RI-beam facilities worldwide
-- present and future –

T. Motobayashi
(RIKEN Nishina Center)

RI (radioactive isotope) beams
- starts, a few early experiments
- facility examples
- “world map”

“new generation” facilities
- fragmentation-based facilities
- ISOL-based (reacceleration) facilities
- other types

Discussions and summary

Energetic beams of unstable nuclei (or radioactive isotopes)

Dreamed in 1970's and 80's

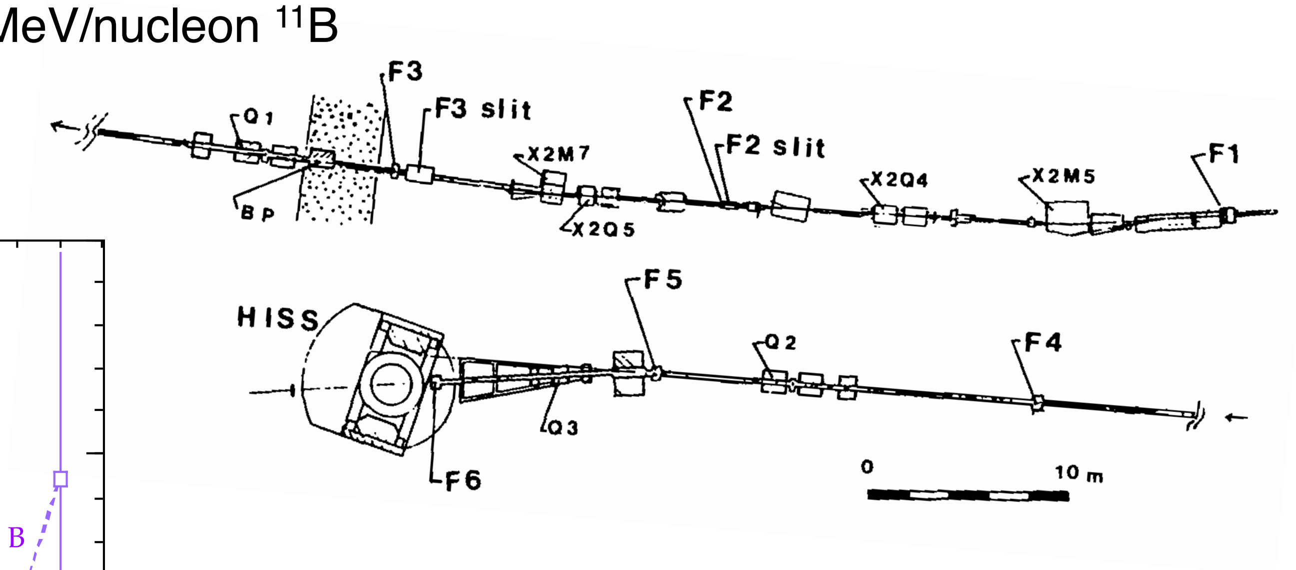
- Structure of nuclei away from the stability by nuclear reaction
- Reactions in explosive nuclear burning
  - *e.g.* in "Cauldrons in the Cosmos" by Rolfs and Rodney

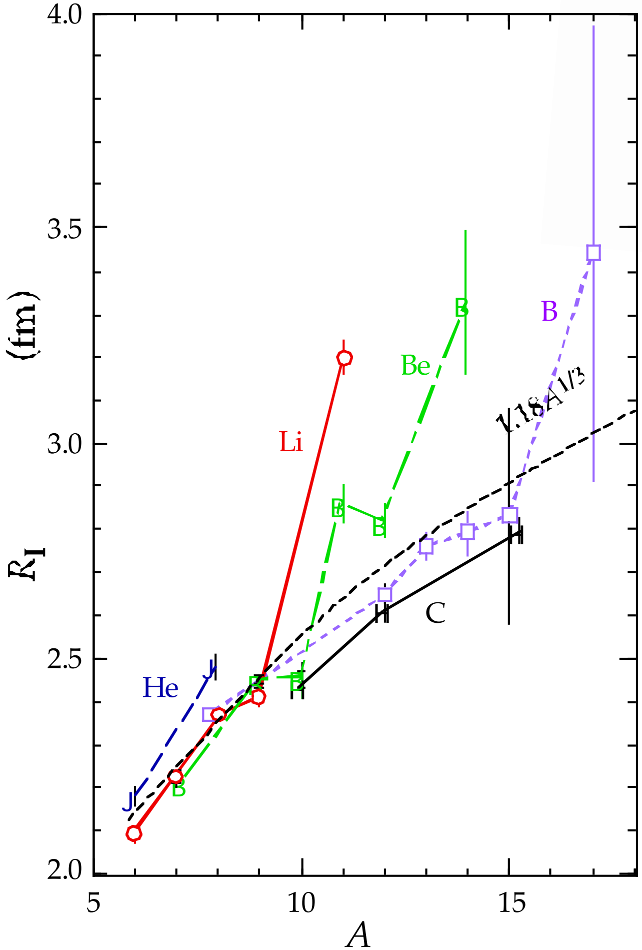
Methods of RI-beam production

- post acceleration (accelerator + ISOL + accelerator)
- in-flight (projectile fragmentation – accelerator + separator)

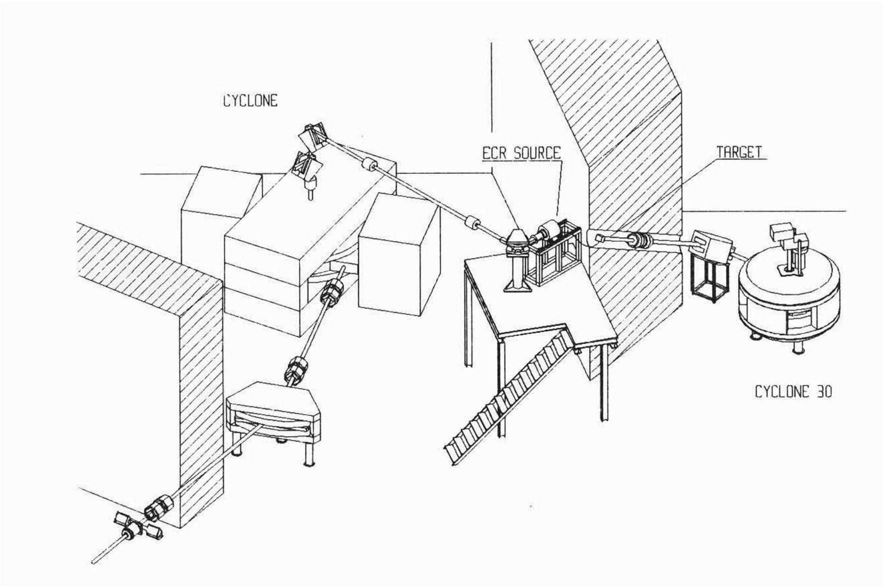
Expected: ISOL based beams
Realized first: fragmentation based beams

fragmentation of 800 MeV/nucleon ^{11}B





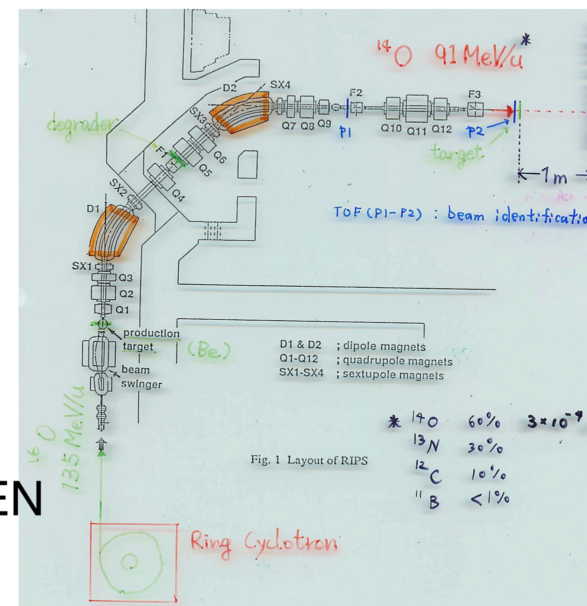
large radius of ^{11}Li (neutron halo)



^{13}N by $^{13}C(p,n)$ reaction by 30 MeV p
^{13}N: ionized in ECR
post accelerated by a cyclotron

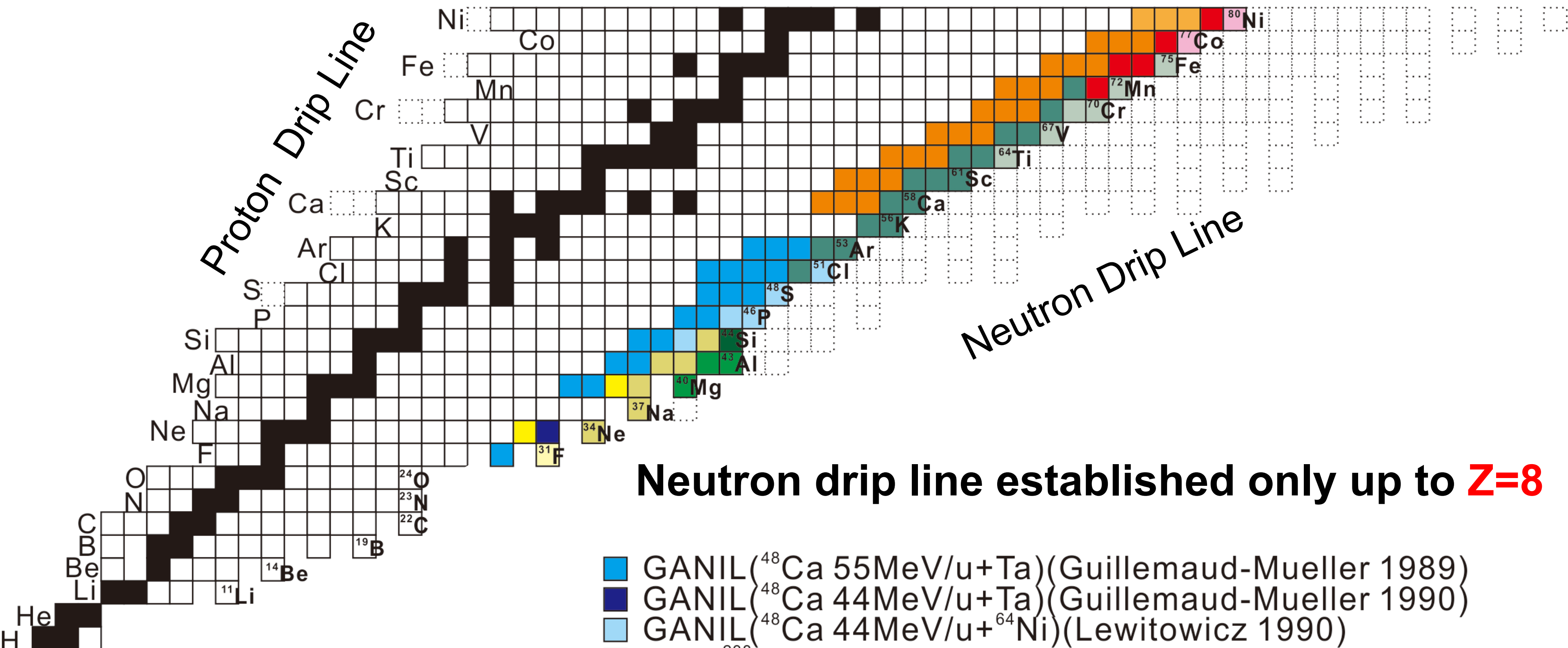
$^{13}N(p,\gamma)^{14}O$ reaction studied by both the methods (1991)
1^{st} experiments of reaction of **astrophysical interest**
(explosive hydrogen burning – hot CNO cycle)

Γ_γ	present	(p,γ)
^{14}O (1^-)	3.1 ± 0.6 eV	(3.8 ± 1.2) (3.2) * 3.4 ± 0.9



Coulomb dissociation of ^{14}O at RIKEN
(by fragmentation)

Fragmentation-based RI beams are useful also for extension of the nuclear chart.



Neutron drip line established only up to Z=8

- GANIL(^{48}Ca 55MeV/u+Ta)(Guillemaud-Mueller 1989)
- GANIL(^{48}Ca 44MeV/u+Ta)(Guillemaud-Mueller 1990)
- GANIL(^{48}Ca 44MeV/u+^{64}Ni)(Lewitowicz 1990)
- GSI (^{238}U 750MeV/u+Be)(Engelmann 1995)
- GSI (^{238}U 750MeV/u+Be)(Bernas 1997)
- RIKEN(^{50}Ti 80MeV/u+Ta)(Sakurai 1996)
- RIKEN(^{40}Ar 94MeV/u+Ta)(Sakurai 1999)
- RIKEN(^{48}Ca 64 MeV/u+Ta)(Notani 2002)
- MSU (^{48}Ca 141 MeV/u+W)(Baumann 2007)
- MSU (^{48}Ca 141 MeV/u+Be)(Tarasov 2007)
- MSU (^{76}Ge 132 MeV/u+Be)(Tarasov 2009)
- MSU (^{82}Se 139 MeV/u+Be/W)(Tarasov 2013)
- RIKEN RIBF(^{238}U 345 MeV/u)(Ohnishi 2010)
- RIKEN RIBF(^{238}U 345 MeV/u)(Xu 2014)
- Prediction by HFB14(Z>10)

T. Nakamura (Tokyo Tech)

Motivations of studying unstable nuclei ← RI beams

nuclear structure

halo, skin, ….

new shell structures / collectivity

e.g. disappearance / appearance of magic numbers

explosive burning – nuclear astrophysics

reaction involving unstable nuclei

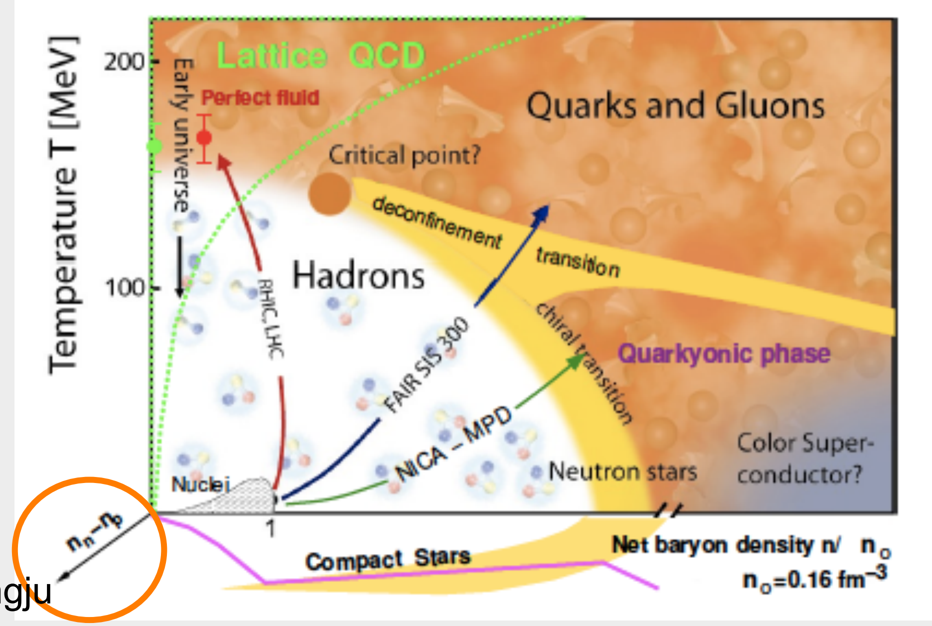
mass (*Q* value), half-life, …

asymmetric nuclear matter

Naïve approach:

← neutron-rich nuclei (by RI beams)

fundamental symmetries



applications

RI (radioactive isotope) beams enable (since 1985):

- extension in the nuclear chart
- reaction experiments
- nuclear astrophysics
- …

(fragmentation – fast beams)

LBL, GANIL, RIKEN, MSU, GSI, IMP, ….

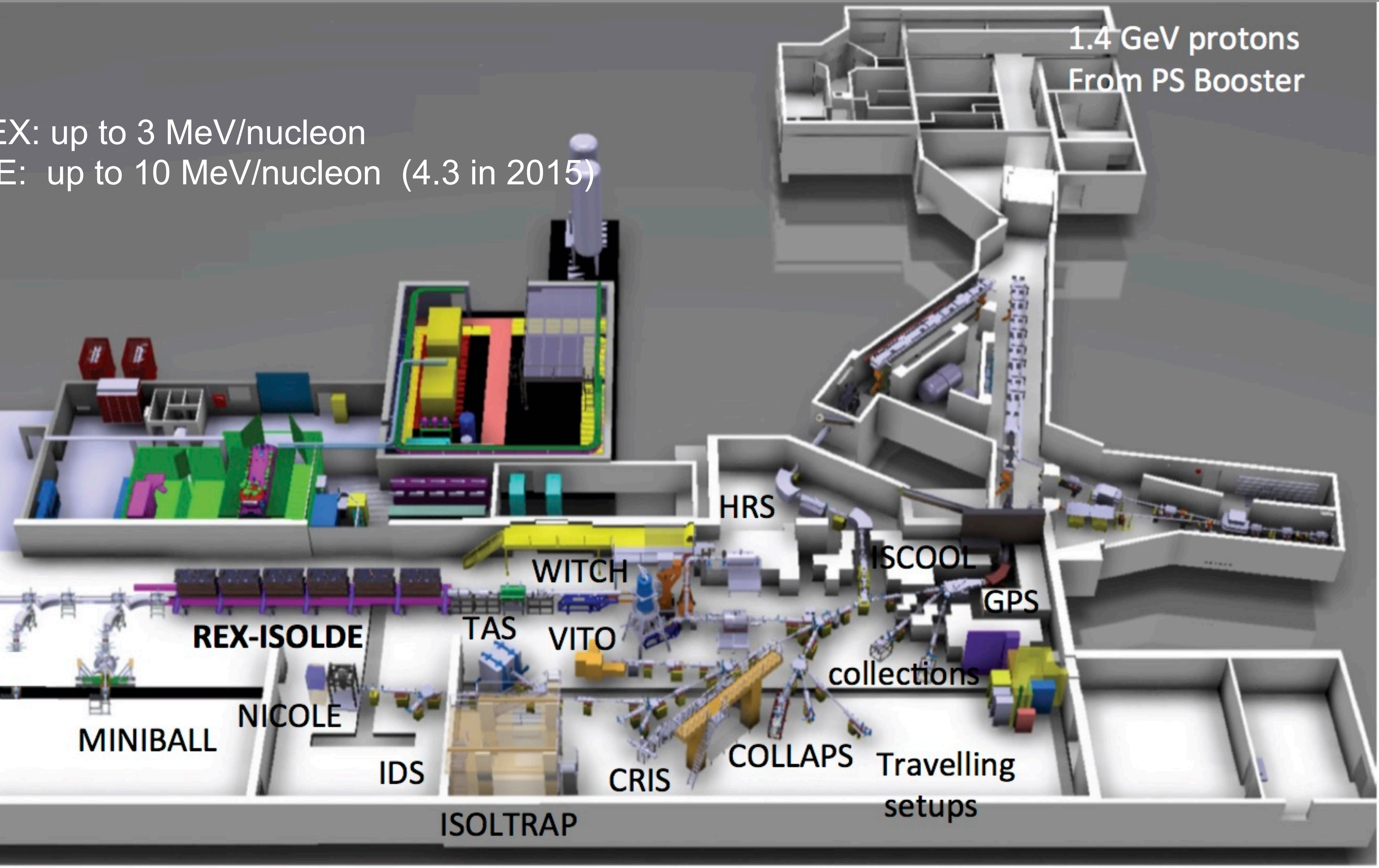
(ISOL-reacceleration – low E beams)

LLN, REX-ISOLDE, SPIRAL, ISAC, EXCYT ..

(Other types – mostly for low E beams)

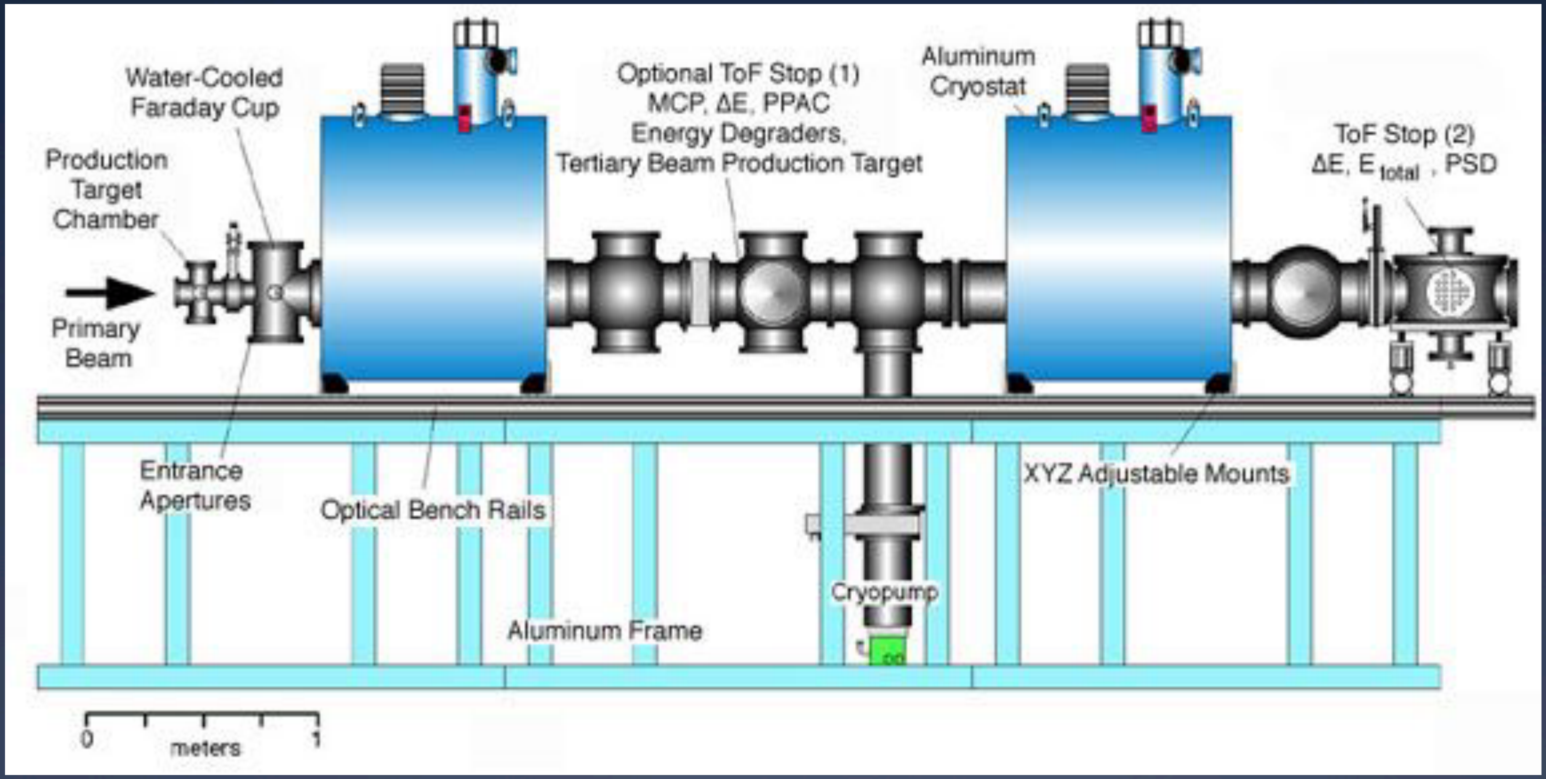
GIRRAFE, CRIB, HIRA, MARS, TwinSol, SOLEROO, BIBRAS …
CARIBO

REX- (HIE-) ISOLDE at CERN as an example of ISOL-based RI beams



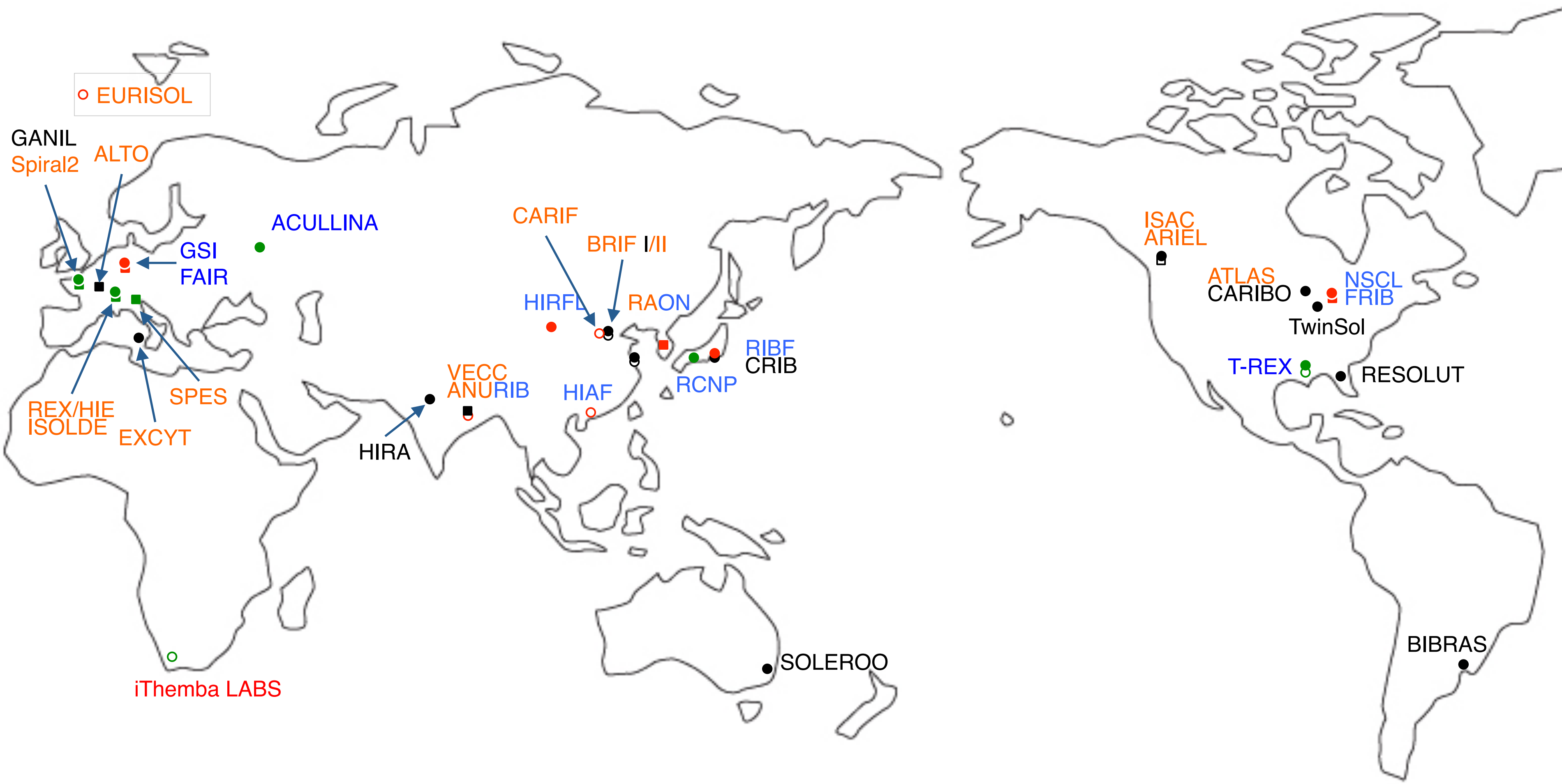
TwinSol at Notre Dame U.   as an example of in-flight RI beams with solenoids

Two superconducting solenoids for focus and separation



In the same scheme: BIBRAS (Brazil), RESOLUT (US), SOLEROO (Australia)
~5 MeV/nucleon typically for light unstable nuclei

World facilities for RI beams



• in operation, ▪ under construction, ◦ being designed

• <10 MeV/nucleon, • <100 MeV, • >100 MeV/nucleon

Fragmentation, ISOL, Hybrid or other type

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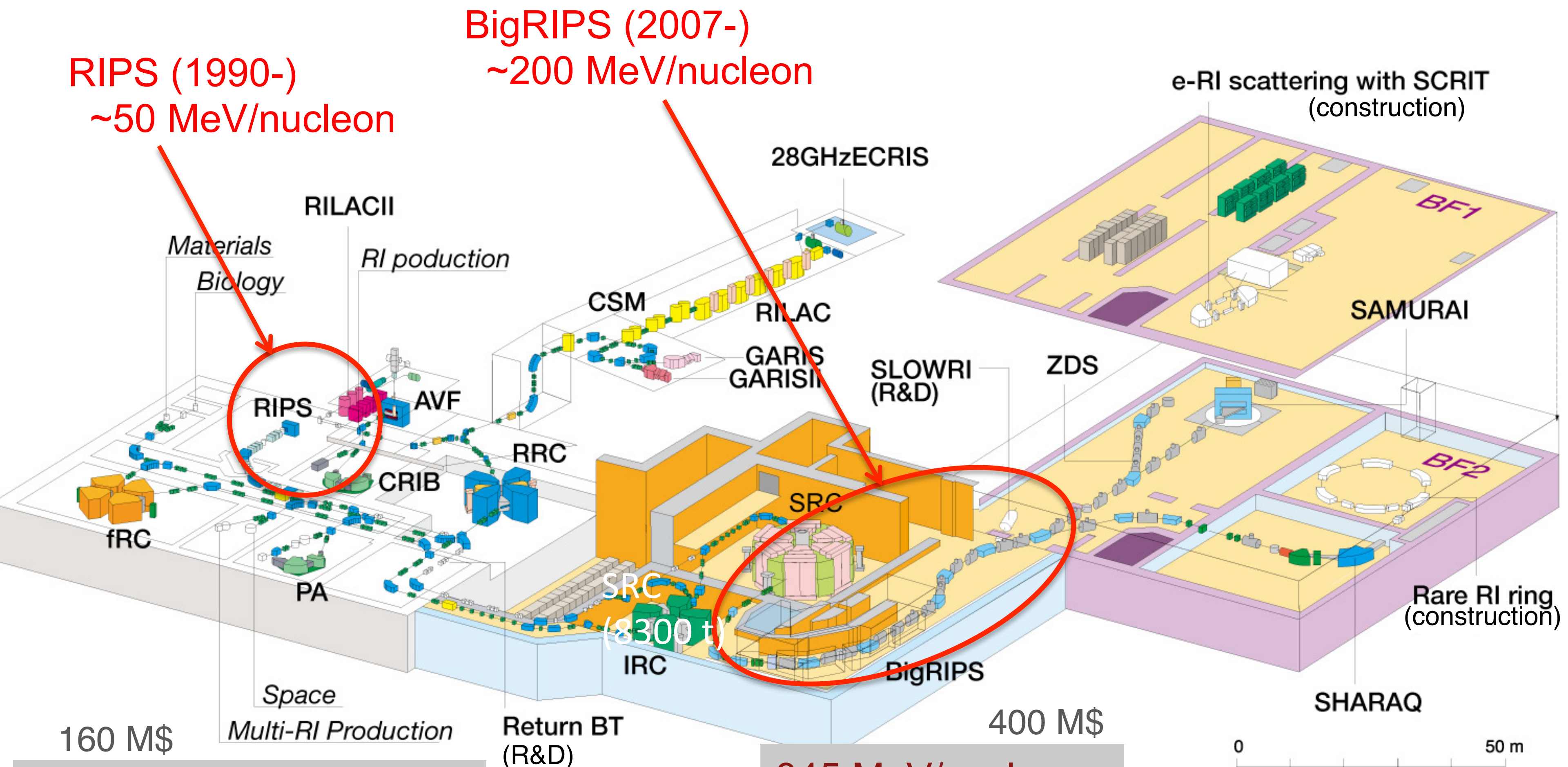
LLN, REX-ISOLDE, SPIRAL, ISAC.. (ISOL-reacceleration – low E beams)

Needs for new-generation (dedicated) facilities
with high-intensity (or to go farther away from the stability*)

RIKEN RIBF (in operation)
FAIR, FRIB, HIAF,
Spiral2, SPES, HIE-ISOLDE, ALTO, ARIEL, BRIF, EURISOL….
Beijing ISOL, ANURIB…
RAON,

RIBF – a new generation RIB facility in operation → **Sakurai**
with world highest capability of providing RI beams in coming years!



160 M$

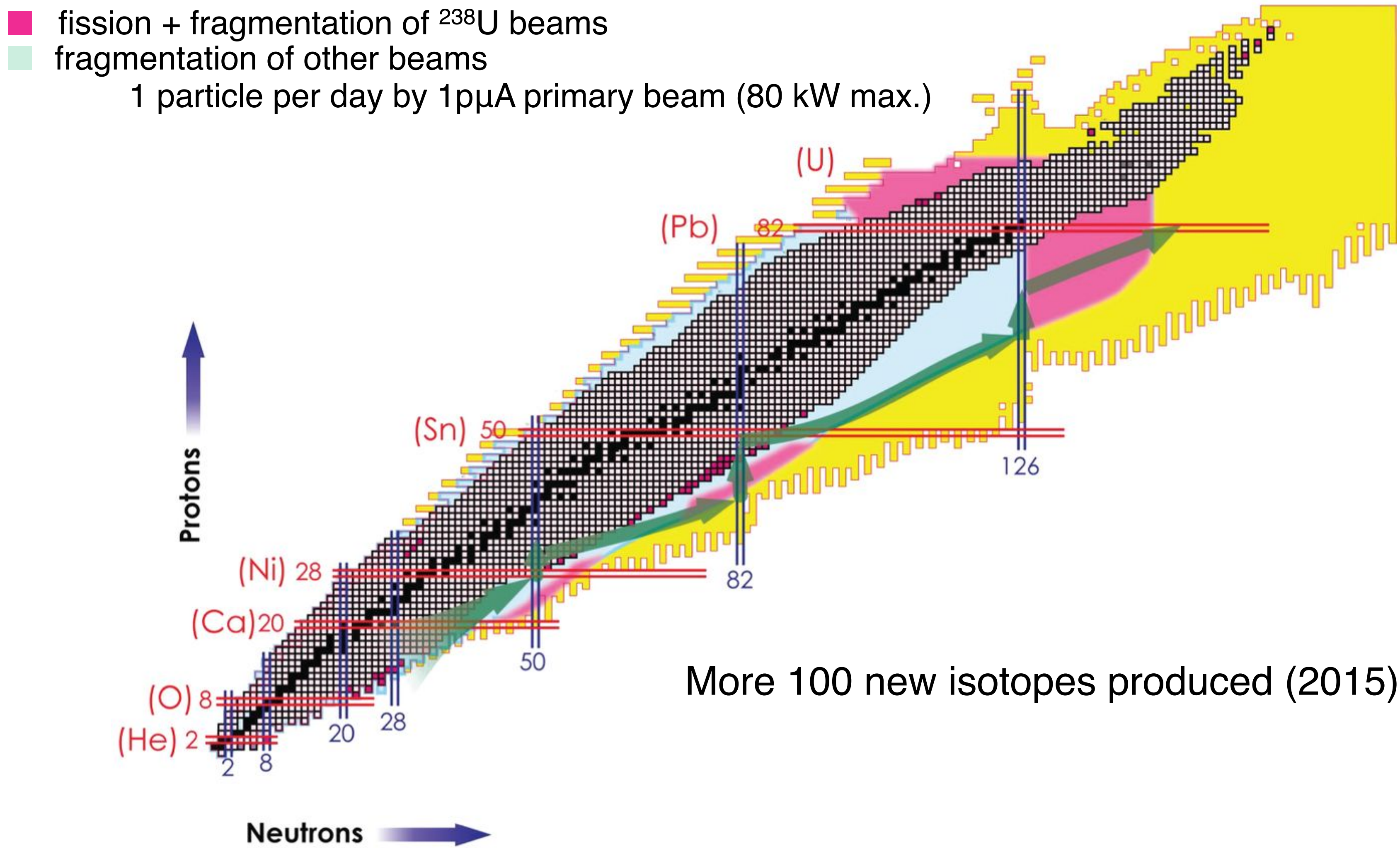
135 MeV/nucleon
for light nuclei (1986-)

400 M$

345 MeV/nucleon
up to U (2006-)

experimental equipment

Nuclear chart potentially covered by RIKEN RIBF（new-generation facility)



More 100 new isotopes produced (2015)

Motobayashi T , and Sakurai H Prog. Theor. Exp. Phys. 2012;2012:03C001

PTEP Progress of Theoretical and Experimental Physics

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➔ nuclear structure / explosive burning / asymmetric matter ..

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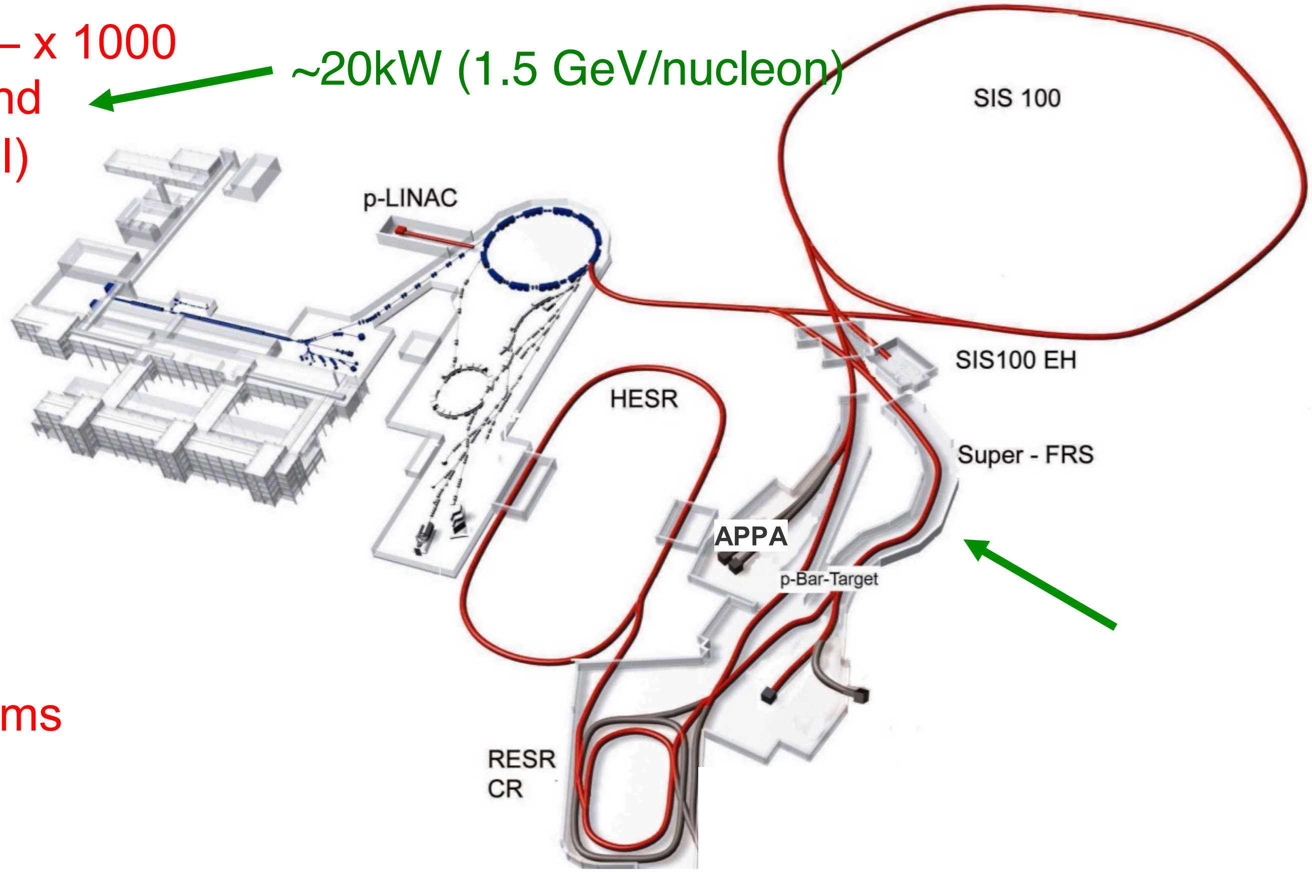
RAON,

Requirements to conduct world class experiments

- Beam intensity increase:
  - Primary beams: x 100 – x 1000 (3*10^11 uranium ions and 2*10^13 protons per spill)
  - Secondary beams: x 10.000
- Beams:
  - Anti protons
  - Protons to uranium
  - RIBs
- Beam quality:
  - Cooled anti proton beams
  - Cooled, intense RIBs
- Beam pulse structure:
  extreme short pulses to quasi continuous



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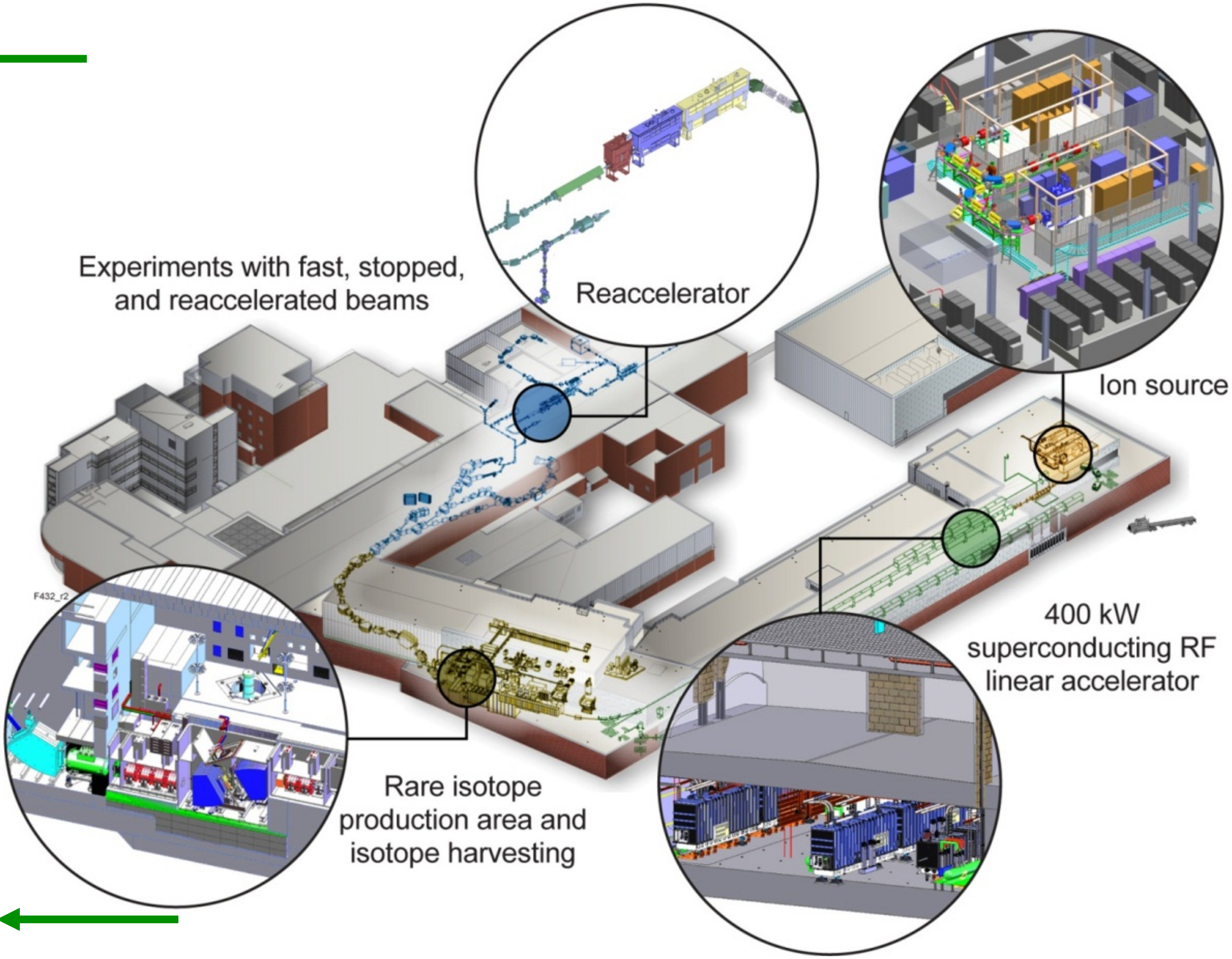
Facility for Rare Isotope Beams, FRIB

- Key Feature is 400kW beam power for all ions
- At least 200 MeV/u ^{238}U beam energy – higher for lighter beams
- Separation of isotopes in-flight
- Fast, stopped and reaccelerated beams (12 MeV/u)
- Managed for completion in 2020



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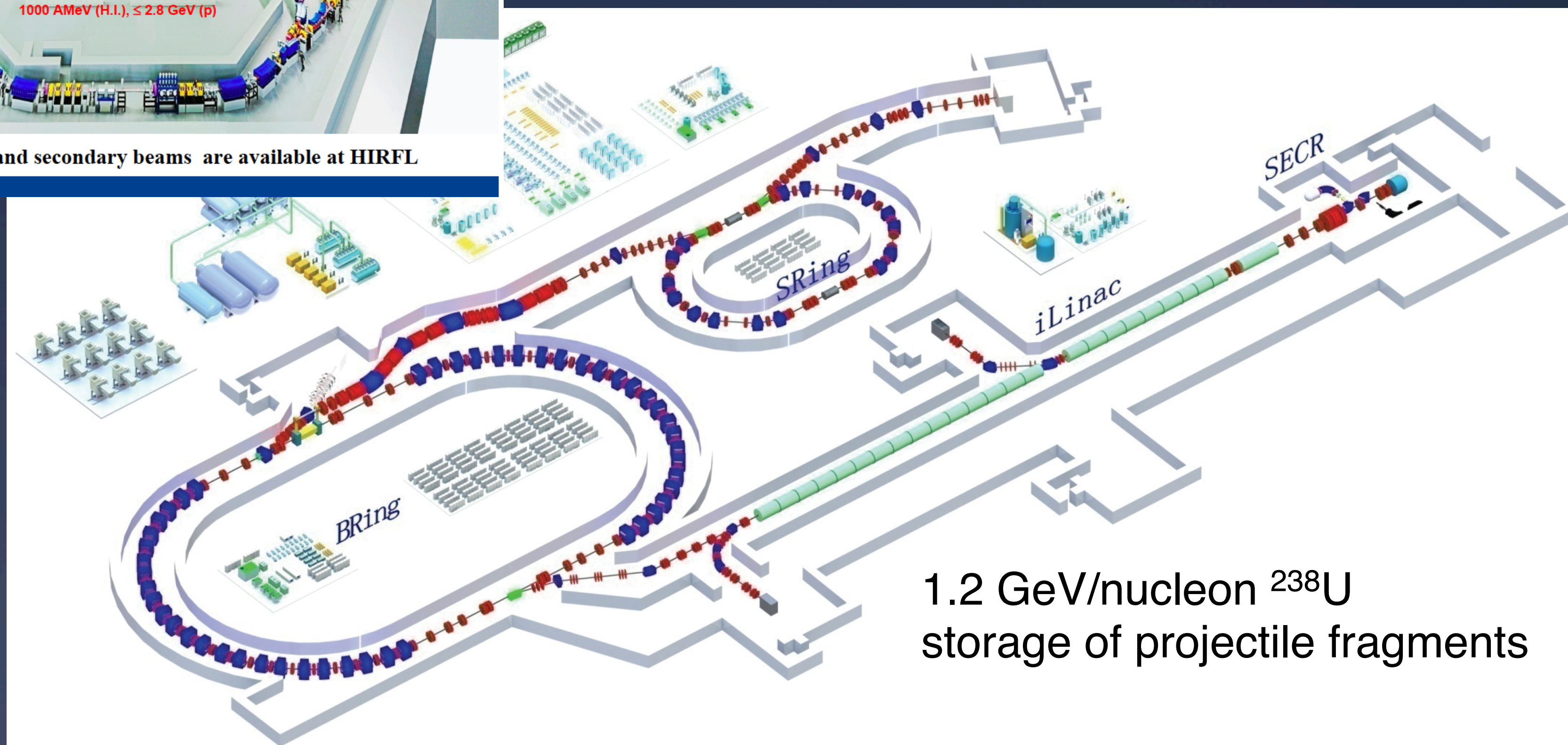
RAON,

HIRFL-CSR and future facility HIAF in China



1.2 GeV/nucleon ^{238}U
storage of projectile fragments

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Beijing ISOL, ANURIB…

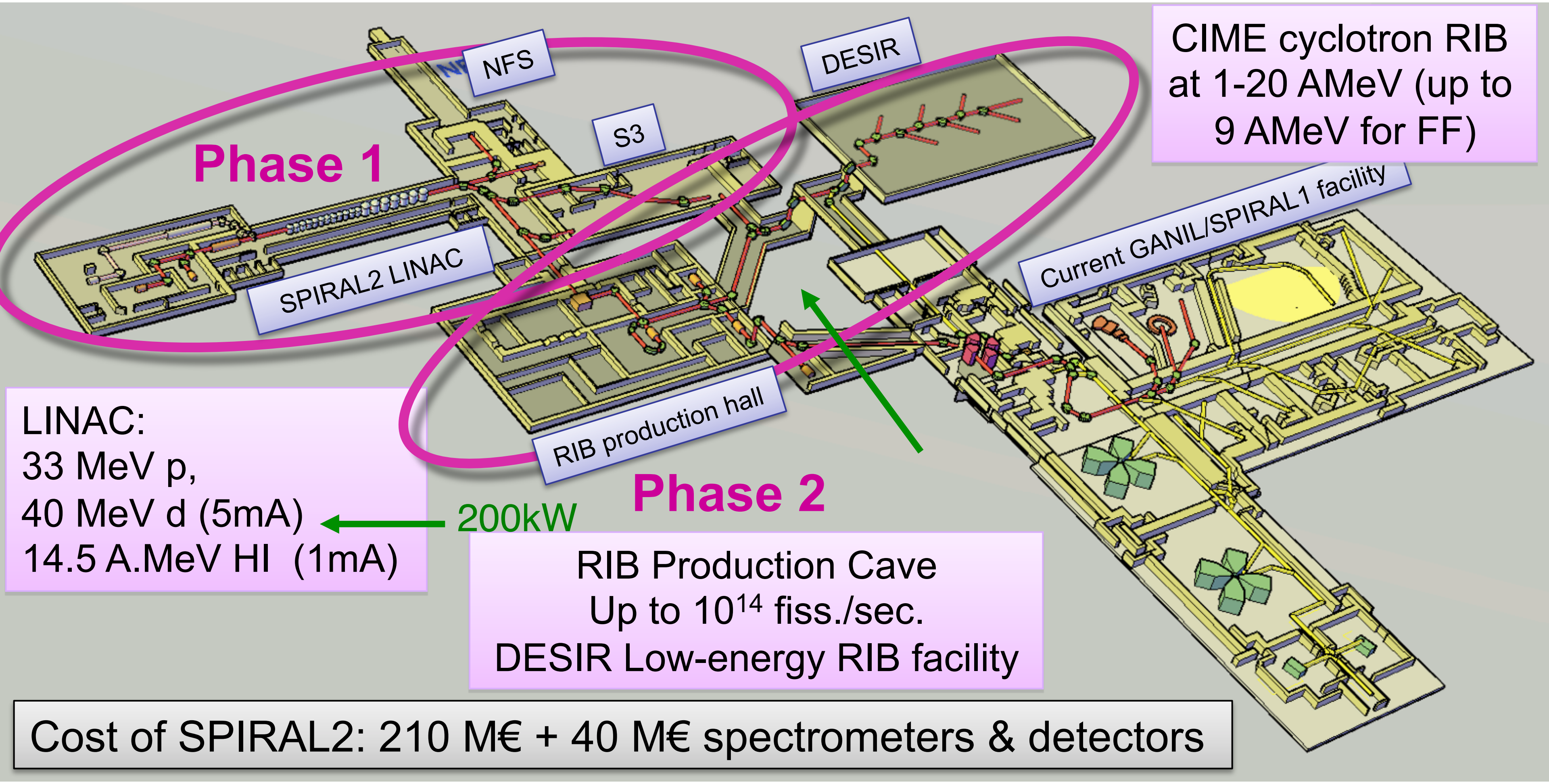
RAON,

Existing GANIL facility &
fragmentation / ISOL
SPIRAL2 under construction
ISOL

Caen, France

Phase 1: High intensity stable beams + Experimental rooms (S^3 + NFS)

Phase 2: High-intensity low-energy (DESIR) & post-accelerated Radioactive Ion Beam facility



CIME cyclotron RIB at 1-20 AMeV (up to 9 AMeV for FF)

LINAC:
33 MeV p,
40 MeV d (5mA)
14.5 A.MeV HI (1mA)

RIB Production Cave
Up to 10^{14} fiss./sec.
DESIR Low-energy RIB facility

Cost of SPIRAL2: 210 M€ + 40 M€ spectrometers & detectors

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RAON,

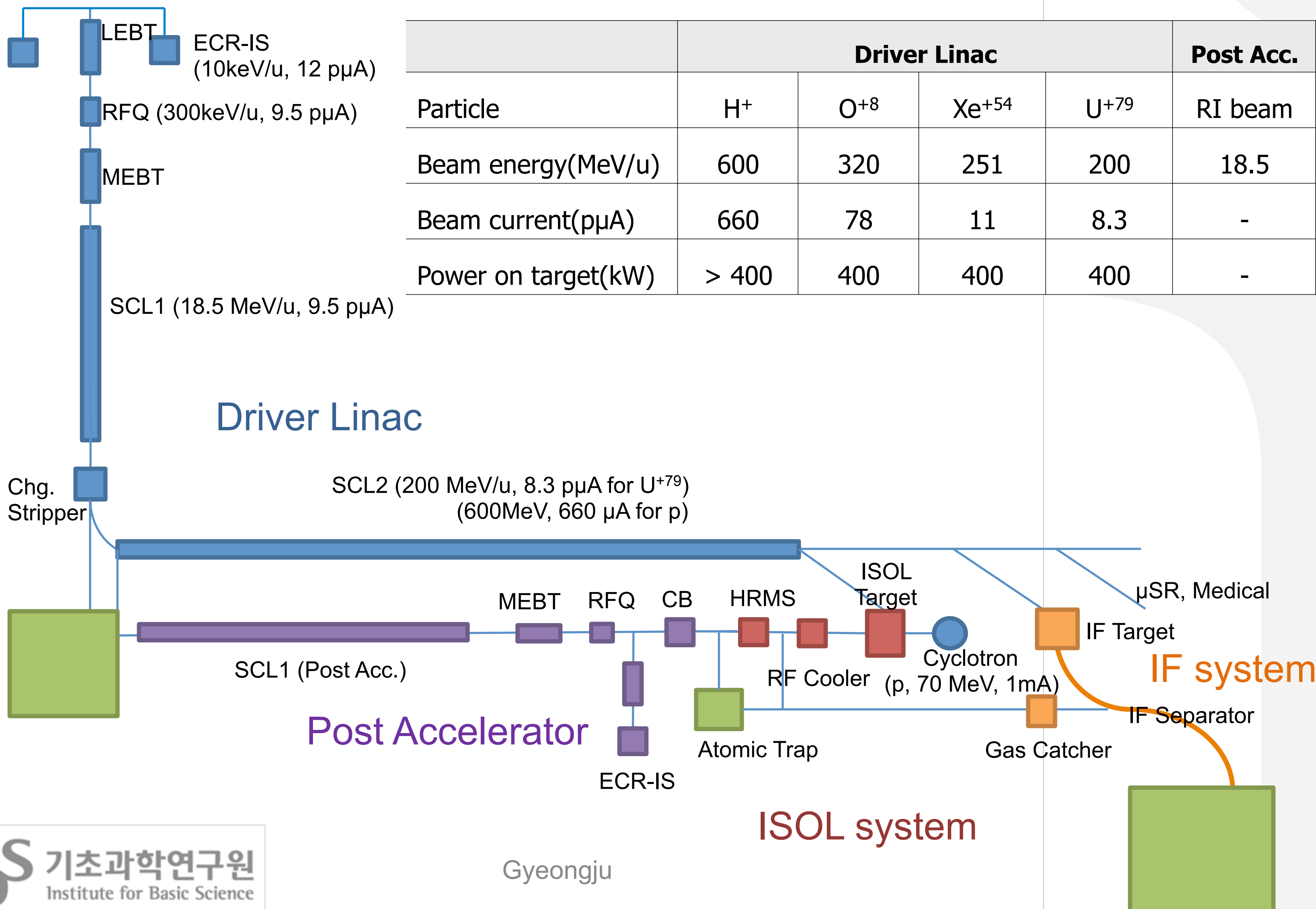
c.f. dedicated talks in “I” sessions

RAON (RISP)

Session IV, …

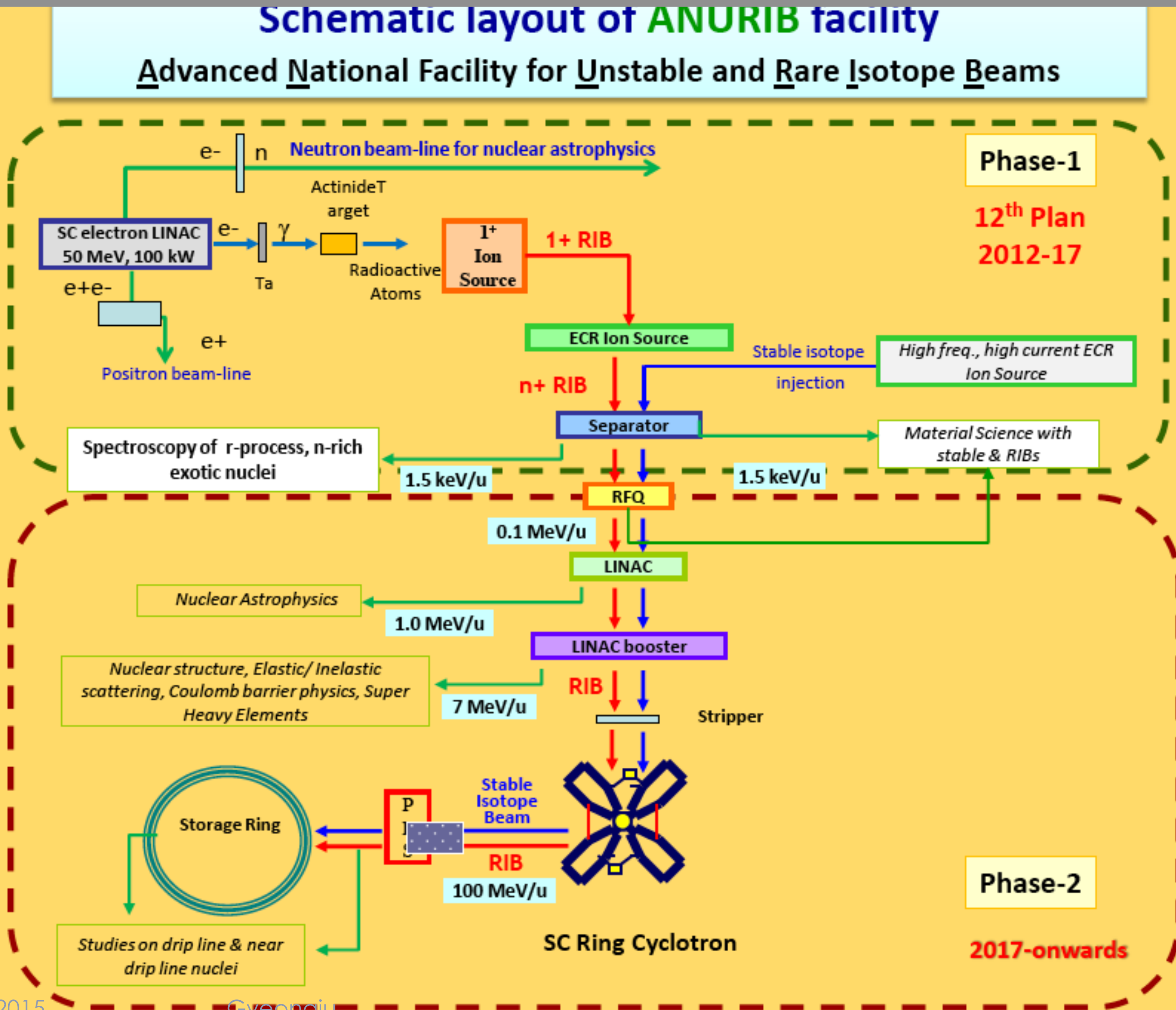
Korea

	Driver Linac				Post Acc.	Cyclotron
Particle	H^{+}	O^{+8}	Xe^{+54}	U^{+79}	RI beam	proton
Beam energy(MeV/u)	600	320	251	200	18.5	70
Beam current(pμA)	660	78	11	8.3	-	1000
Power on target(kW)	> 400	400	400	400	-	70



Project for an ISOL-based facility at VECC, Kolkata

India



ISOL Roadmap in EUROPE

TODAY

SPIRAL – GANIL

ISOLDE CERN

2 MeV/n (A=130)

INFN

LNS - EXCYT

10-20 kW

2014-2025

GANIL spiral2

HIE-ISOLDE

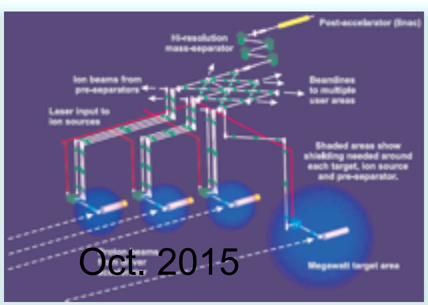
$10^{13\text{-}14}$ fission/s
10 MeV/n (A=130)

SPES exotic beams for science

100-200 kW

FROM 2025

EURISOL



> 10^{15} fission/s
100 MeV/n (A=130)

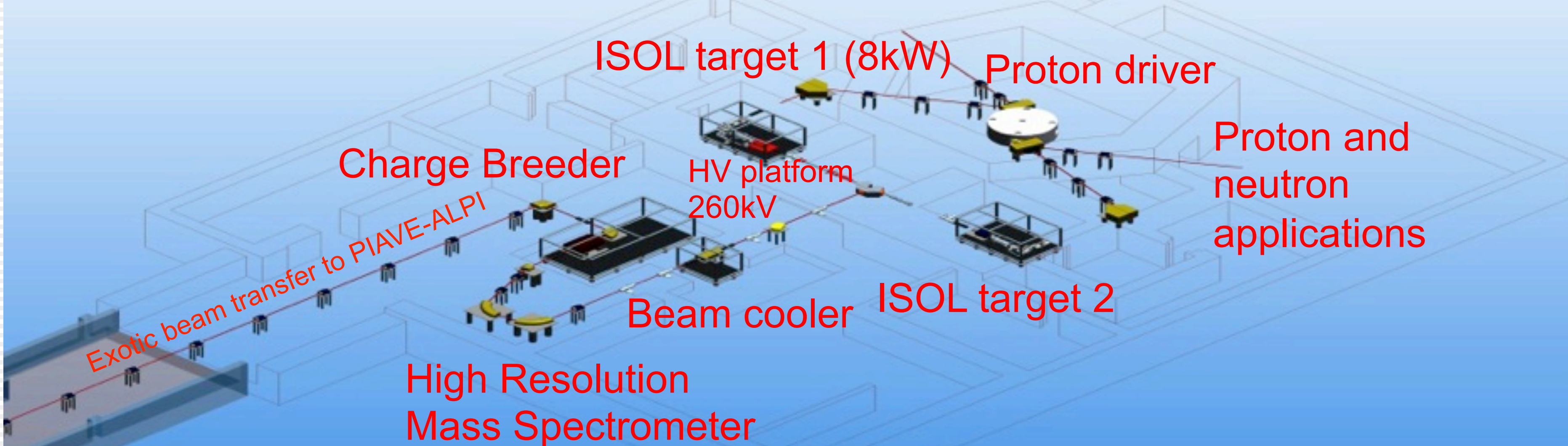
3x 100 kW direct target
1x 5 MW 2-step target

SPES ISOL facility @LNL Italy

A second generation ISOL facility for neutron-rich ion beams and an interdisciplinary research center

Proton induced fission on UCx
10^{13} fission/s - 8 kW on direct target

Selective Production of Exotic Species



Expected beam poser of “new” RI-beam facilities
estimated in 2013

in 2015? …

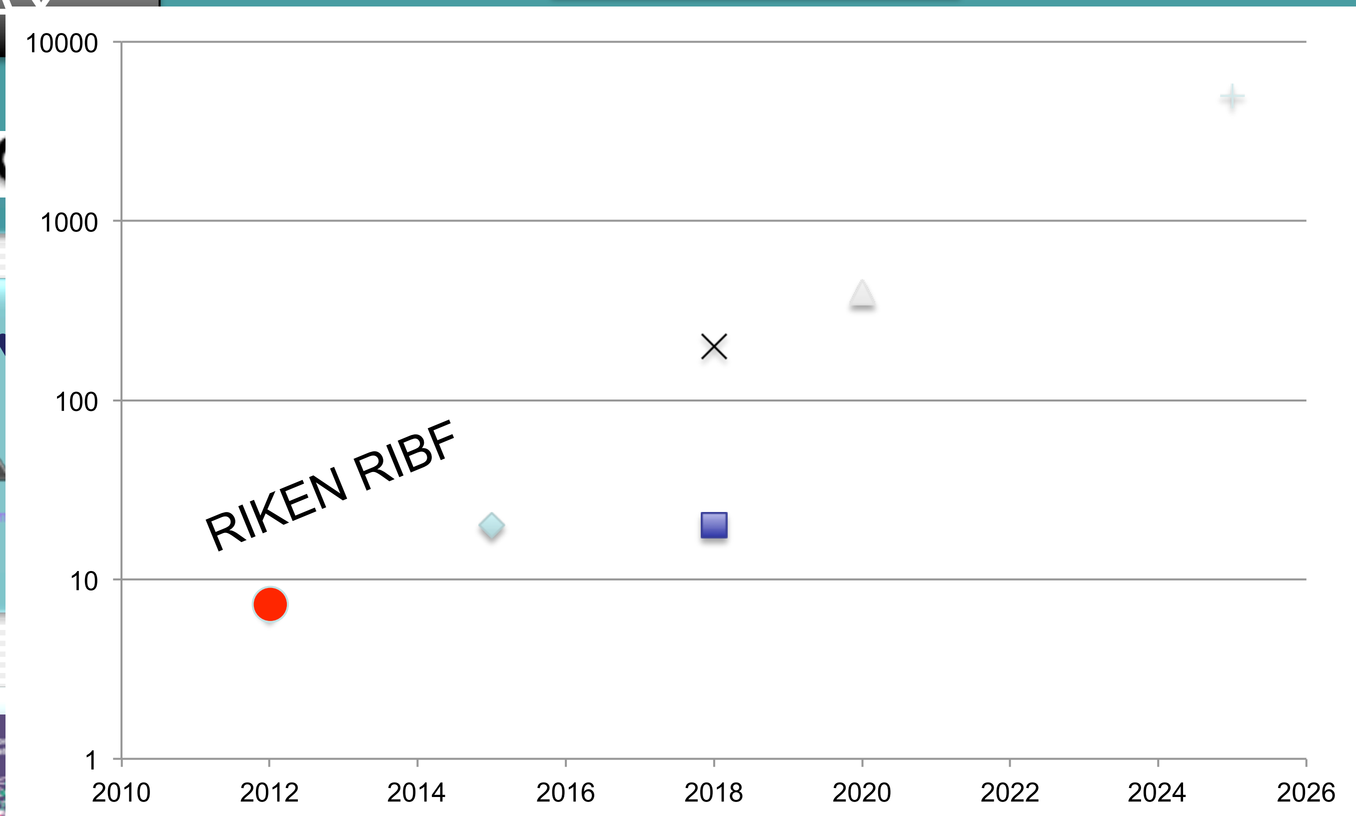
2 MeV/n (A=130)

10-20 kW

TODAY

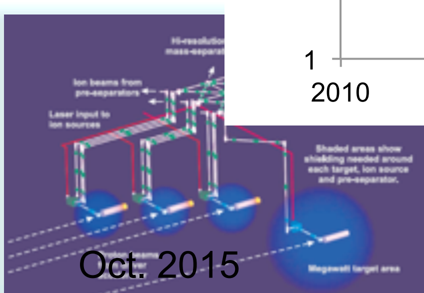
SPIRAL –

- EXCYT



100-200 kW

on/s
(A=130)



Oct. 2015

FROM 2025

Gyeongju

3x 100 kW direct target
1x 5 MW 2-step target

Questions for new/future RIB facilities

Budget
delays of construction / beam-time backlogs

Primary-beam accelerators
energy, intensity

Production scheme
developments for post-acceleration-scheme*
two-step fragmentation useuful? ← fragmentation cross section

Experimental equipment

Roadmaps
in Asia? -- ANPhA *c.f.* European ISOL Roadmap

- For difficult elements in the energy region for transfer, fusion .. (~10 MeV/nucleon)
  - deceleration of fast beams
  - gas catcher + reacceleration
  - ion source development

Summary

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- facility examples
- “world map”

“new generation” facilities
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- ISOL-based (reacceleration) facilities
- other types

“Questions”
- to ANPhA

Thanks to many colleagues