Nuclear Physics & Astrophysics at CERN - NuPAC

Review 1: Present and Future of ISOLDE

Facilities for Radioactive Beams – a brief overview
Input for nuclear physics and astrophysics modeling
Tests of Fundamental Interactions & Symmetries
Solid State Physics
A Scenario for ISOLDE at CERN in the coming years

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GSI Darmstadt and University of Heidelberg

CERN, Geneva, Switzerland, October 10 - 12, 2005

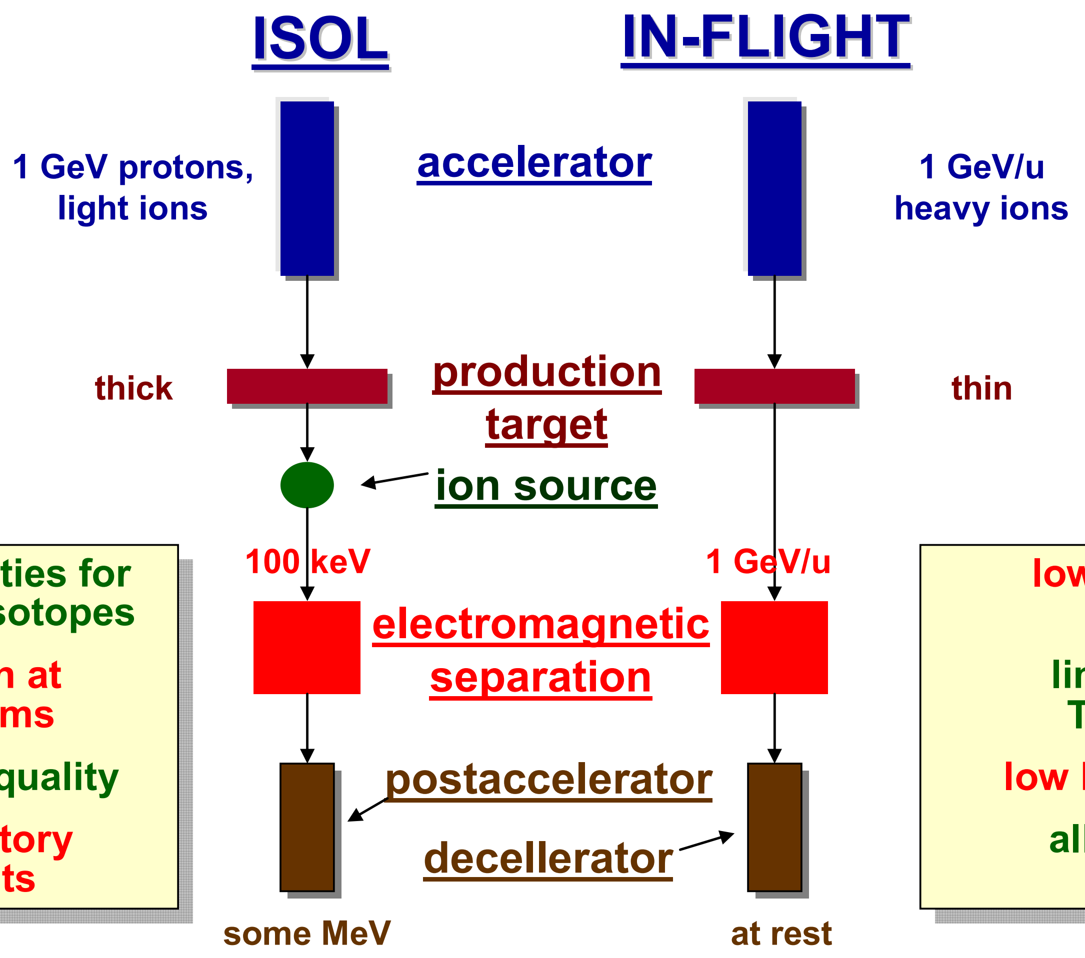
..... also my believe .....

Heinz Maier-Leibnitz (1911-2000)

"Whenever you invent a method* ten or a hundred times better than the existing ones, you can be sure that this will lead to new science!"

* or facility

RIB Production: ISOL Versus In-Flight



ISOL

IN-FLIGHT

1 GeV protons,
light ions

accelerator

1 GeV/u
heavy ions

thick

production
target

thin

ion source

100 keV

1 GeV/u

electromagnetic
separation

postaccelerator

decellerator

some MeV

at rest

high intensities for
long-lived isotopes

limitation at
$T_{1/2} < 10$ ms

high beam quality

no refractory
elements

low intensities

limitation at
$T_{1/2} < 10\ \mu s$

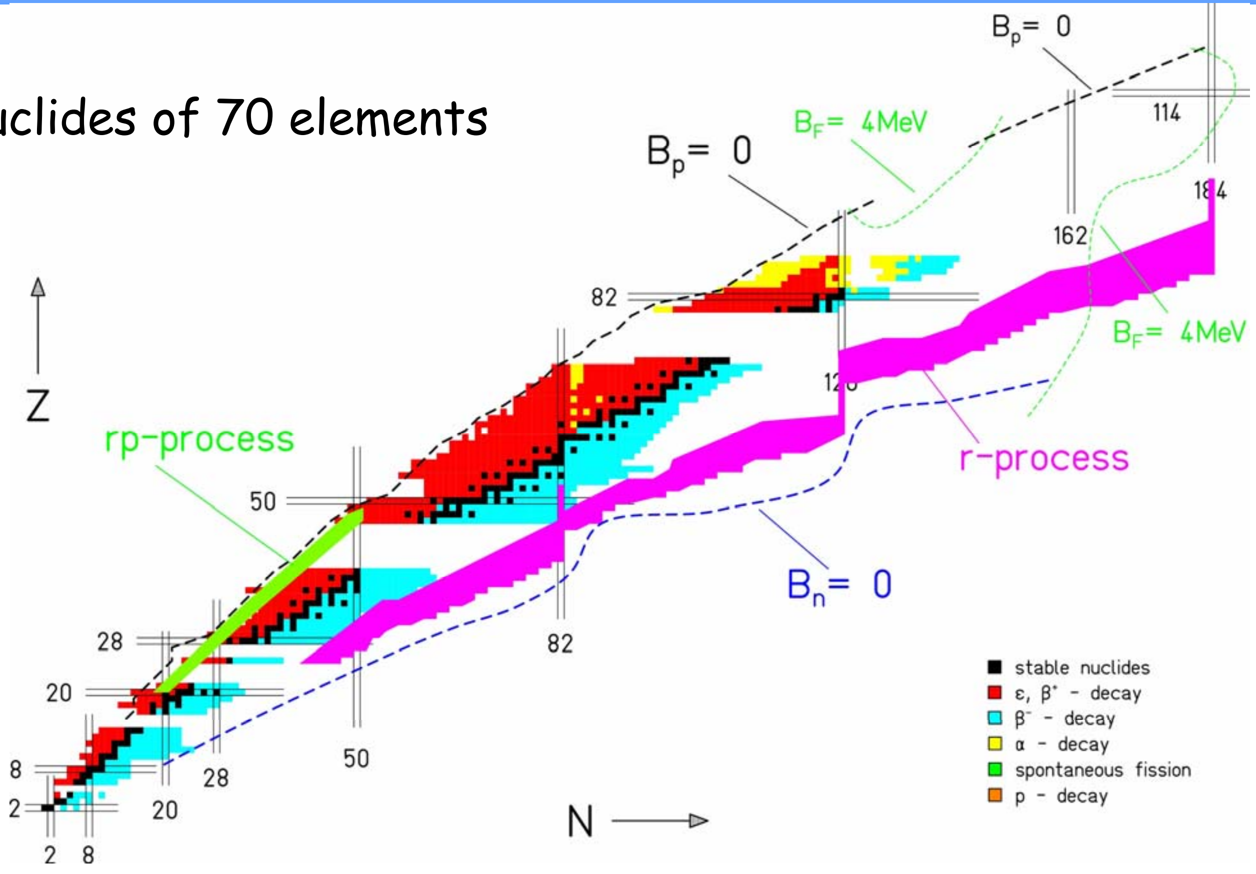
low beam quality

all elements

ISOL and in-flight facilities have unique
and complementary features

Elements and Isotopes Accessible at ISOL Facilities

850 radionuclides of 70 elements



Gaps can be filled by IGISOL and in-flight facilities.
Elements and isotopes above uranium are accessible by fusion reactions.
Third dimension (high spin states) is domain of heavy-ion facilities.

What Should be Measured? An Example:

Request by Stéphane Goriely:
Challenges in *experimental* nuclear physics

Measurement of given properties for a large set of nuclei:

- masses and structure properties of stable and exotic nuclei
- resonance spacings at S_n
- photo absorption data and $<\Gamma_\gamma>$ data
- n, p and α elastic scattering and $<\Gamma_n>$ data
- fission barriers
- reaction cross section (n,p,α-captures)

Cross section measurement for a given well-defined astrophysics scenario:

- stellar evolution:
  hydrostatic burning phases (H-, He-, C-burning): $^{12}C(\alpha,\gamma)^{16}O$, $^{12}C+^{12}C$
  explosive phases (SNIa): α-chains on ^{12}C and ^{14}C
- neutron source for nucleosynthesis: $^{22}Ne(\alpha,n)^{25}Mg$
- nucleosynthesis: (n,γ) cross sections for the s-process
- γ-astronomy: e.g $^{60}Fe(n,\gamma)^{61}Fe$

Example for Input for Nuclear Physics and Astrophysics Modeling: Nuclear Ground State Properties

* **MASS** — nuclear binding energy

* **NUCLEAR HALF-LIFE** — decay rates

* **HYPERFINE STRUCTURE**

1. Hyperfine Interaction
   $J + I = F$ — nuclear spin
2. Magnetic Dipole HFS
   $A = \mu_I \langle H(0)\rangle / I\,J$ — nuclear magnetic moment
3. Electric Quadrupole HFS
   $B = e_0 Q_s \langle \varphi_{zz}(0)\rangle$ — spectroscopic quadrupole moment

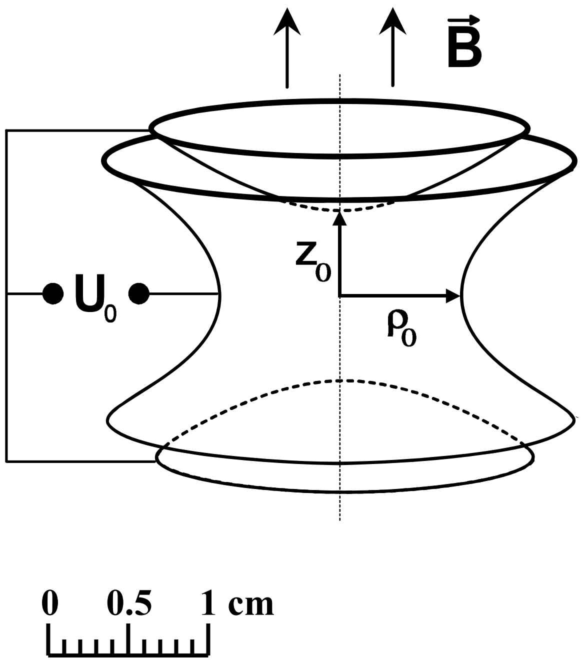
* **ISOTOPE SHIFT**

Finite Size Effect
$\delta \langle r^2\rangle^{A,A'}$ — change of ms charge radius

This information is model independent

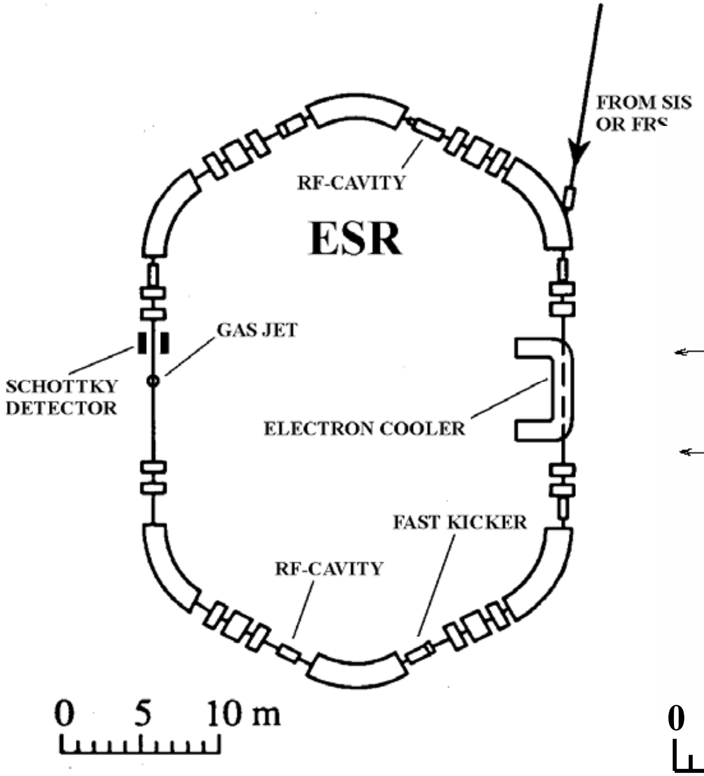
New Devices at Accelerators for Nuclear Studies

PENNING TRAP
or PAUL TRAP



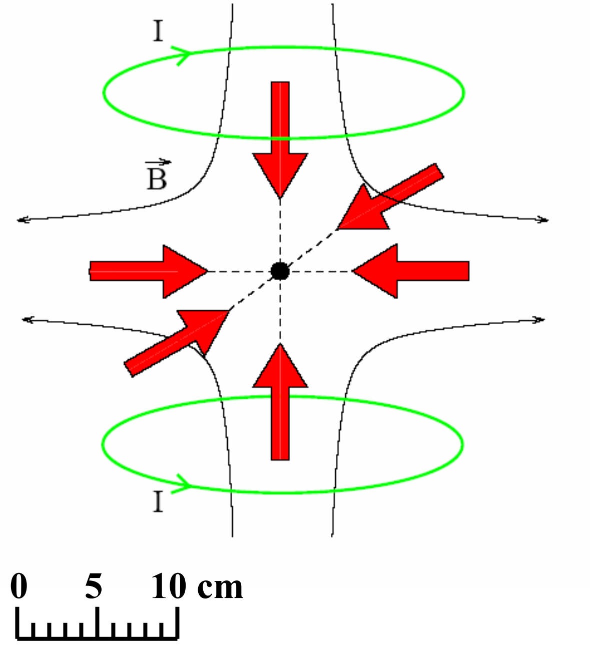
particles at nearly rest in space

STORAGE RING



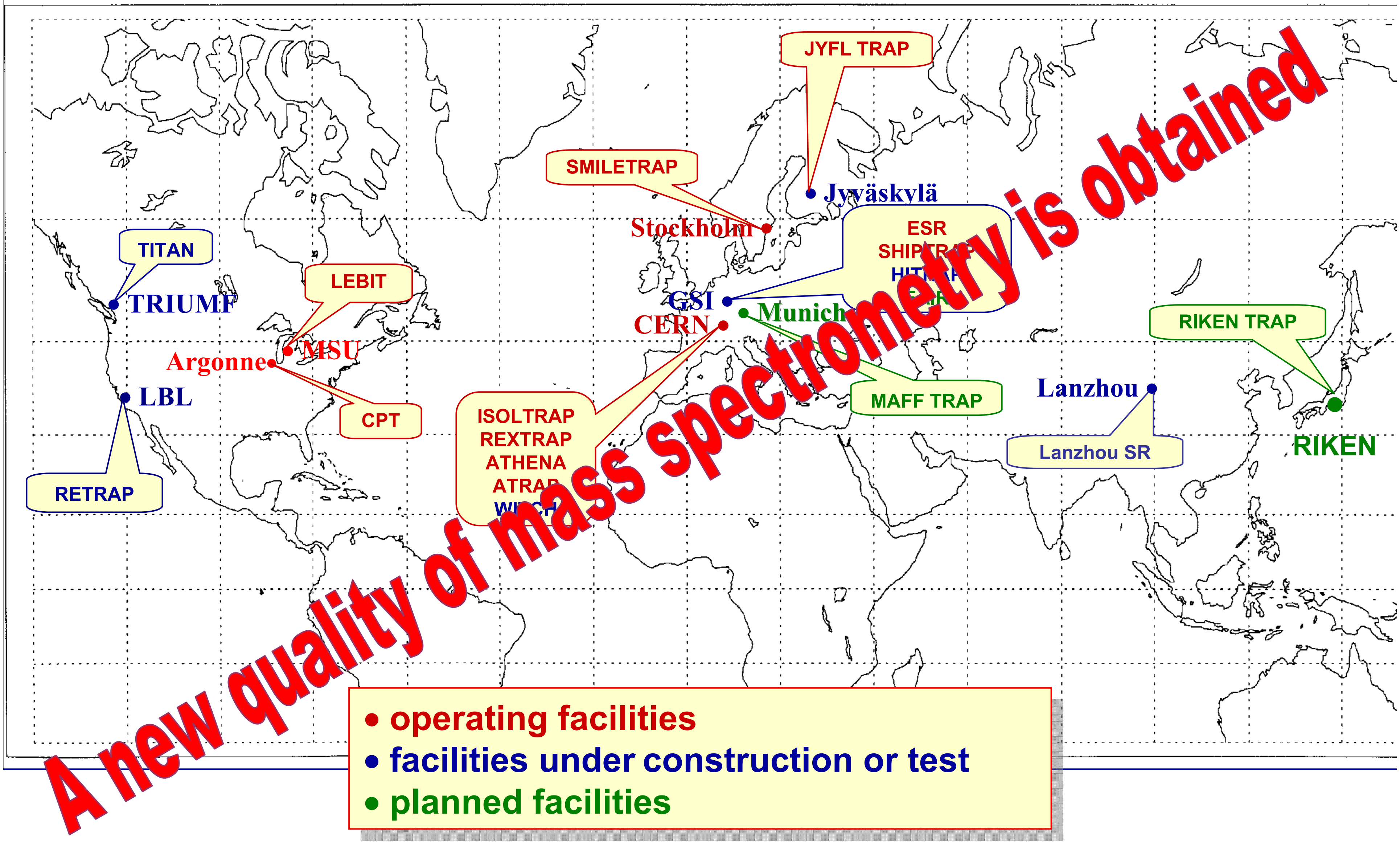
relativistic particles

LASER TRAP



particles at nearly rest in space

Penning Traps and Storage Rings at Accelerators for Nuclear Physics



A new quality of mass spectrometry is obtained

- operating facilities
- facilities under construction or test
- planned facilities

Expectations for Mass Measurements at ISOLDE

Solving the isobar problem for low-energy radioactive ion beams
  laser ion source (trap), better performance of HRS

Reaching single-ion sensitivity
  non-destructive ion detection (FT-ICR), single-ion detection for RIB

Towards higher resolving power and isomer separation
  higher charge states

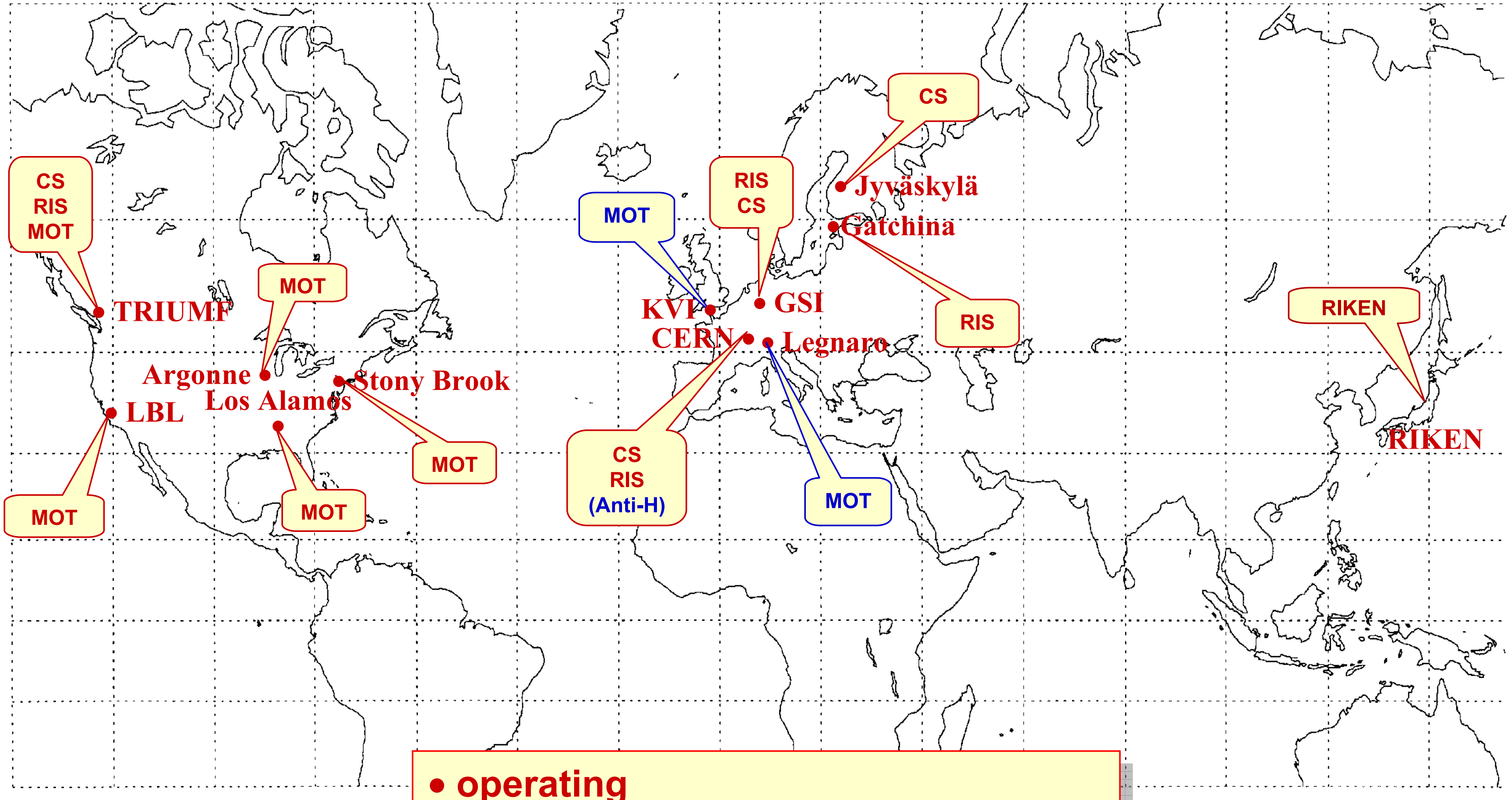
Towards shorter-lived nuclides
  higher intensities, higher charge states, higher efficiencies

Reaching extreme accuracy
  higher charge states, higher magnetic field, carbon cluster

Mass measurements with storage rings require masses for calibration of effective magnetic field

Presently, high-accuracy mass measurements ($\delta m/m \leq 10^{-7}$) are only possible by use of Penning traps

Laser Spectroscopy of Radionuclides at Accelerators



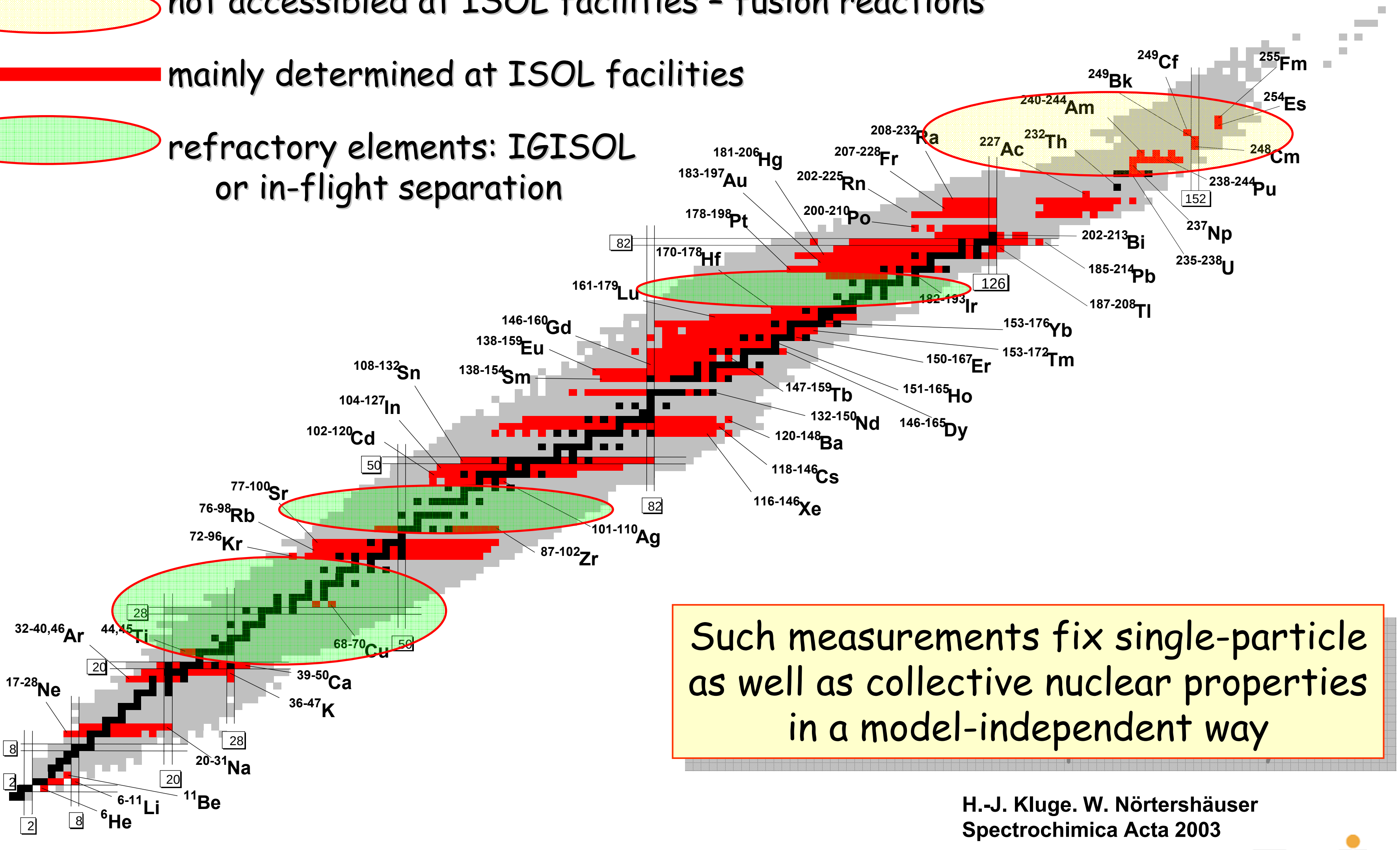
- ● operating
- ● under development or test

Laser Spectroscopy in Long Isotopic Chains

🟨 not accessible at ISOL facilities – fusion reactions

🟥 mainly determined at ISOL facilities

🟩 refractory elements: IGISOL
or in-flight separation



Such measurements fix single-particle as well as collective nuclear properties in a model-independent way

H.-J. Kluge. W. Nörtershäuser
Spectrochimica Acta 2003

Expectations for Laser Spectroscopy at ISOLDE

...... and also generally for nuclear spectroscopy

Solving the isobar problem for low-energy radioactive ion beams
    laser ion source (trap), better performance of HRS

Towards higher sensitivity
    cooled and bunched beams, spectroscopy in the laser ion source (trap), magneto-optical trap

Towards higher resolution
    cooled beams, magneto-optical trap

Towards shorter-lived nuclides
    higher intensities, higher efficiencies

ISOL facilities are best suited for laser spectroscopy of RIB

Experiments performed at ISOLDE are and were most successful

Hyperfine fields have to be known with high accuracy
– theoretical work or exp. information from few-electron systems required

A close collaboration between theoreticians and experimentalists
is required for determination of charge radii of light isotopes

Test of Fundamental Interactions and Symmetries

Search for scalar and tensor contributions to weak interaction

Test of CVC hypothesis

Unitarity of the CKM quark mixing matrix

Parity violation by neutral currents in heavy atomic system

Search for an electric dipole moment

Traps for Weak Interaction Physics

Atom traps

- TRIUMF-ISAC	^{38m}K, $\beta\nu$-correlation (J. Behr et al.) A. Gorelov et al., Hyperfine Interactions 127 (2000) 373
- LBNL & UC Berkeley	^{21}Na, $\beta\nu$-correlation (S.J. Freedman et al.) N. Scielzo, Ph. D. Thesis (2003)
- LANL Los Alamos	^{82}Rb, β-asymmetry (D. Vieira et al.) S.G. Crane et al., Phys. Rev. Lett. 86 (2001) 2967
- KVI-Groningen	Na, Ne, Mg, D-coefficient (K. Jungmann et al.) Ra, EDM experiment G.P. Berg et al., NIM B204 (2003) 526

Ion traps

- LPC-Caen	^{6}He, $\beta\nu$-correlation (O. Naviliat-Cuncic et al.) G. Ban et al., NIM A518 (2004) 712
- Leuven-ISOLDE	^{35}Ar, $\beta\nu$-correlation (N. Severijns et al.) M. Beck et al., Nucl. Inst. Methods Phys. Res., A 503 (2003) 567
- CPT-trap Argonne	^{14}O, $\beta\nu$-correlation (G. Savard et al.) G. Savard et al., Nucl. Phys. A654 (1999) 961c
- ISOLTRAP-CERN	mass for $0^+ \rightarrow 0^+$ decays (K. Blaum et al.)
- CPT-Argonne	mass for $0^+ \rightarrow 0^+$ decays (G. Savard et al.)
- JVL-Trap, Jyväskylä	mass for $0^+ \rightarrow 0^+$ decays (J. Äystö et al.)
- LEBIT, MSU	mass for $0^+ \rightarrow 0^+$ decays (B. Bollen et al.)

Expectations for Weak Interaction Studies at ISOLDE

Solving the isobar problem for low-energy radioactive ion beams
  laser ion source (trap), better performance of HRS

Towards higher injection efficiency into traps
  cooled and bunched beams

Towards higher accuracy
  higher intensities

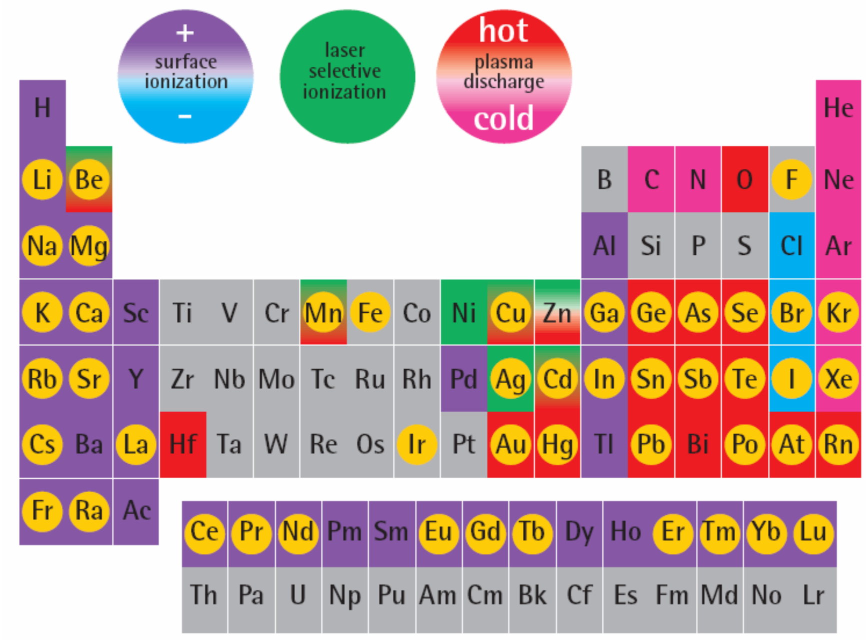
More beam time

ISOL facilities are best suited for weak interaction studies and parity tests

Such experiments need a lot of beam time for checking systematic errors

Parity tests and determination of the anapole moment require high intensities. Experiments on Fr only realistic at ISOLDE.

Why Radioactive Isotopes for Solid State Physics and Life Sciences?



isotopes of this element

●

used for solid state physics
or life science

Sensitivity: Nothing is more easily to detect with high sensitivity than nuclear radiation. Very low concentrations of radioactive impurity atoms in a material or on a surface or interface can be detected.

Local information: Hyperfine interaction (ME, PAC) and emission channeling deliver local information on lattice sites and neigborhood.

Selectivity: Element transmutation due to the radioactive decay add chemical selectivity to “classical” spectroscopy techniques (photoluminescence, deep level transient spectroscopy)

Expectations from Solid State Physics and Life-Sciences at ISOLDE

Solving the isobar problem for low-energy radioactive ion beams
  laser ion source (trap), better performance of HRS

New beams: Filling up gaps in the available elements
  radioactive beams with sufficient yield for elements in the region Mn to Ni, S, P, and possibly the light elements N and O

Higher yields
  at least 10^7 – 10^8 ions/s

Beam focusing down to 0.5 mm diameter for emission channeling
  cooled beams

Repetition rate
  specific RIBs should be available several times per year

On-line space for permanent equipment installed at a beam line
  ASPIC, EC, diffusion,…

Lab space for pre- and post-implantation treatment and off-line experiments

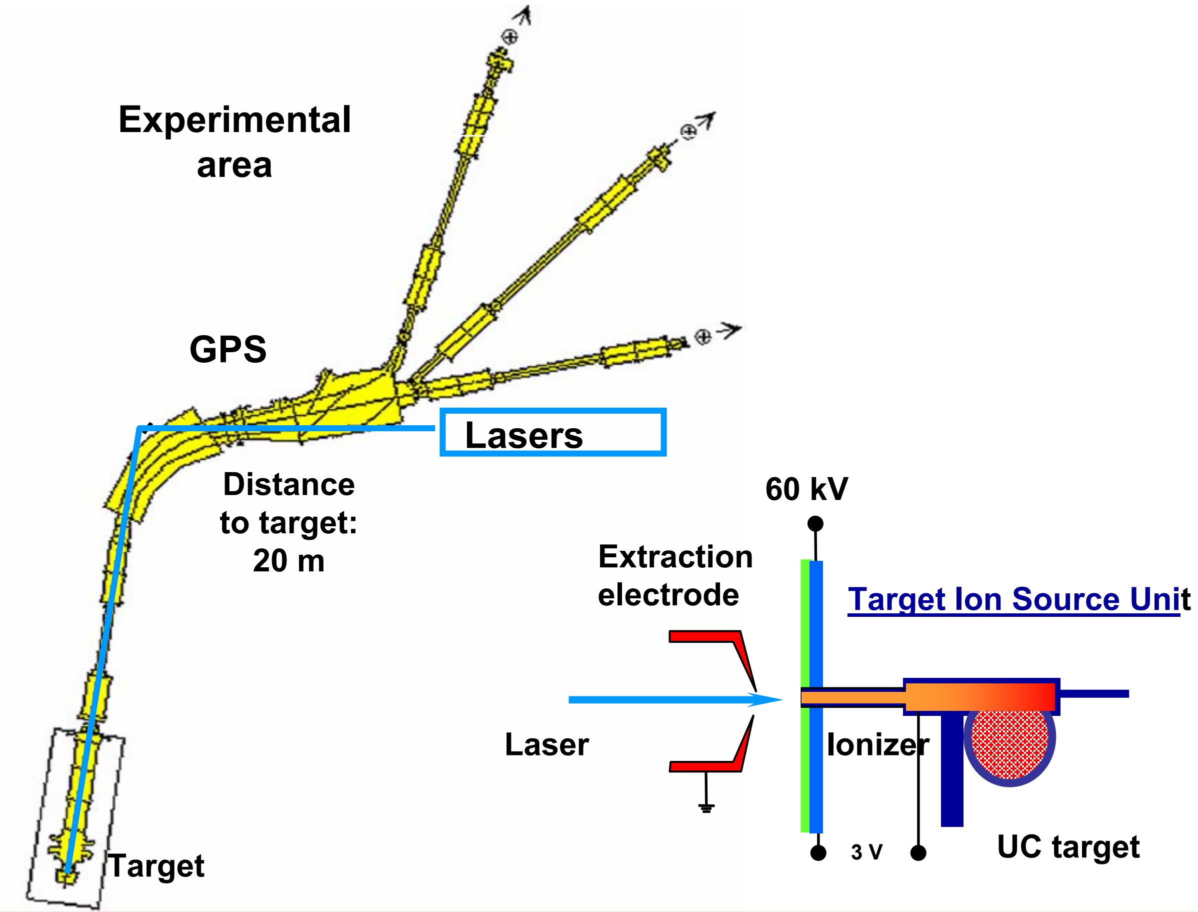
What Makes ISOLDE (still) World-Wide Competitive, if not Leading?

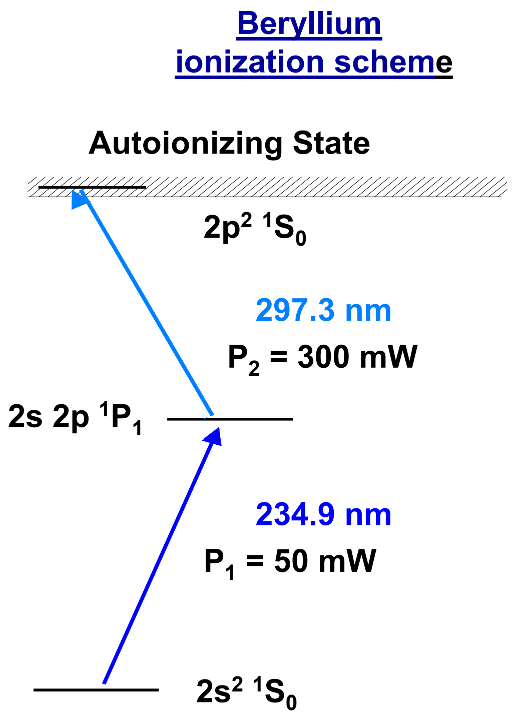
.... the unique methods developed at ISOLDE...

- long-standing expertise in target/ion source systems
  developed since more than 30 years
- diversity of available ion species
  for example, uranium target with different ion sources
- fast change over from one target/ion source system to another
  short beam times possible with optimized target/ion source
- diversity of scientific disciplines
  nuclear, solid state, surface, atomic, bio physics
- on-the-spot expertise in complex experimental set-ups
  laser spectroscopy – LIS – LIST
  mass spectrometry – RFQ Cooler – REX-ISOLDE

example: laser ion source

Laser Ion Source



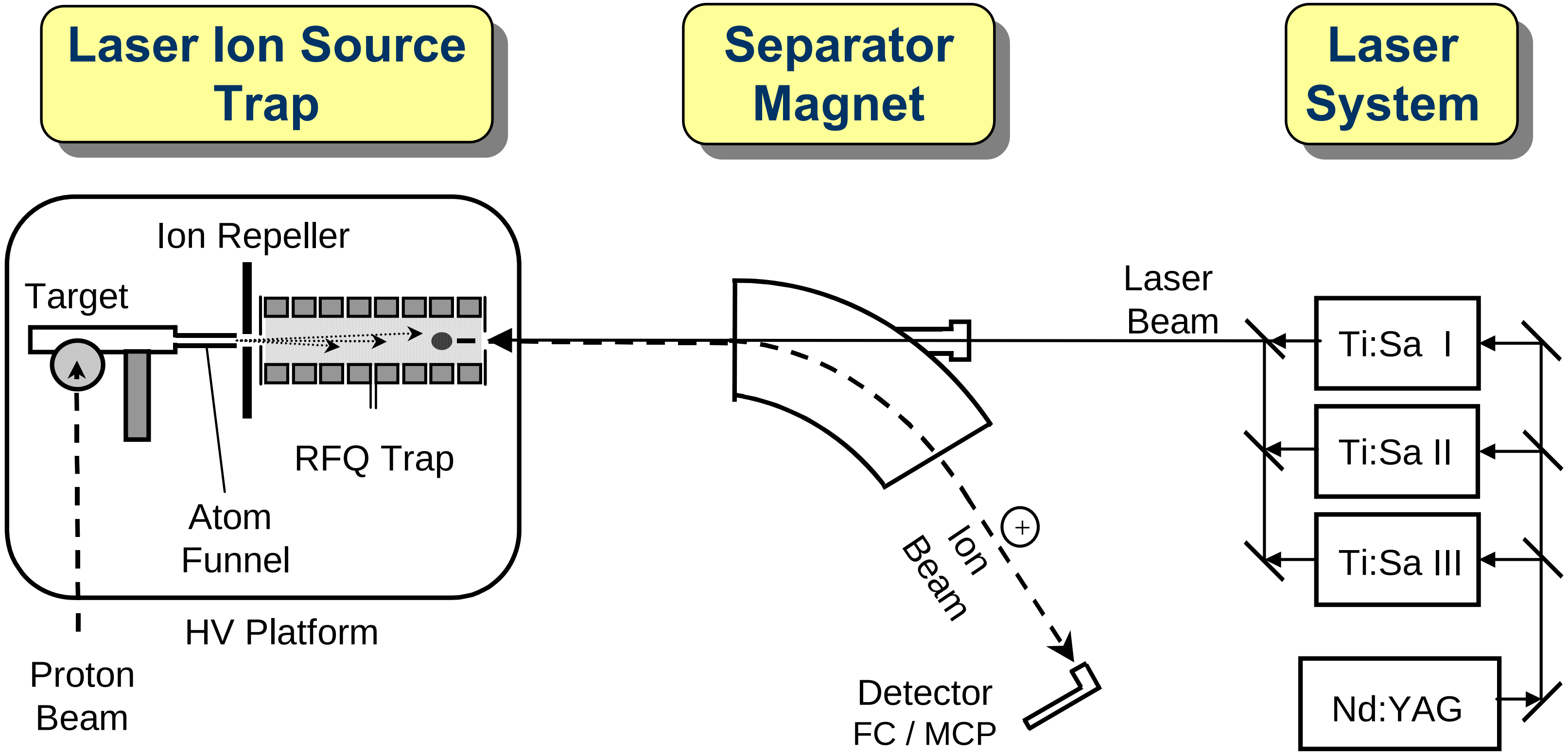


First developed for trace analysis and laser spectroscopy of radionuclides

Now applied at ISOL facilities for selective and efficient ionization

Problem to be solved: interference by isobaric ions and molecules which are surface ionized

LIST – Laser Ion Source Trap



First off-line demonstration at Mainz (Klaus Wendt et al., 2004)
Development going on at Mainz and Jyväskylä
Efficient and highly selective ionization
Suppression of isobars
Dc and bunched beams with low emittance
Polarized radioactive ion beams by optical pumping

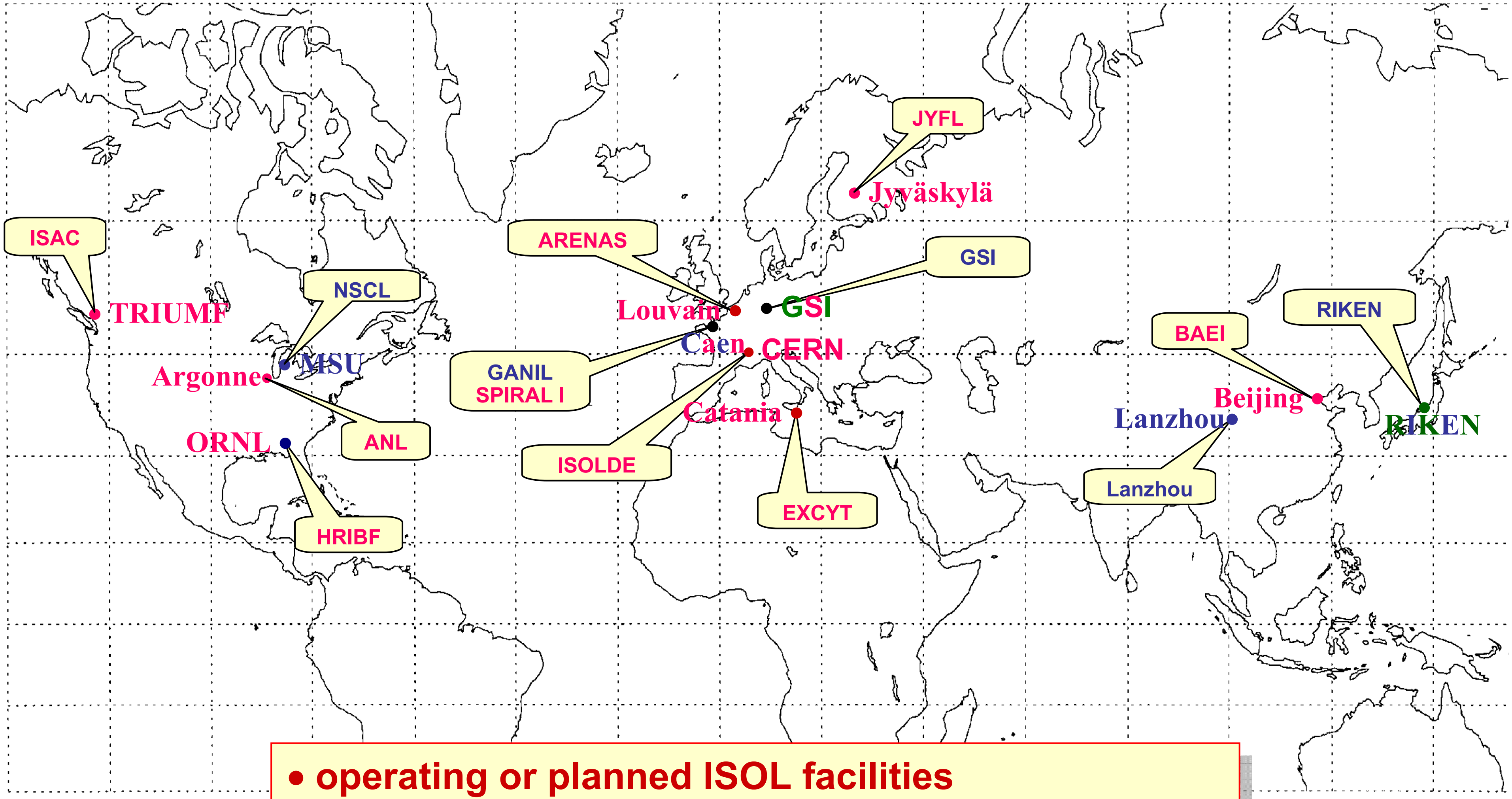
K. Blaum et al., NIM 2003

What Should be Done to Keep ISOLDE Unique and Competitive?

1. Purer radioactive ion beams
   HRS upgrade, laser ion source (trap), negative-ion source for halogens
2. Intensified development of new target/ion source systems for RIB
   increase of personnel
3. Improved beam quality: emittance, time structure, higher charge states
   radio frequency quadrupole cooler and buncher, laser ion source (trap), charge breeding
4. More beam time and intensity
   more protons for ISOLDE, faster cycling of PSB, new injector (LINAC 4), more personnel
5. Higher energies for REX-ISOLDE
   see review by Isao Tanihata
6. Better use of available beam time and more efficient service to users
   increase of technical staff

see the HIE-ISOLDE proposal

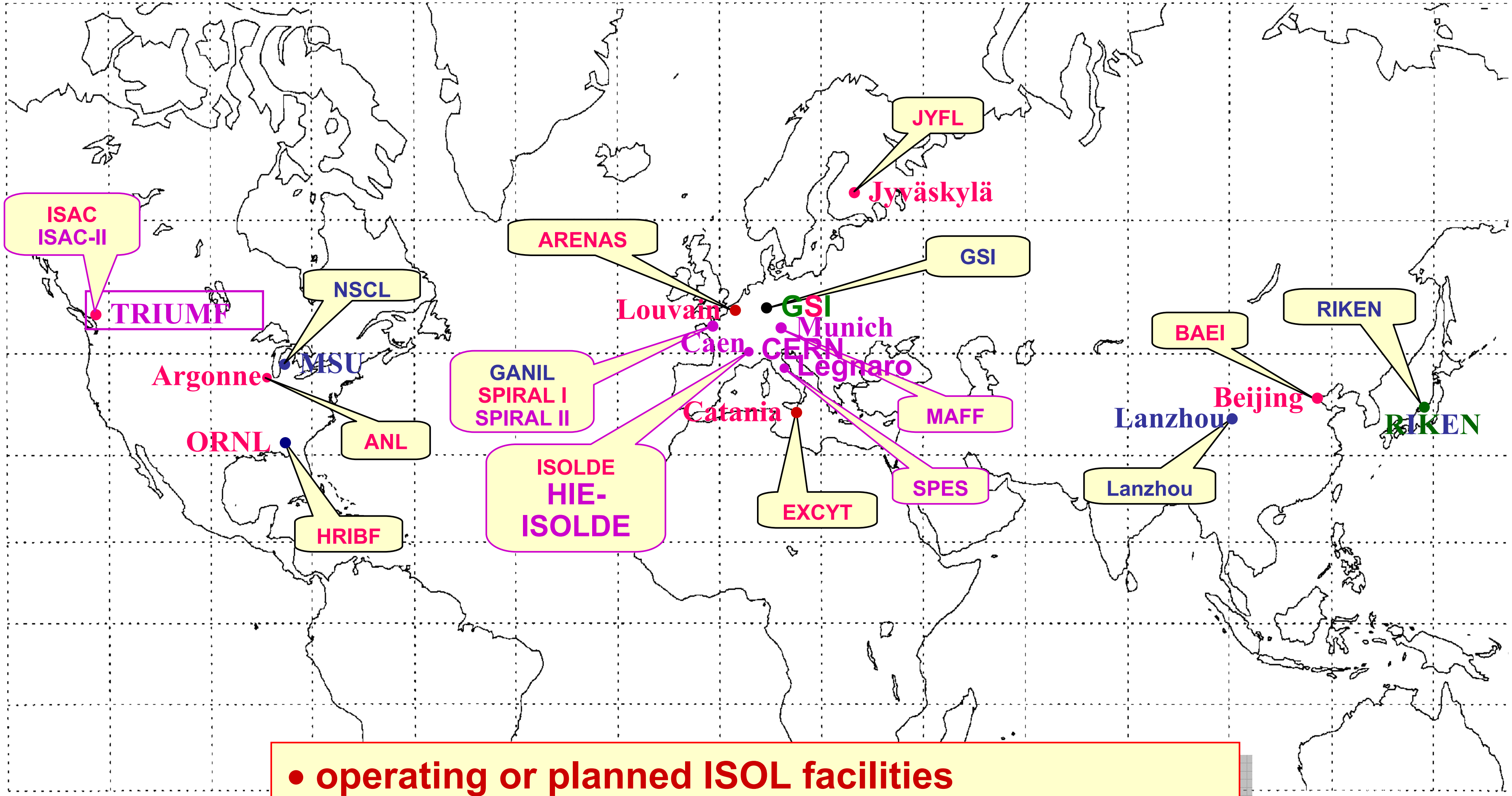
Radioactive Ion Beam Facilities
Present = 1st Generation



- ● operating or planned ISOL facilities
- ● operating or planned in-flight separation facilities

Radioactive Ion Beam Facilities

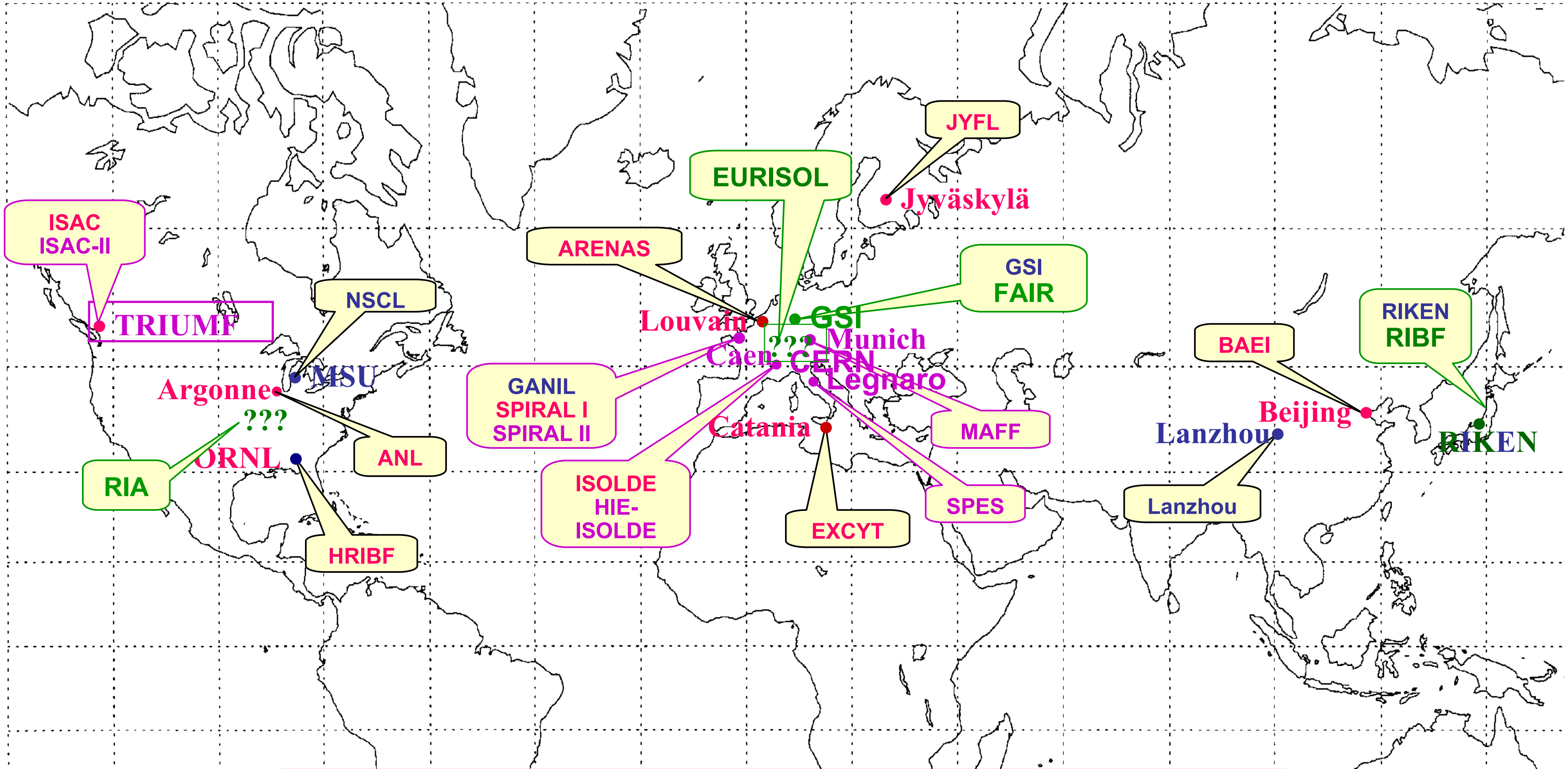
Next: 2nd Generation



- operating or planned ISOL facilities
- operating or planned in-flight separation facilities
- 2nd generation

Radioactive Ion Beam Facilities

Next: 3rd Generation



- ● operating or planned ISOL facilities
- ● operating or planned in-flight separation facilities
- ● 3rd generation

Conclusion

Invent methods which are ten or a hundred times better than the existing ones.

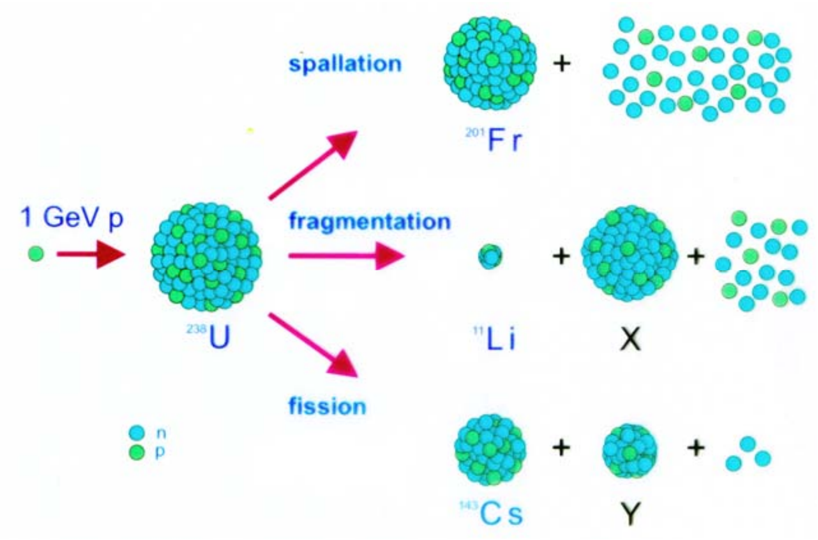
There are many route to this goal:

Increase the primary-beam intensity.
Improve the efficiency of secondary-beam production.
Reduce the background.
Push your experiment to maximum effectiveness.

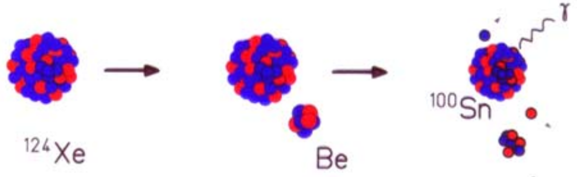
We should use all possibilities!

Reaction Mechanisms for RIB

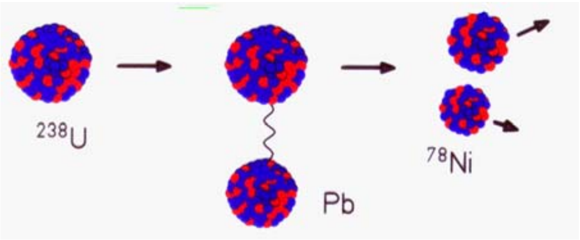
Proton-induced reactions



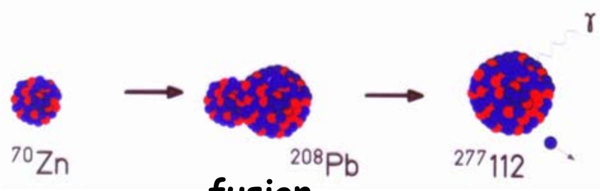
Heavy-ion-induced reactions



fragmentation



Coulomb dissociation



fusion

Reaction rate:

$$R = \sigma_{reaction} \cdot \phi_{primary} \cdot N_{target}$$

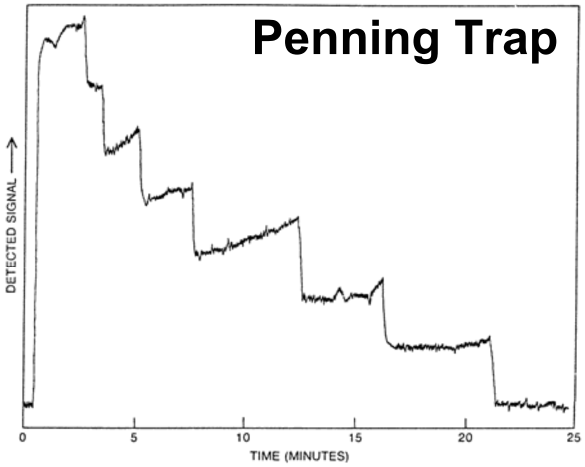
cross sections	1 pb – > 10 b
beam flux	10^{11} – 10^{15} /cm^2 /s
target thickness	0.1 – 100 g/cm^2

$$I_{RIB} = \varepsilon \cdot R$$

→

1 / months - > 10^{12} / s

In Principle: Single-Atom Sensitivity

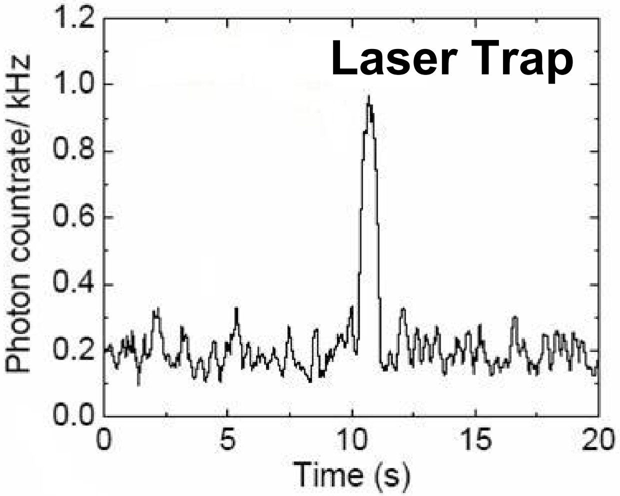


Electronic Detection of 1–7 Electrons

Dehmelt et al.

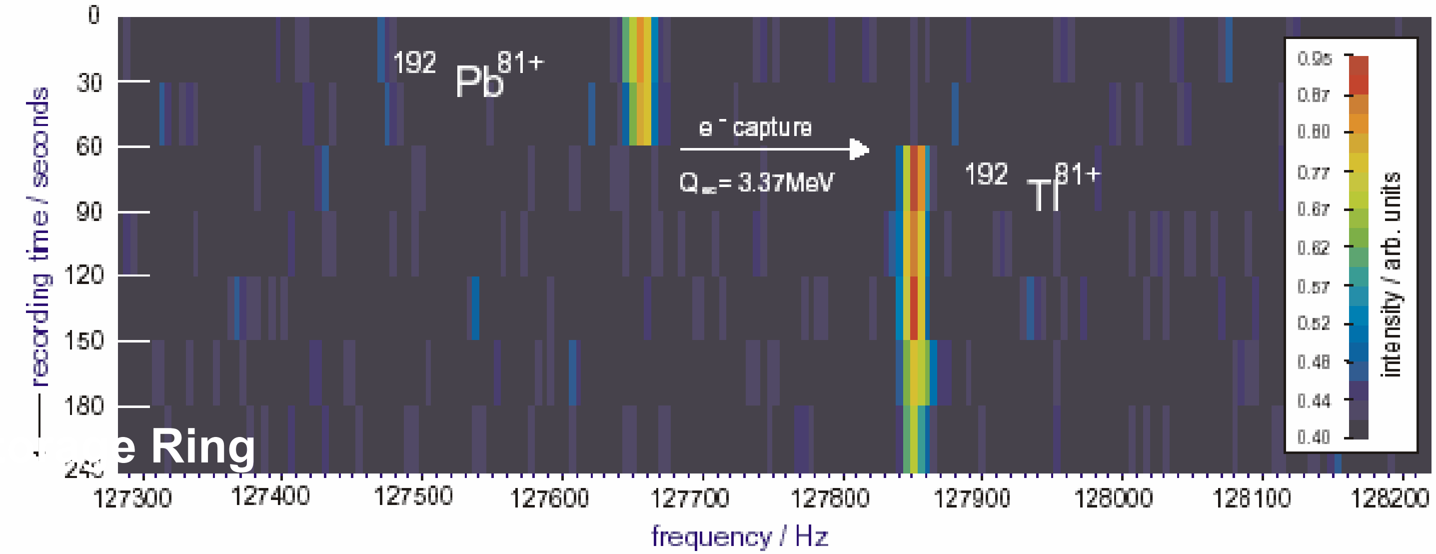
Optical Detection of a Single Barium Ion

Dehmelt, Toscheck et al.



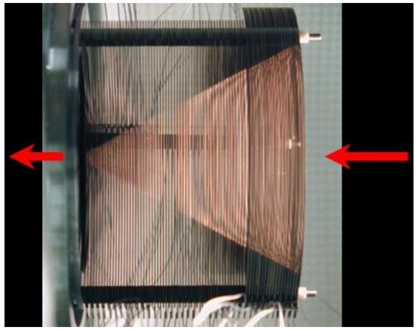
Optical Detection of a Single ^{6}He atom

Müller, Lu et al.



Electron Capture of a Single Tungsten Ion, Bosch, Litvinov et al.

Nuclear-Physics Applications of Storage Rings and Traps



Ion Beam Handling

Accumulation, cooling, bunching

Stopping of Energetic Ion Beams

Argonne, KVI, SHIP, MSU, RIA, RIKEN

Storage Device

Nuclear half life, nuclear reactions, hyperfine structure splitting, nuclear decay studies, nuclear polarization

Charge Breeding

Electron beam ion source /trap

Symmetry Tests and Weak Interaction Studies

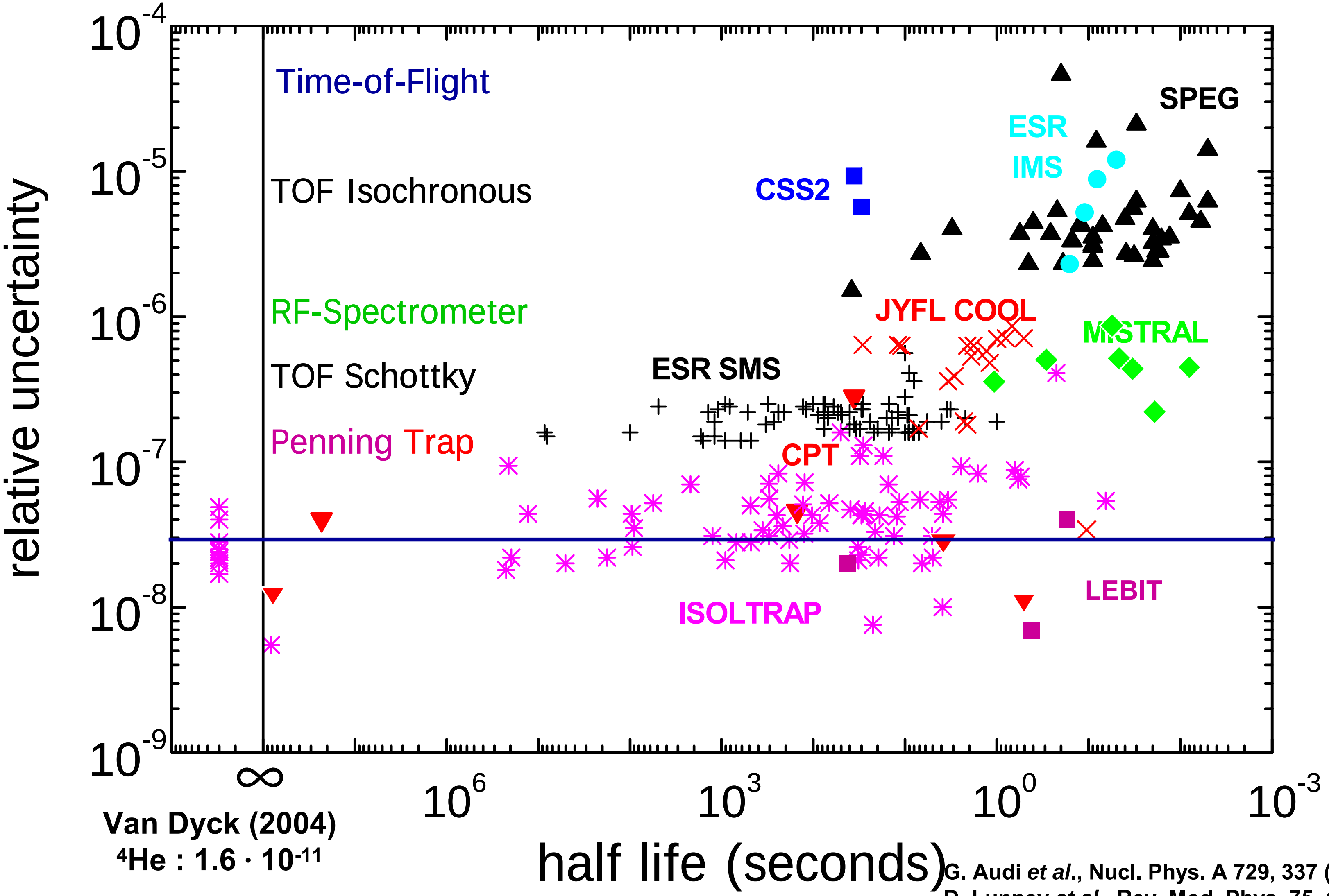
Stony Brook, TRIUMF, Los Alamos, Berkeley, ISOLDE, KVI, Legnaro

Mass Spectrometry

Isomer separation

Accuracy: $\delta m/m = 10^{-8}$

Accuracy of Mass Data Obtained 2003-2005

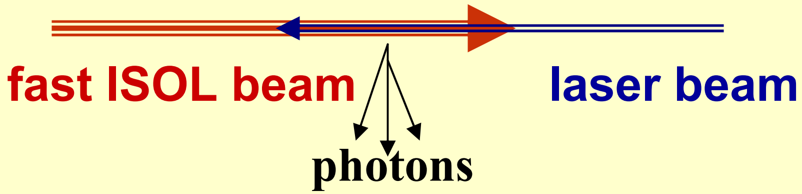


Van Dyck (2004)
^{4}He : 1.6 · 10^{-11}

G. Audi *et al*., Nucl. Phys. A 729, 337 (2003)
D. Lunney *et al*., Rev. Mod. Phys. 75, 1021 (2003)
updated by K. Blaum and G. Bollen

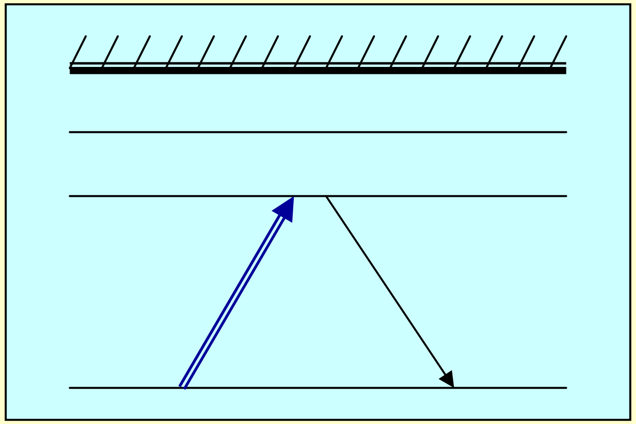
Tools for Laser Spectroscopy of Short-Lived Nuclei

COLINEAR SPECTROSCOPY

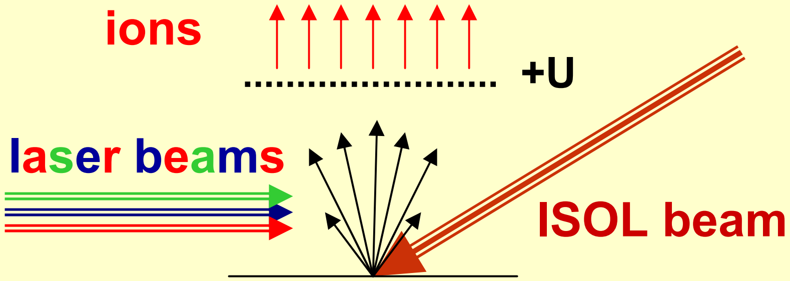


$$\Delta E = \text{const.} = \delta(\tfrac{1}{2}mv^2) = mv\cdot\delta v$$

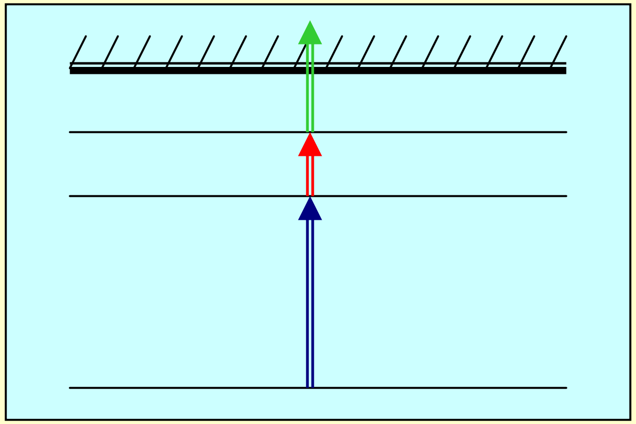
HIGH RESOLVING POWER !



RESONANCE IONIZATION SPECTROSCOPY



HIGH SENSITIVITY !



WI Experiments

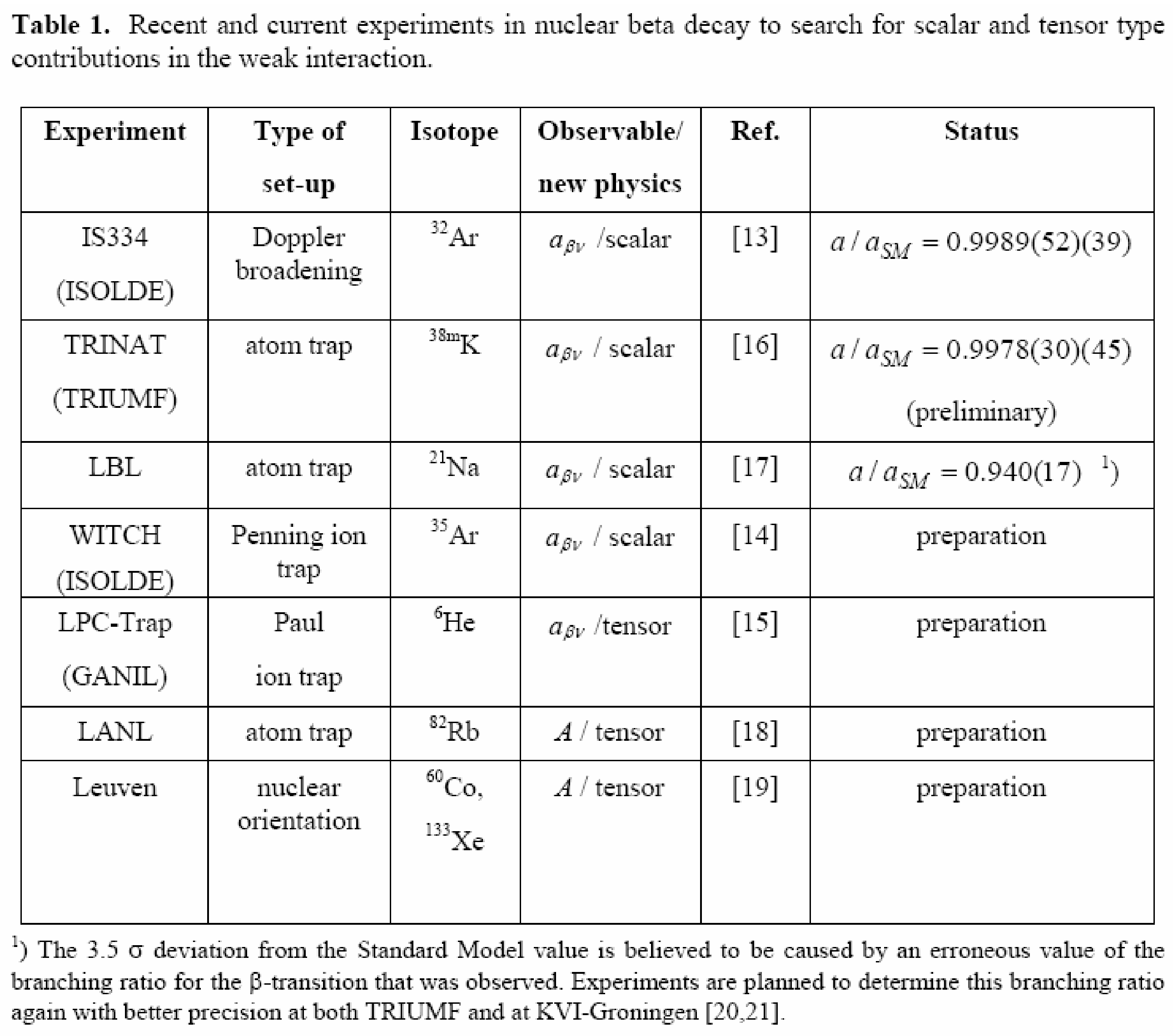


Table 1. Recent and current experiments in nuclear beta decay to search for scalar and tensor type contributions in the weak interaction.

Experiment	**Type of set-up**	**Isotope**	**Observable/ new physics**	**Ref.**	**Status**
IS334 (ISOLDE)	Doppler broadening	^{32}Ar	$a_{\beta\nu}$ /scalar	[13]	$a / a_{SM} = 0.9989(52)(39)$
TRINAT (TRIUMF)	atom trap	^{38m}K	$a_{\beta\nu}$ / scalar	[16]	$a / a_{SM} = 0.9978(30)(45)$ (preliminary)
LBL	atom trap	^{21}Na	$a_{\beta\nu}$ / scalar	[17]	$a / a_{SM} = 0.940(17)$ ^{1})
WITCH (ISOLDE)	Penning ion trap	^{35}Ar	$a_{\beta\nu}$ / scalar	[14]	preparation
LPC-Trap (GANIL)	Paul ion trap	^{6}He	$a_{\beta\nu}$ /tensor	[15]	preparation
LANL	atom trap	^{82}Rb	A / tensor	[18]	preparation
Leuven	nuclear orientation	^{60}Co, ^{133}Xe	A / tensor	[19]	preparation

^{1}) The 3.5 σ deviation from the Standard Model value is believed to be caused by an erroneous value of the branching ratio for the β-transition that was observed. Experiments are planned to determine this branching ratio again with better precision at both TRIUMF and at KVI-Groningen [20,21].

Some ISOL User Facilities of Today (1st Generation)

Location	Driver	Primary beam	Postaccelerator
ISOLDE @ CERN Switzerland	PS booster	Protons 1.4 GeV, 2 μA	2001: Linac 0.8–3.1 *A* MeV
Jyväskylä Finland	Cyclotron K = 130	Protons - heavy ions < 70 MeV, up to 100 μA	–
Louvain-la-Neuve Belgium	Cyclotron K = 30	Protons 30 MeV, 200 μA	1989: Cyclotrons *K* = 110, 44
HRIBF Oak Ridge, USA	Cyclotron	Protons, deuterons, α, < < 85 MeV, < 12 μA	1997: Tandem 25 MV
ISAC @ TRIUMF Canada	Cyclotron	Protons 500 MeV, 100 μA	2000: Linac up to 1.5 *A* MeV
SPIRAL @ GANIL France	Two cyclotrons	Heavy ions up to 95 *A* MeV, 6 kW	2001: Cyclotron CIME *K* = 265, 1.7–25 *A* MeV
EXCYT Catania, Italy	Cyclotron K = 800	Heavy ions A ≤ 48 up to 100 *A* MeV, ≤ 1pμA	2005: Tandem 0.2–8 *A* MeV

ISOL Facilities of Second Generation

Location	**RIB Starting Date**	**Driver**	**Post-accelerator**
SPIRAL-II: GANIL Caen, France	2008	SC linear accelerator deuterons up to 40 MeV heavy ions up to 15 *A* MeV	cyclotron CIME $K = 265$, 2–25 *A* MeV
MAFF Munich, Germany	2008	Reactor 10^{14} n/cm^2·sec	Linac up to 7 *A* MeV
SPES Legnaro, Italy	2008 (Initial phase)	SC proton linac	ALPI linac
ISAC-II TRIUMF	2007	Cyclotron p, 500 MeV, 100 μA	Linac up to 6.5 *A* MeV
HIE-ISOLDE CERN	2008	PS booster p, 1.4 GeV, 10 μA	Linac up to 5 *A* MeV (10 *A* MeV)

RIB Facilities of Third Generation

Location	**Driver**	**Post-accelerator**	**Type of facility**
Europe: FAIR (Germany)	synchrotron, heavy ions, 2 A GeV	-	In-Flight
Europe: EURISOL ??	protons, 1 GeV, 1- 5 MW	CW Linac, up to 100 *A* MeV	ISOL
USA: RIA ??	900 MeV protons, heavy ions, 400 *A* MeV, 100 kW	Linac up to 8–15 A MeV	ISOL & In-Flight
JAPAN: RIKEN RIB Factory	Ring-cyclotrons up to 400 *A* MeV (light ions), up to 150 *A* MeV (heavy ions)	-	In-Flight