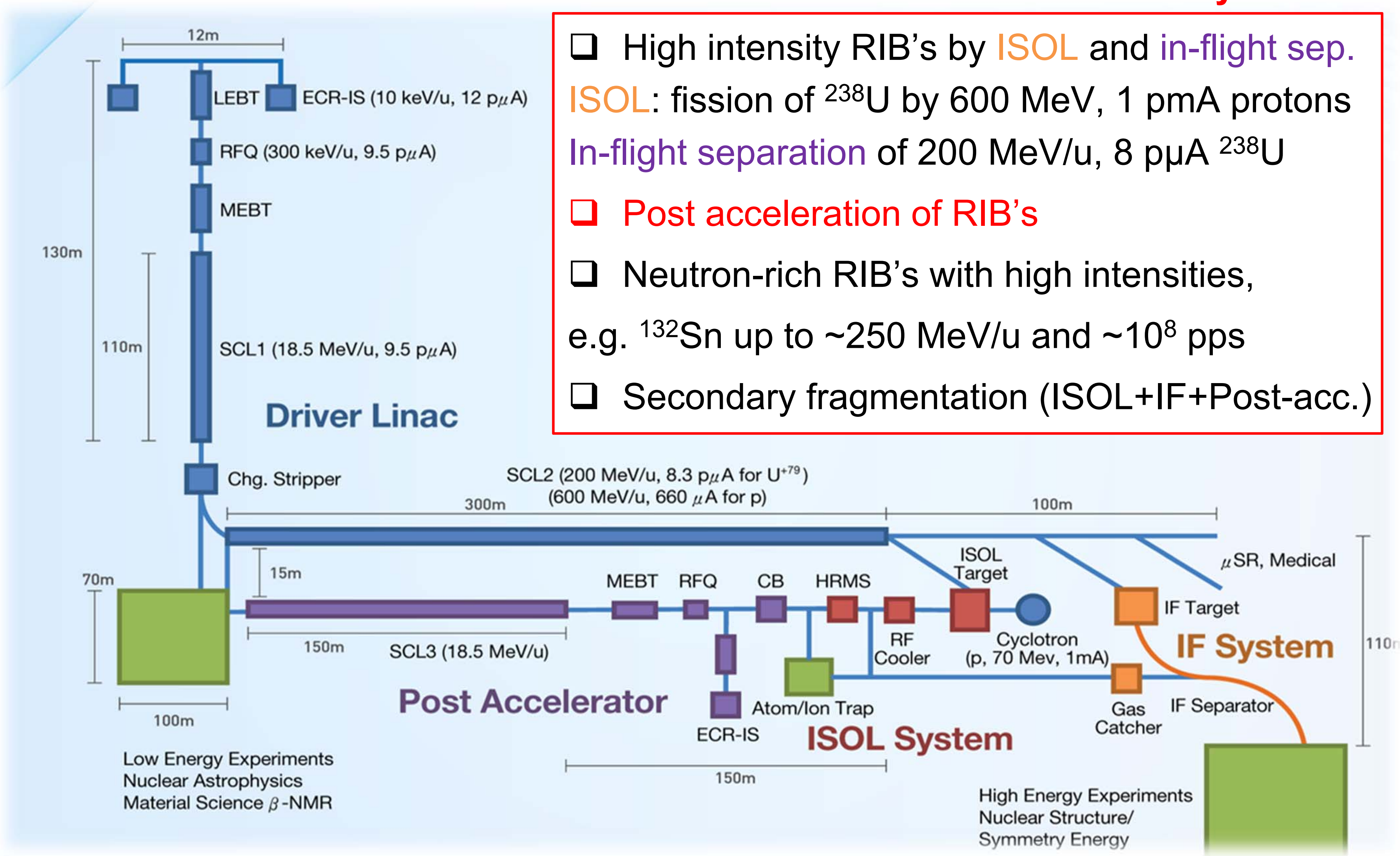
Concept for Beijing-ISOL facility: CARIF



RAON facility in Korea

See contribution by Y. Kim

- ❑ High intensity RIB's by ISOL and in-flight sep.
  ISOL: fission of ^{238}U by 600 MeV, 1 pmA protons
  In-flight separation of 200 MeV/u, 8 pμA ^{238}U
- ❑ Post acceleration of RIB's
- ❑ Neutron-rich RIB's with high intensities,
  e.g. ^{132}Sn up to ~250 MeV/u and ~10^8 pps
- ❑ Secondary fragmentation (ISOL+IF+Post-acc.)

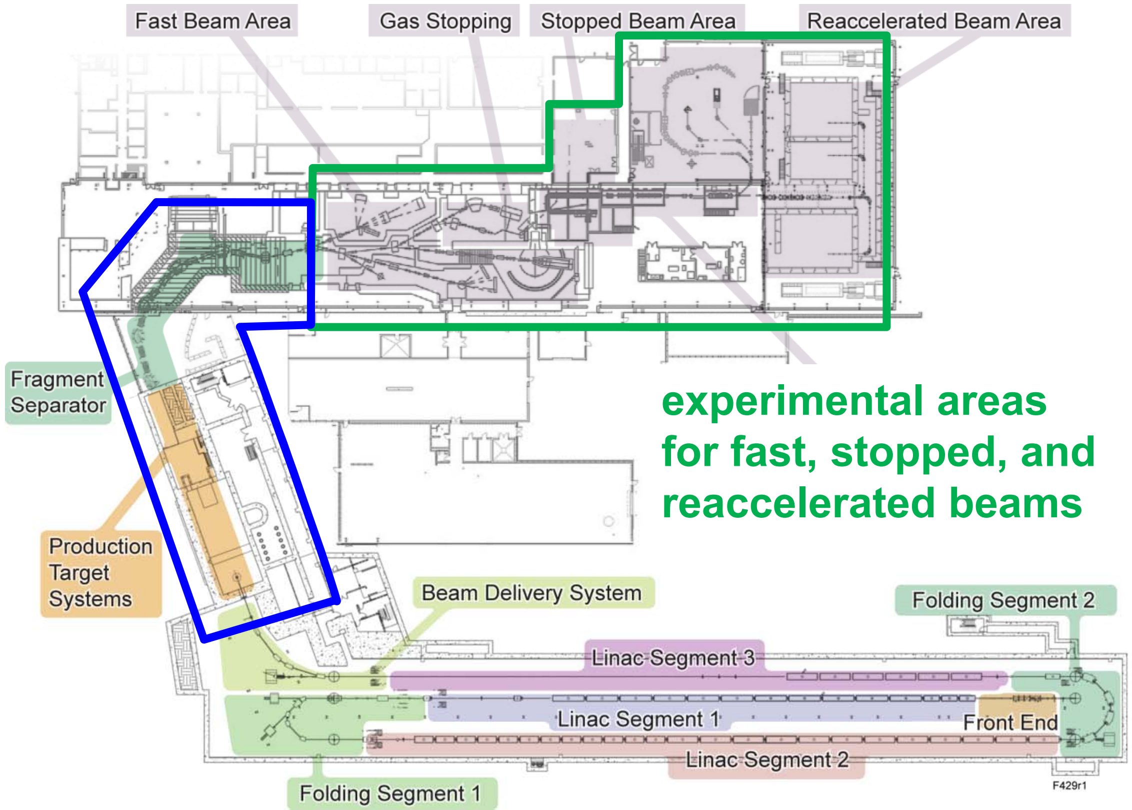


FRIB - Facility for Rare Isotope Beams

Facility performance expectations

- Rare isotope production with primary beams up to 400 kW, 200 MeV/u uranium
- Fast, stopped and reaccelerated beam capability
- Experimental areas and scientific instrumentation for fast, stopped, and reaccelerated beams
- Energy upgrade to 400 MeV/u for uranium

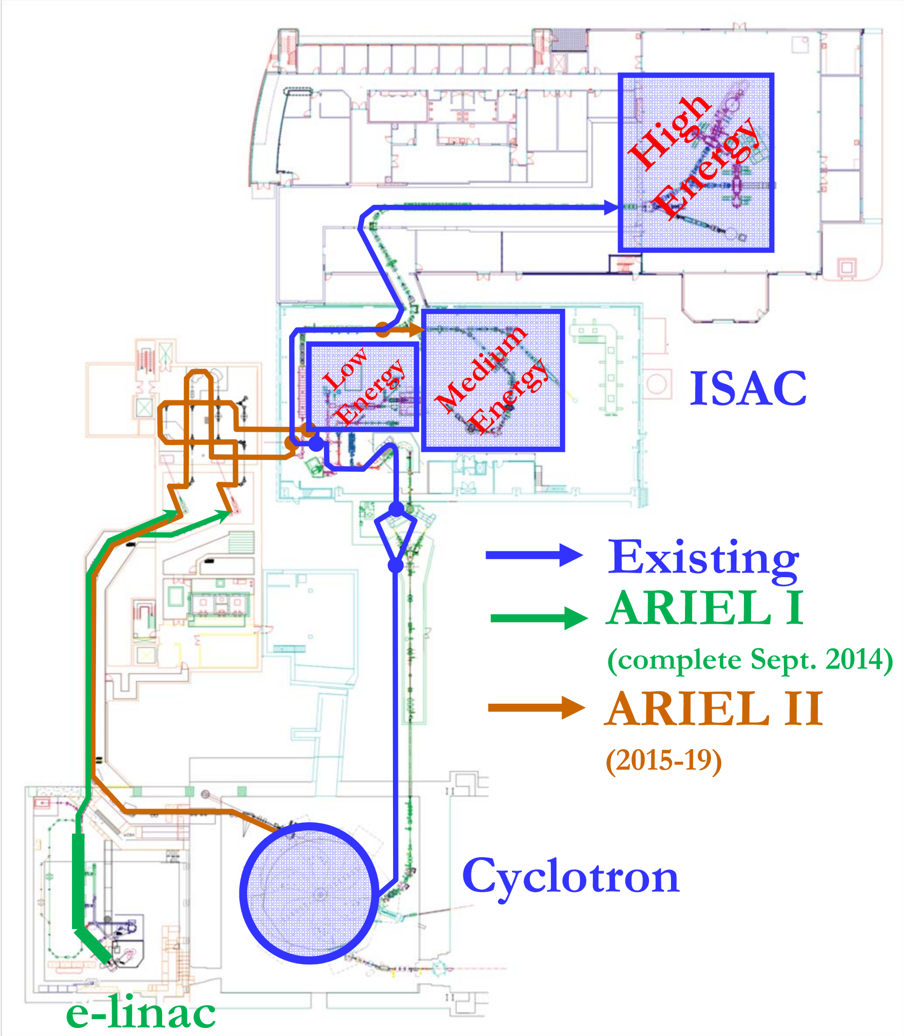
- Fragment separator
  - » **Acceptance:**
    ± 40 mrad (angular)
    ± 5% (momentum)
  - » **Magnetic rigidity:**
    8 Tm after target



New opportunities:

- multi-user operation
- isotope harvesting

TRIUMF: ARIEL



Timeline:

- 2014 first beam, target R&D
- 2018 photo fission
- 2020 proton beam (3 beams)

ARIEL is TRIUMF's flagship: isotopes for science & medicine: 500 kW e-linac for photo-fission and extra proton beam line

Three simultaneous RI-beams

- 2 proton driven
- 1 electron (photo-fission) driven
- 4,000 h/a → 12,000 h/a RIB's
- Phased implementation, (first e-beam Sept 2014)

up to 10^{14} fissions/s

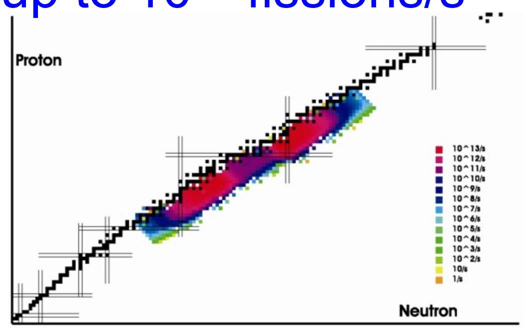


Photo-fission using 50MeV 10mA e- onto Hg convertor + UC_x target.

The European roadmap towards EURISOL

Today — few MeV/u, 10...20 kW

- SPIRAL – GANIL
- ISOLDE
- INFN: LNS - EXCYT, LNL - SPES

2014 - 2025 — $10^{13...14}$ fiss/s, ~10 MeV/u, 100...200 kW

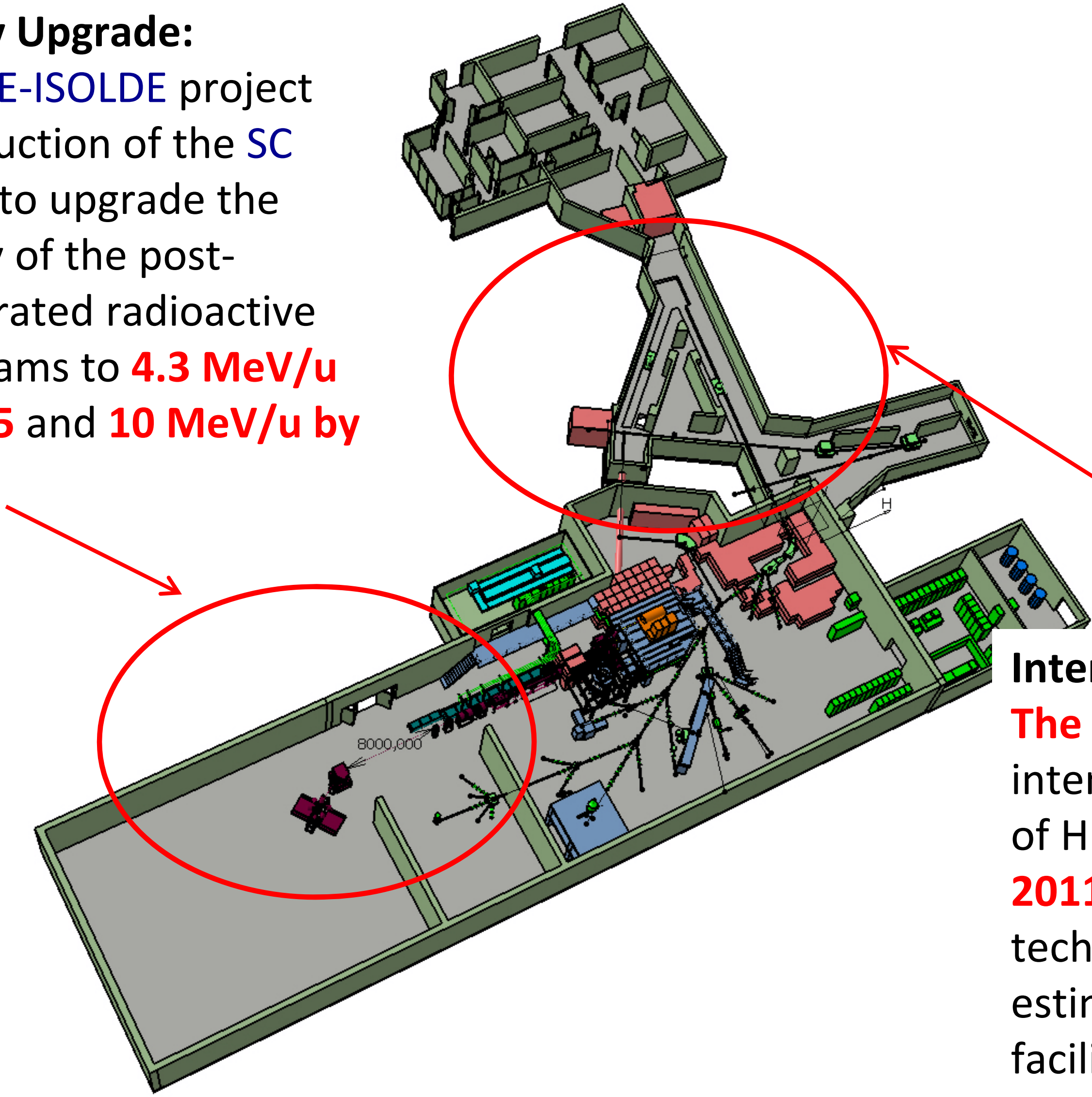
- GANIL spiral2 — laboratoire commun CEA/DSM CNRS/IN2P3
- HIE-ISOLDE
- SPES — exotic beams for science
- ISOL@MYRRHA

→ EURISOL

2025 - .... — > 10^{15} fiss/s, 100 MeV/u, 3x 100 kW direct target, 1x 5 MW target

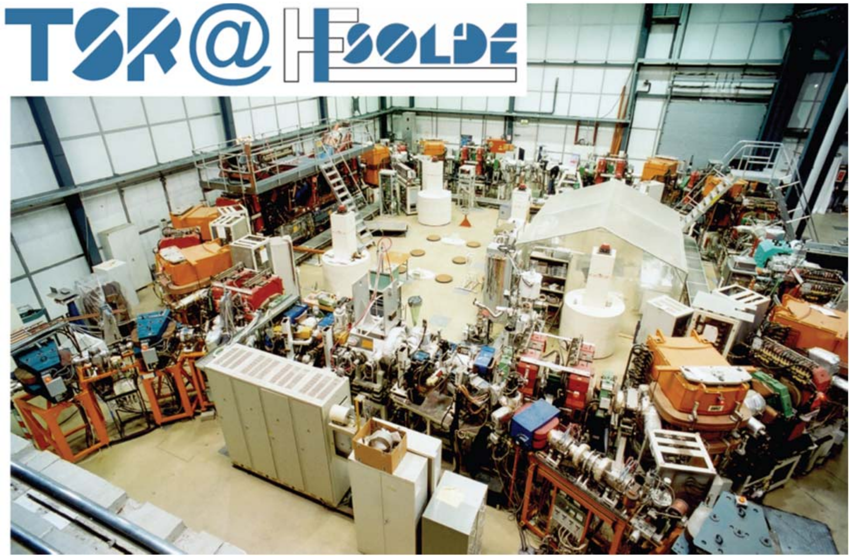
HIE-ISOLDE

Energy Upgrade:
The HIE-ISOLDE project construction of the SC LINAC to upgrade the energy of the post-accelerated radioactive ion beams to **4.3 MeV/u in 2015** and **10 MeV/u by 2017**



Intensity Upgrade:
The design study for the intensity upgrade, also part of HIE-ISOLDE, **started in 2011**, and addresses the technical feasibility and cost estimate for operating the facility at **10 kW** once LINAC4 and PS Booster are online.

New concept: storage ring for post-accelerated beams



Nuclear physics:

study of isomeric states

heavy-element synthesis

charge radii measurements

Atomic physics

dielectric recombination

highly-charged ions & collisions

Neutrino physics

e.g. production of ^{8}Li/^{8}B ions with stored ^{7}Li ions

- Typical storage energy for ~1...5 MeV/u
- Multiturn injection → mA of stored beam possible
- Electron cooler → transverse cooling time of ~1s
- RF acceleration and deceleration
- Typical storage times:

  $^{9}Be^{1+}$ @ 7 MeV: 16 s

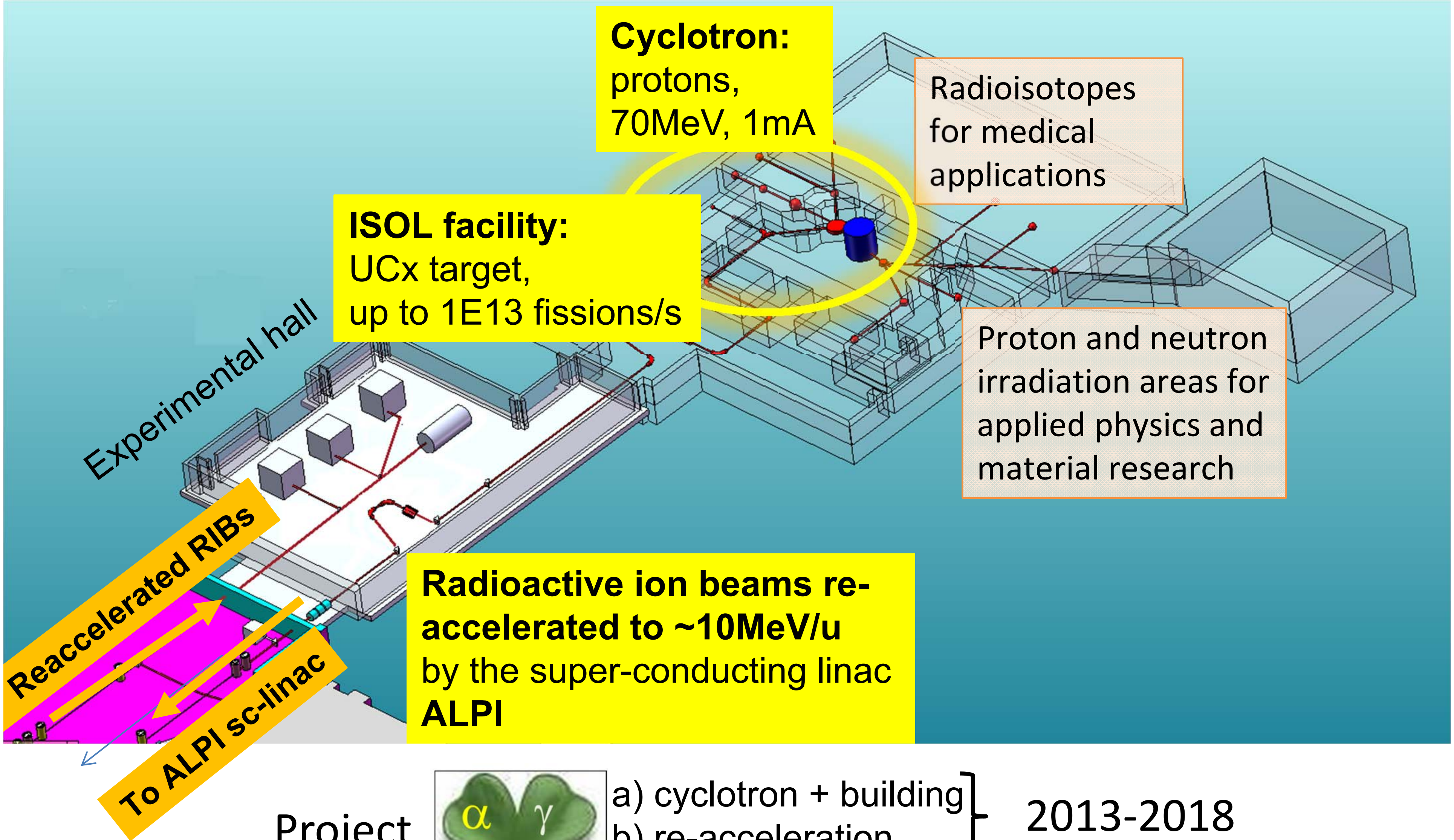
  $^{12}C^{6+}$ @ 73 MeV: 7470 s

  $^{35}Cl^{17+}$ @ 202 MeV: 318 s

  $^{197}Au^{51+}$ @ 710 MeV: 23 s

- A storage ring at an ISOL facility: a unique instrument
- Novel opportunities in atomic, nuclear, astro- and neutrino physics
- Will enhance the science reach and the community of this facility

Legnaro: SPES



Project phases

a) cyclotron + building
b) re-acceleration
} 2013-2018

c) medical isotopes
d) neutron source
} > 2018

GANIL: SPIRAL-2 project

Phase 1 (2015-2016)

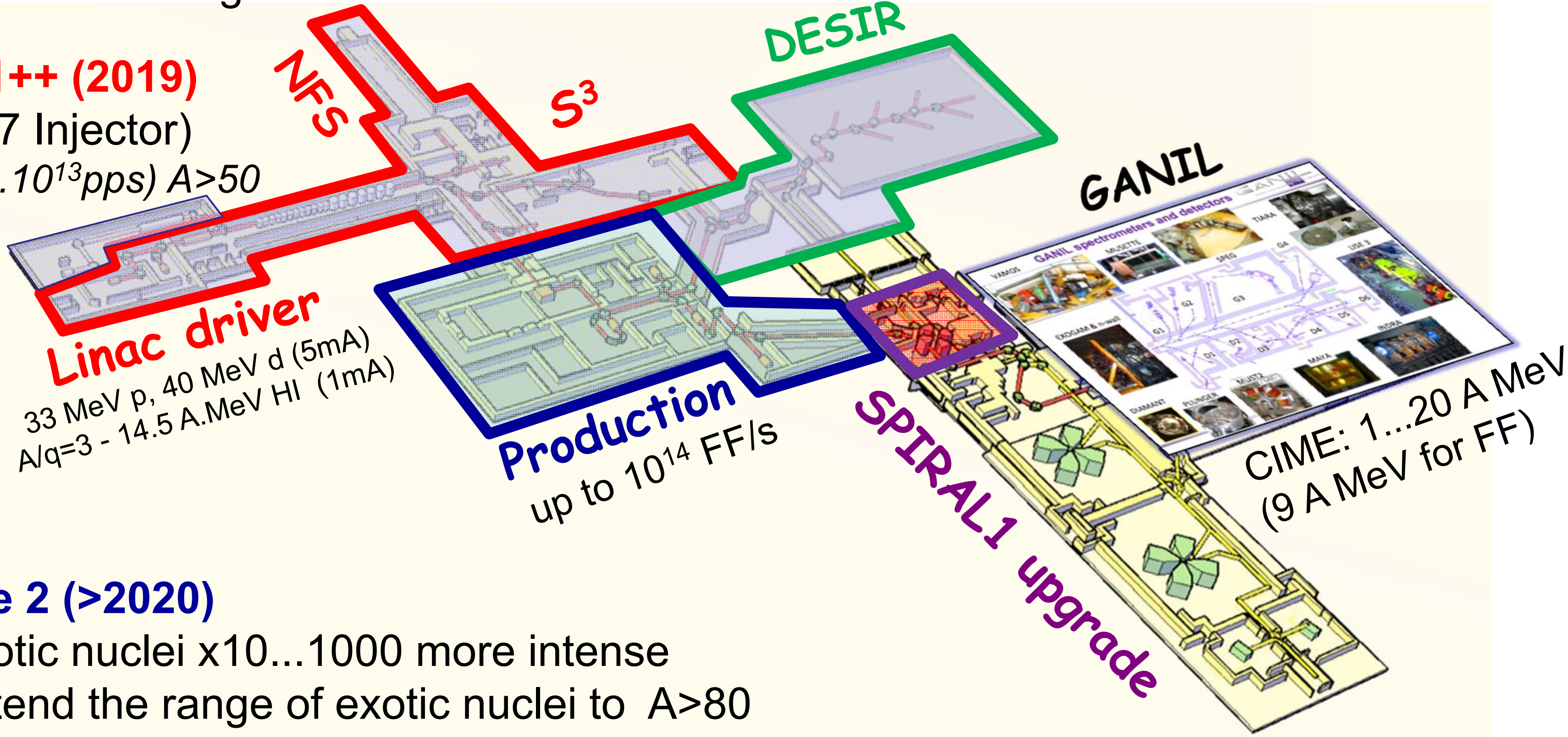
•Stable beam intensity increase by a factor 10 to 100 (*10pµA (6.10^13pps) A<50*)
•Intense neutron source: NFS
•S3 commissioning

DESIR Phase 1+ (2017-2018)

Low energy facility

Phase 1++ (2019)

(A/Q=6-7 Injector)
10pµA (6.10^13pps) A>50



Phase 2 (>2020)

- Exotic nuclei x10...1000 more intense
- Extend the range of exotic nuclei to A>80
- Post-acceleration of high intensity RIB's

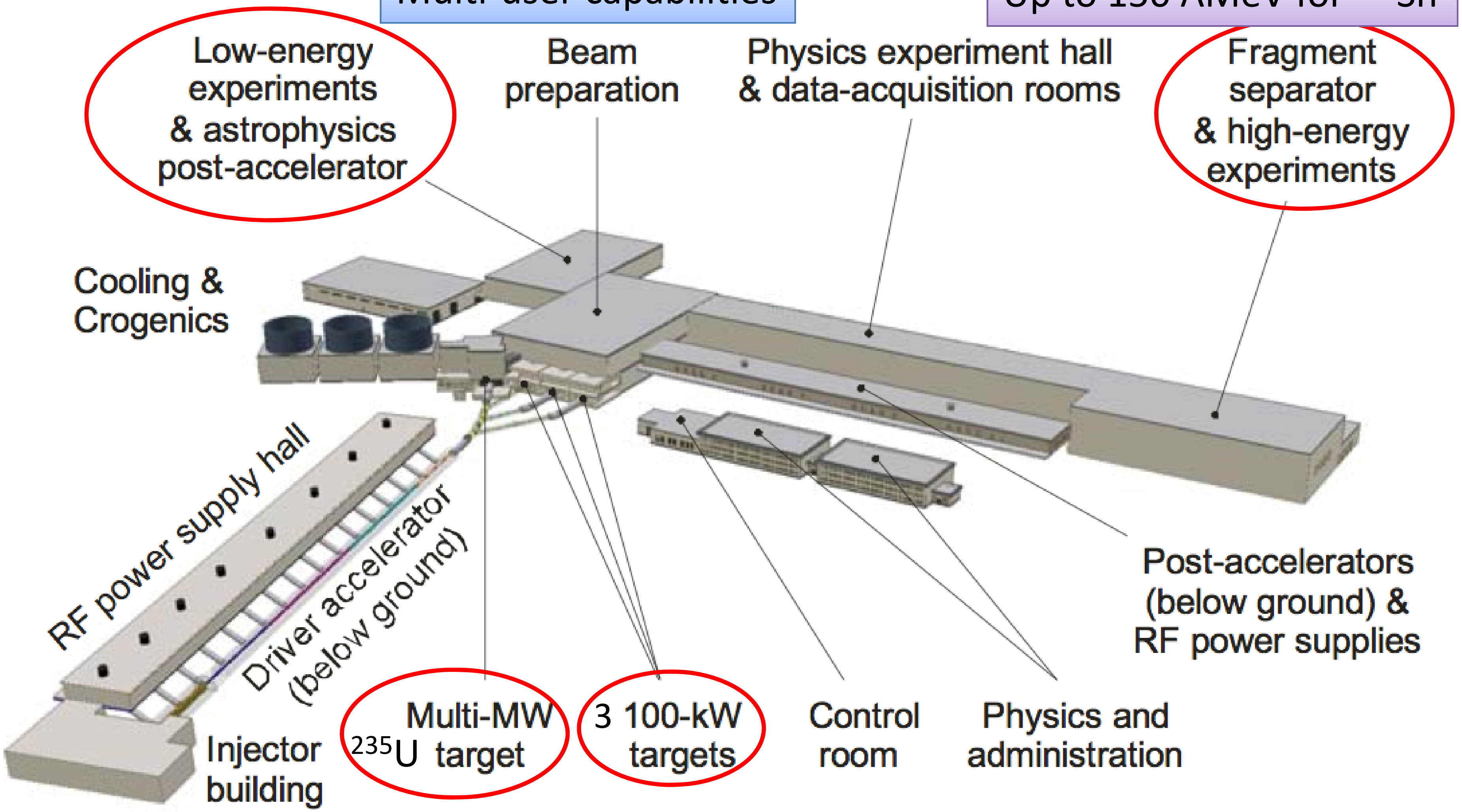
SPIRAL-1 upgrade (2016)

New light RIB's from fragmentation
Hadron therapy research (^{12}C beam)

EURISOL facility

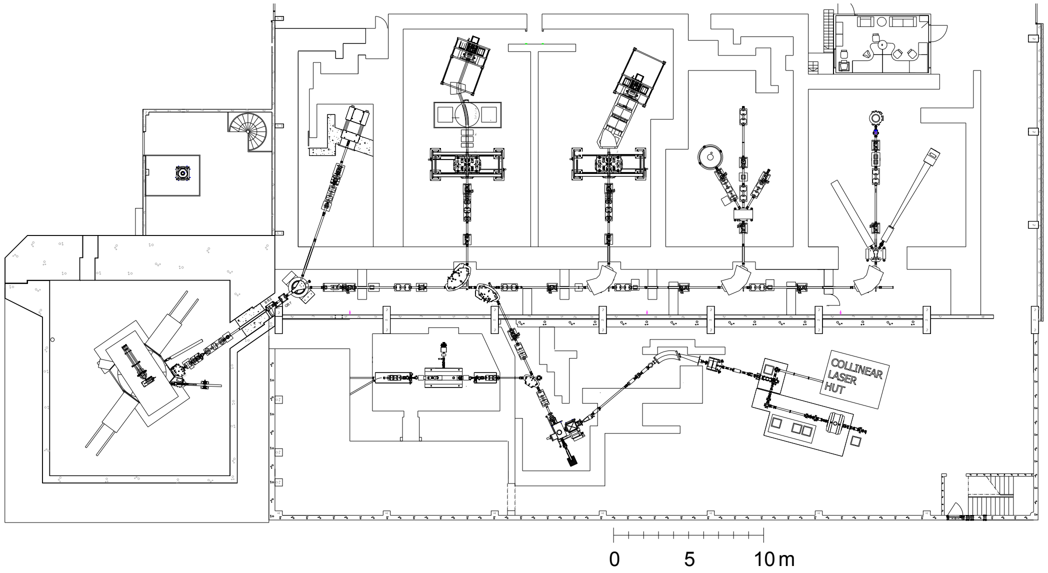
Multi-user capabilities

Up to 150 AMeV for ^{132}Sn



LINAC: H, D, He and A/q=2 ions up to 1 A GeV

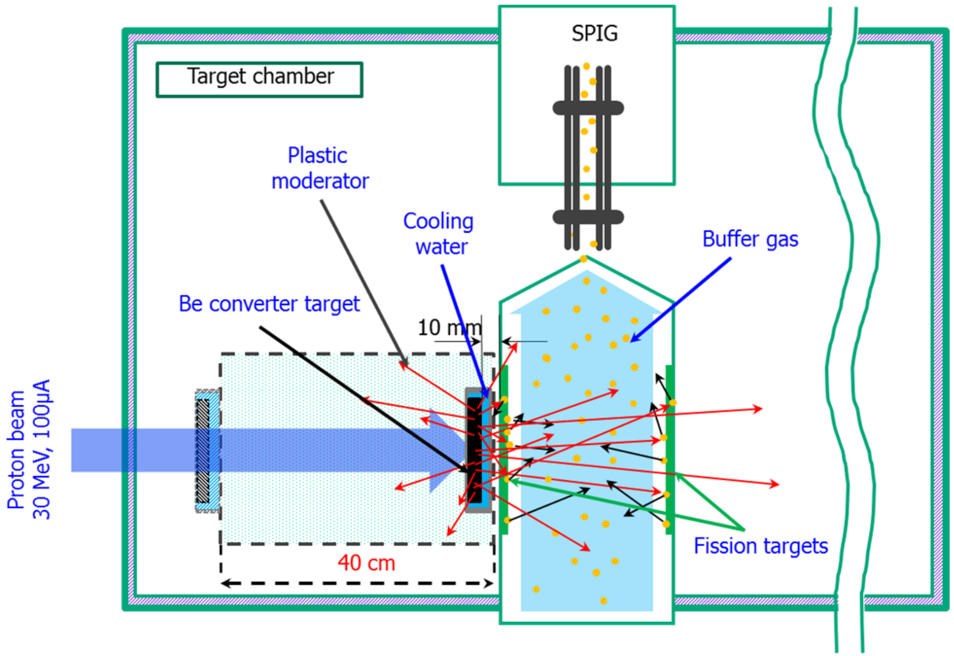
JYFL – IGISOL facility



ECR ion source
Cyclotrons: K=30, K=130

Ion guide technique:
p + ^{238}U fission
Laser ionization

Heavy and light ion fusion
Transfer reactions



NUSTAR@FAIR

Important beam parameters:
- all elements from H through U
- intensity up to ~ 10^{12} ions/sec.
- beam energies up to 1.5 GeV/u
- slow (DC-type) and fast extraction

NUSTAR Collaboration:
~ 800 scientists

146 institutes

38 countries

~150M€ investment

Super-FRS characteristics:

$\varepsilon_x = \varepsilon_y = 40\ \pi$ mm mrad

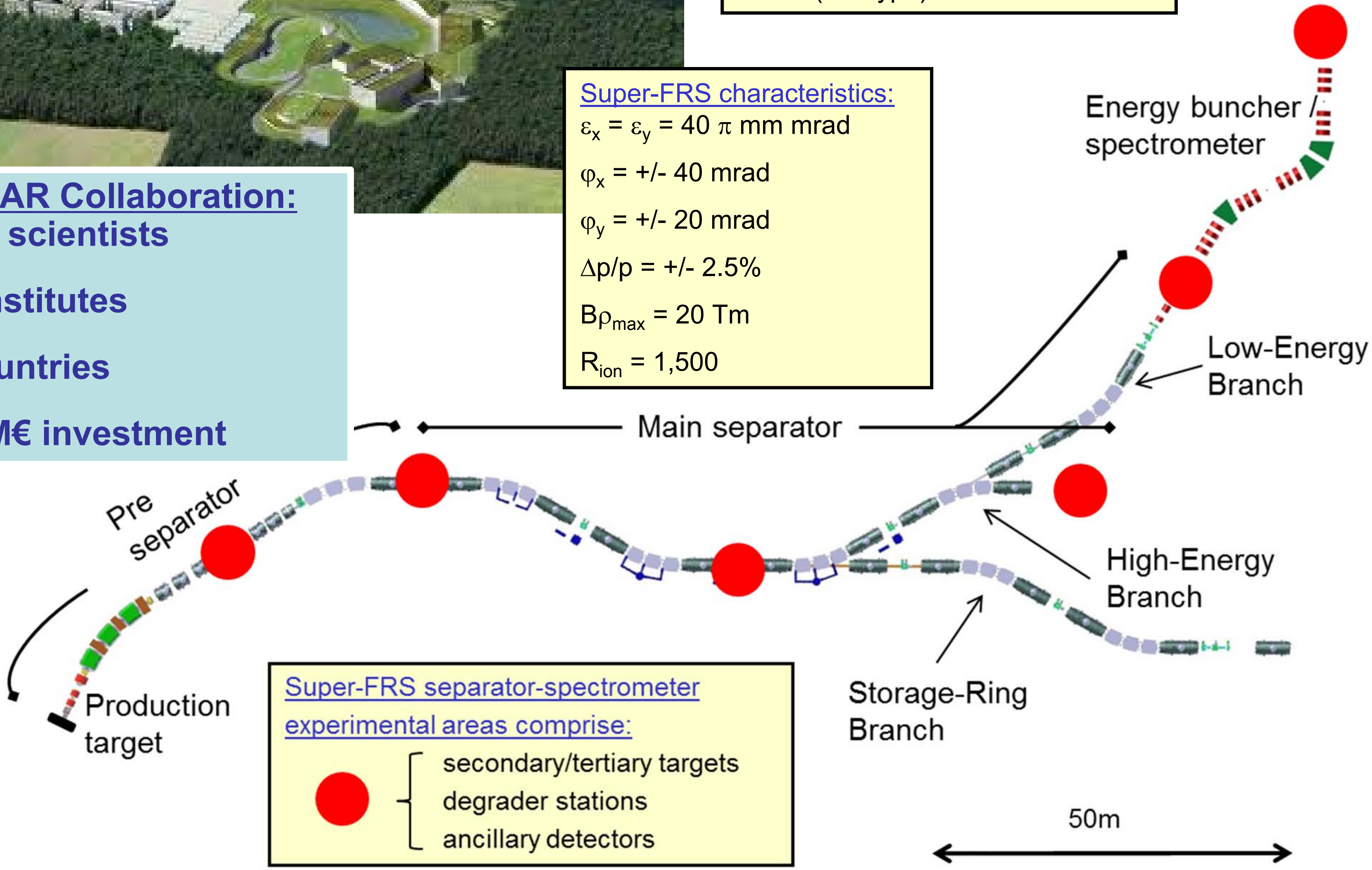
φ_x = +/- 40 mrad

φ_y = +/- 20 mrad

$\Delta p/p$ = +/- 2.5%

$B\rho_{max}$ = 20 Tm

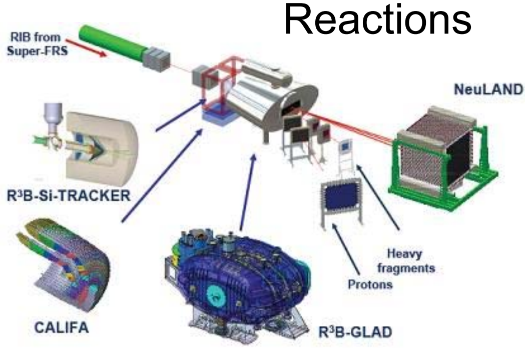
R_{ion} = 1,500

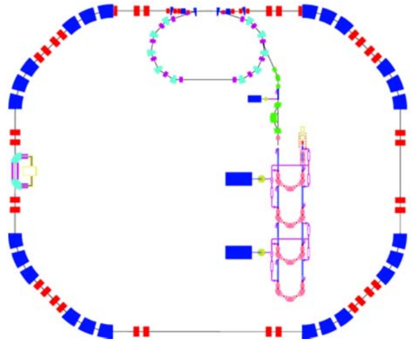


Super-FRS separator-spectrometer experimental areas comprise:
- secondary/tertiary targets
- degrader stations
- ancillary detectors

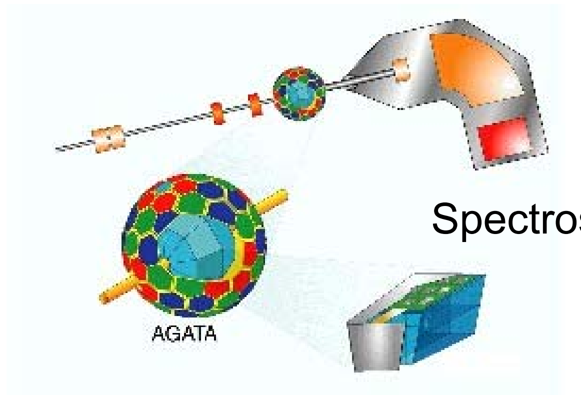
NUSTAR@FAIR

Reactions



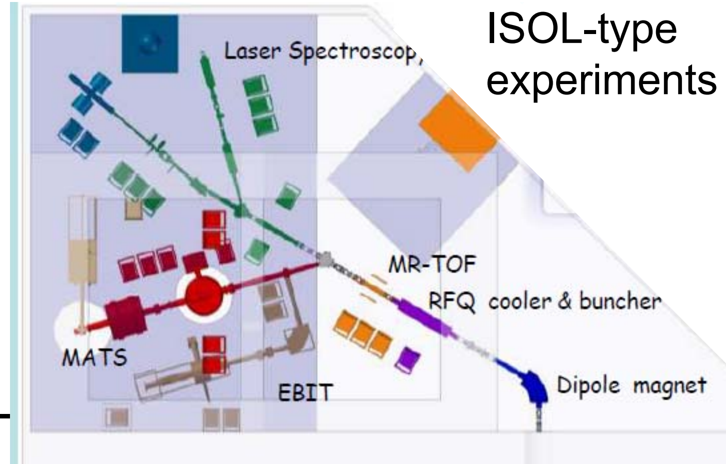


Stored-beam experiments



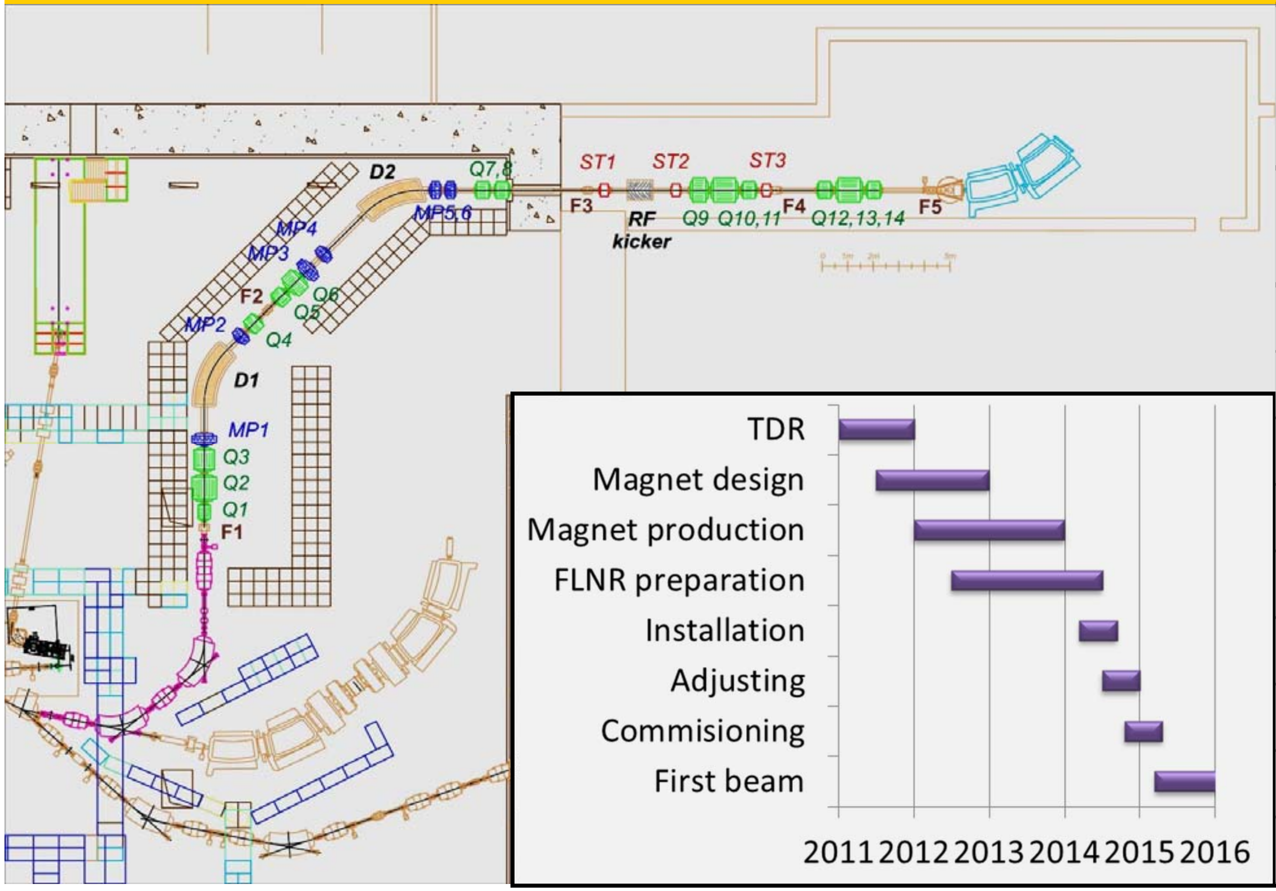
Spectroscopy

ISOL-type experiments



Super-FRS	Isotope identification and high-resolution spectrometer experiments
DESPEC	γ-, β-, α-, p-, n-decay spectroscopy
HISPEC	in-beam gamma-spectroscopy at low and intermediate energy
ILIMA	masses and lifetimes of nuclei in ground and isomeric states
LASPEC	Laser spectroscopy
MATS	in-trap mass measurements and decay studies
R^3B	kinematically complete reactions at high beam energy
ELISE	elastic, inelastic, and quasi-free e—A scattering
EXL	light-ion scattering reactions in inverse kinematics

Dubna: ACCULINNA-2

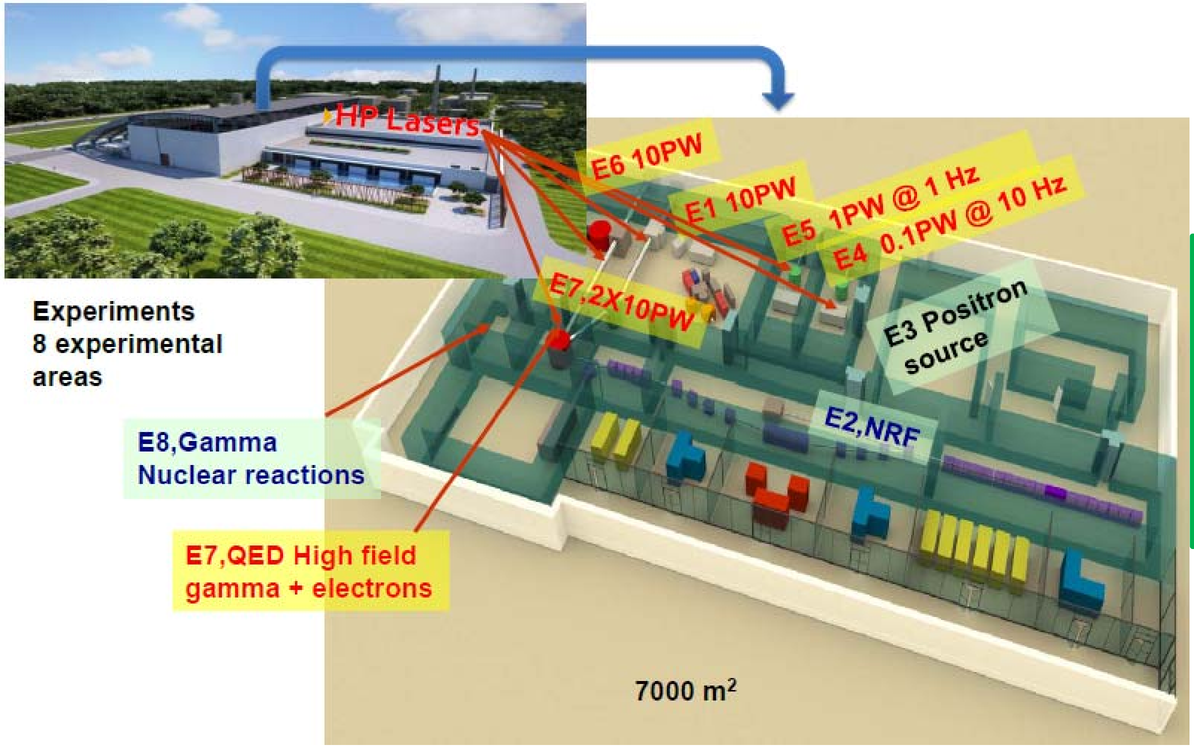


U400M E=30 ÷ 50 MeV/A E=4.5 ÷ 9 MeV/A		
Ion	**Ion energy [MeV/A]**	**Output intensity**
^{7}Li	35	6×10^{13}
^{18}O	33	1×10^{13}
^{40}Ar	40	1×10^{12}
^{48}Ca	5	6×10^{12}
^{54}Cr	5	3×10^{12}
^{58}Fe	5	3×10^{12}
^{124}Sn	5	2×10^{11}
^{136}Xe	5	4×10^{11}
^{238}U	7	2×10^{10}

- Properties and structure of light exotic nuclei
- Astrophysics
- Reactions with exotic nuclei
- Light neutron-rich nuclei
- Deep inelastic scattering
- Producing of RIBs

☺ Installation ongoing
☺ Commissioning 2016
☺ First expt's. 2017

ELI-NP: laser-driven nuclear physics experiments



See contribution by S. Gales

Laser intensities > 1E23 W/cm2

→Heavy-ion laser acceleration
→Laser plasma
→Screening in stellar reactions

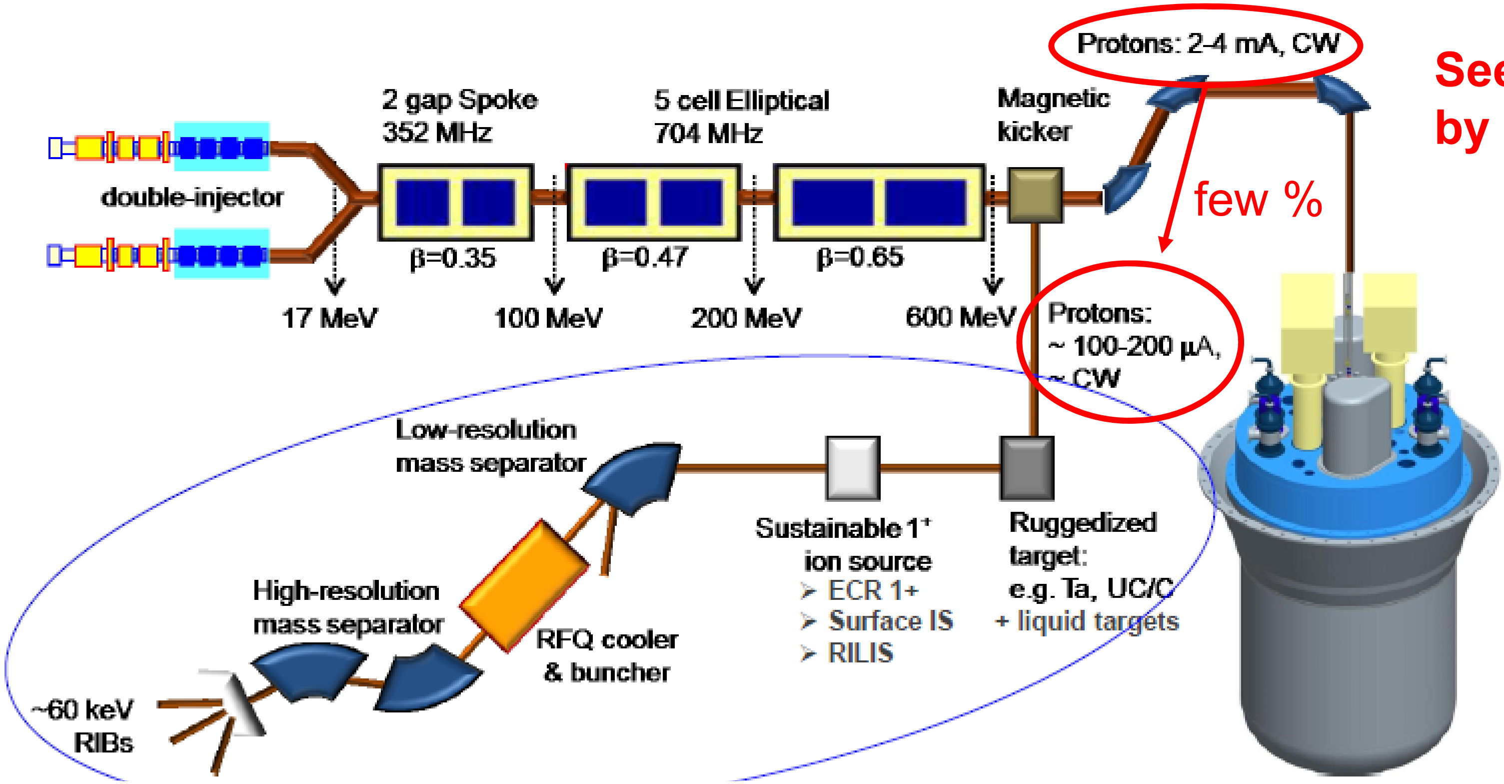
Gamma Beams System

1. Gamma Beam Delivery & Diagnostics
2. NRF Experiments and applications
3. Photo–fission experiments
4. (γ,n) experiments
5. (γ,p) experiments
6. Positron source for material science

High–Power Laser System

1. Laser delivery and beam lines
2. Fission–fusion experiments
3. Strong field QED
4. Laser + Gamma interaction
5. Applications

ADS test facility at SCK-CEN (Mol, Belgium): ISOL@MYRRHA



See contribution by H. Oigawa

- Current ISOL@MYRRHA Design envisages 1 target station (600-MeV <200 μA protons) and a high resolution mass purification system => high-purity RIBs ~100 times more intense than today at ISOLDE

ISOL@MYRRHA will prioritize experimental programmes which require of extended beam times with stable operation

Experiments which
- hunt for very rare phenomena
- need high statistics
- need many time-consuming systematic measurements
- have inherent limited detection efficiency

2012-2014: Design
2023: Commissioning (?)
2025: Experiments (?)

Financial and geographic „scale“

30 M€	100 M€	300 M€	1,000 M€	3,000 M€
Institutional / national		regional		international
ARIEL HIE-ISOLDE SPES		FRIB HIAF RIBF SPIRAL-2	CARIF, EURISOL, RAON FAIR	

Collaboration and mutual support mandatory (due to man-power / money-power limitation)
→ gain in effectiveness, but stretch in time, loss of efficiency

Different approaches and exchange required
→ **a good balance of competition and collaboration is fruitful and stimulating for the whole field**
→ **small / local AND large / regional facilities needed!**

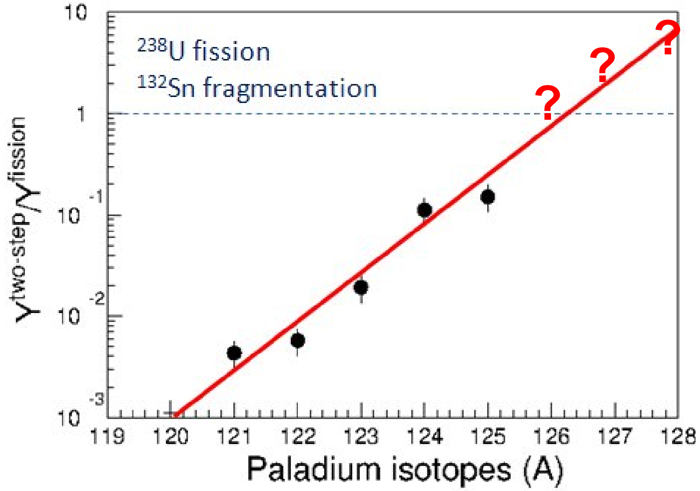
Future directions (?)

Implementation of new concepts

- Multi-beam acceleration
- Efficient use: large acceptance separators, high-resolution detectors, high-efficiency detectors
- Multi-user separators / spectrometers, multi-user concepts
- Beam recycling: re-circulate beams, use all charge states
- Isotope harvesting: chemical separation of isotopes from beam dumps

→ see recent EMIS contribution by W. Mittig, NIM B Volume 317, 186 (2013)

Production of n-rich beams in „2-step“ reactions



Courtesy of J.Benlliure

Observations

Science and developments:

- The scientific case of our field is mature
- The present decade is dominated by construction of next-generation facilities
- Progress and developments are exciting

Beams:

- The future will focus on neutron-rich nuclei (this holds also for SHE)

Projects:

- Projects integrate the worldwide science community
- Projects rely on technological challenges
- Projects take more time, become more expensive, materialize in stages

Essential ingredients for success:

- Ideas, enthusiasm, resources: “brains, hands, money, time”
- Concerted activities (community = users + laboratories)
- Concentrated + coordinated efforts (users, laboratories, funding agencies)
- Sustained effort and funding

Summary

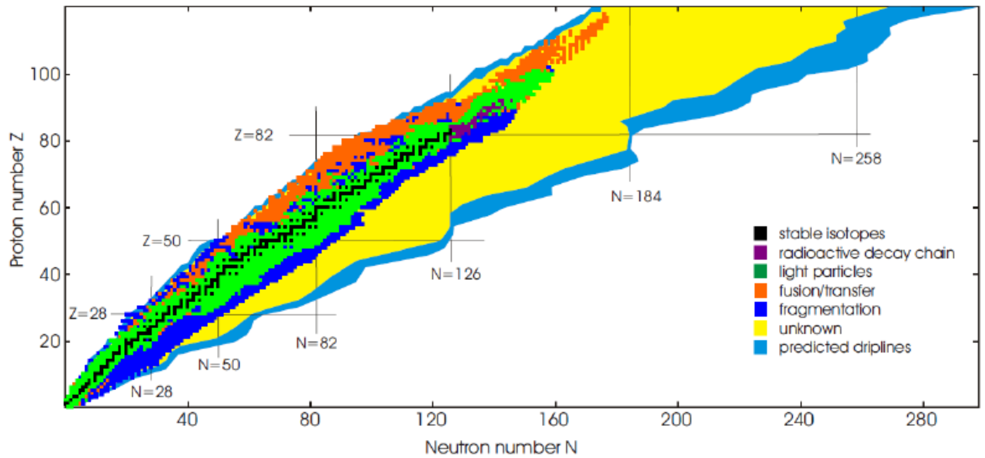
New stable-beam and large-scale RIB facilities appear on the world scene and will open up a bright future for the world-wide nuclear physics community

RIBF, the first „next-generation“ radioactive beam facility, is in operation and serves as good example

The “new generation” facilities build on in-flight separators and ISOL systems including re-acceleration, and hybrid systems

The common goal is the extension of the nuclear chart and to perform experiments, increase understanding of strong force and nuclei, and develop new applications

Great scientific opportunities ahead of us!



7000 bound nuclide should exist (Erler *et al.*,Nature 486 (2012) 509)

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