Radioactive Ion Factories

Norbert Angert

- Motivation

- Radioactive Ion Beam Production Techniques
  - Fast beam fragmentation/fission and in-flight-separation
  - ISotope On-Line production-method (ISOL)

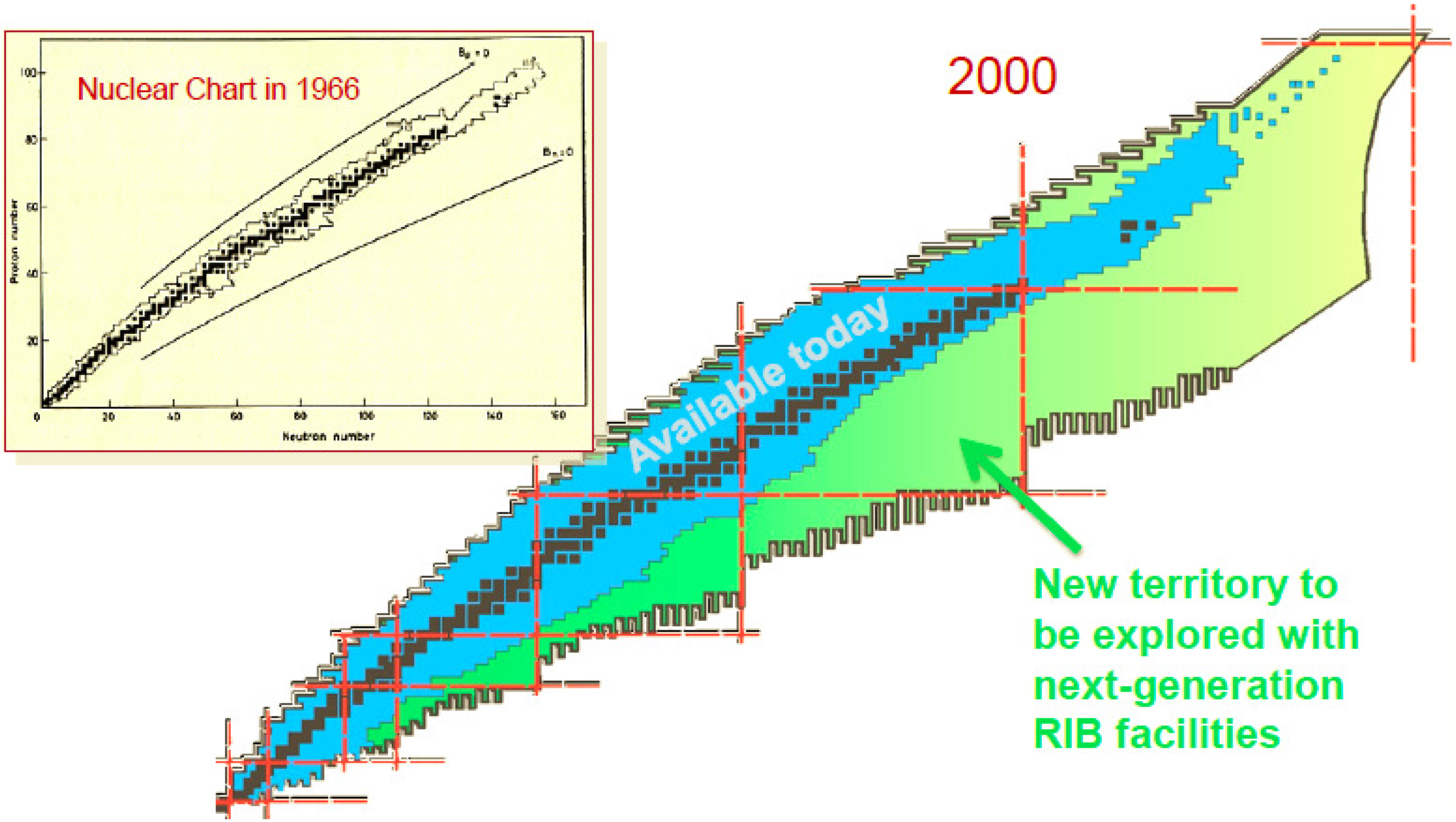
- Special Issues of Heavy Ion Accelerators
  - Ion sources (OK)
  - Charge-changing processes
  - Low-β super-conducting linac structures (UR, HP)

- In-flight Facilities
  - RIKEN/RIBF
  - GSI/FAIR
  - MSU/FRIB

- ISOL Facilities
  - ISAC
  - GANIL/SPIRAL2
  - HIE-ISOLDE

Motivation

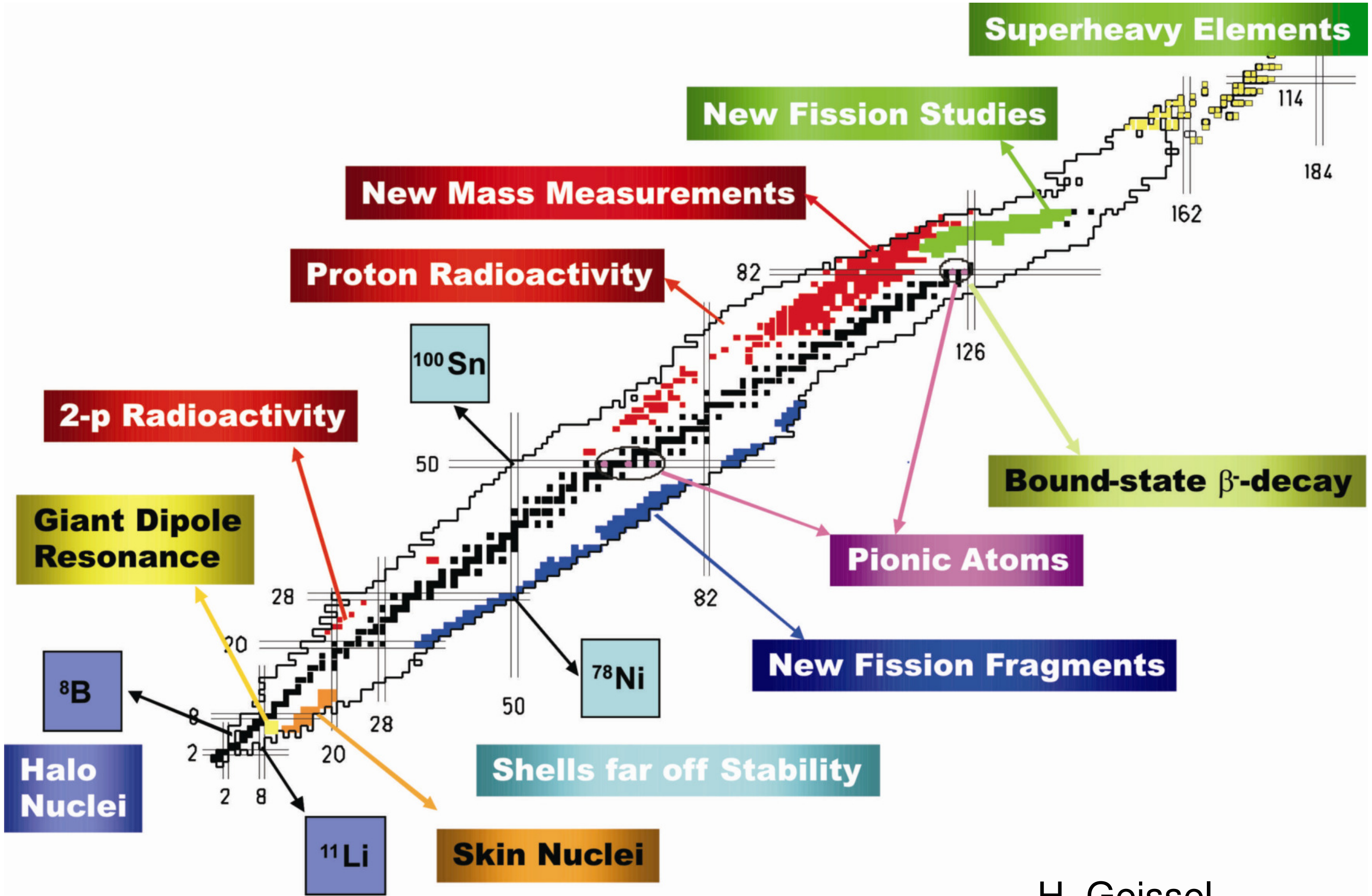
Progress in the production of radioactive isotopes



G. Bollen 2011

Motivation

Landmarks from Unilac and SIS/ESR experiments



H. Geissel

Motivation

International Union of Pure and Applied Physics (IUPAP) made a formal decision to establish an ad-hoc Committee on International Cooperation in Nuclear Physics (CICNP).

A new IUPAP Working Group, WG.9, had the mandate to provide a description of the landscape of key issues in nuclear physics research for the next 10 to 20 years (**http://www.iupap.org/wg/**), report 2010, contains list of facilities.

In Nuclear Physics ..wordwide..development of high-quality multi-faceted ….radioactive beams allows one to move from a one-dimensional picture …, to a two-dimensional picture where both proton and neutron numbers vary over a wide range.

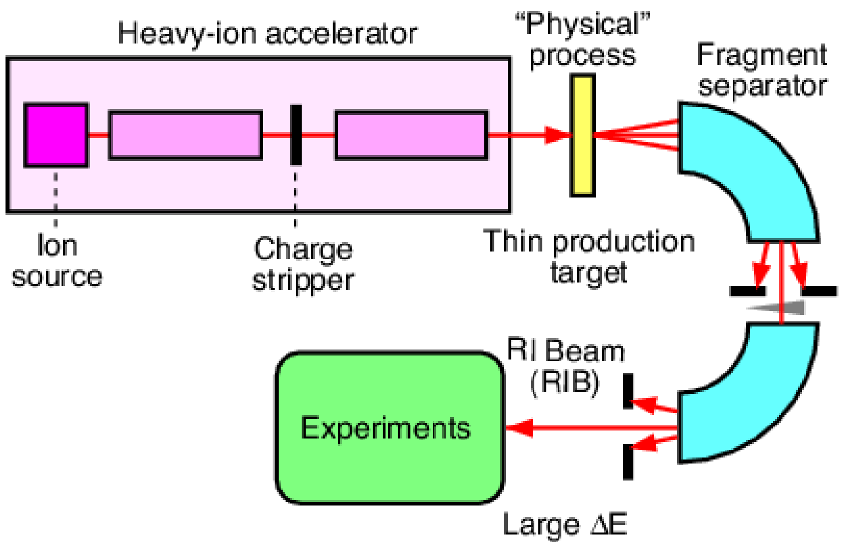
Equivalent recommendations are given in the Nuclear Physics European Collaboration Committee **(**NuPECC) Long Range Plan 2010 for Europe **(http://www.nupecc.org**).

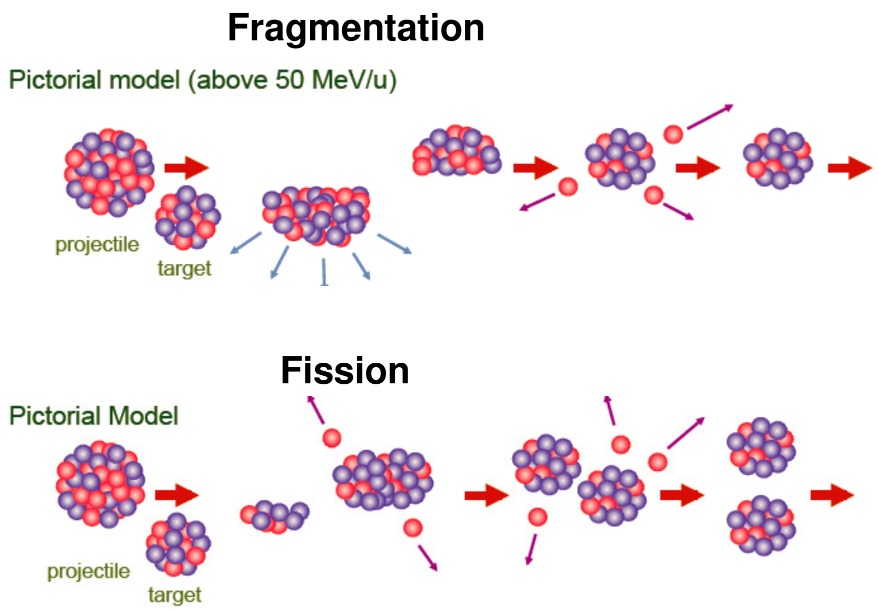
In addition: Super-Heavy Element (SHE) research (race), 116√, 118?, 120?

Production Techniques

In-flight technique: Needs heavy ion accelerators for medium energy (≥ 50 MeV/u) stable isotope beams. RIs are produced via fragmentation/fission in a thin target and the fast RIs are in-flight separated.

Universal, no chemistry involved, fast (≥ μs lifetime), experiments with few isotopes, large ΔE

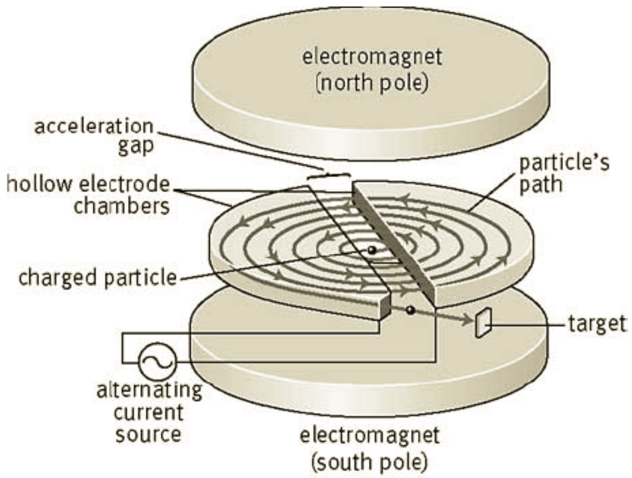


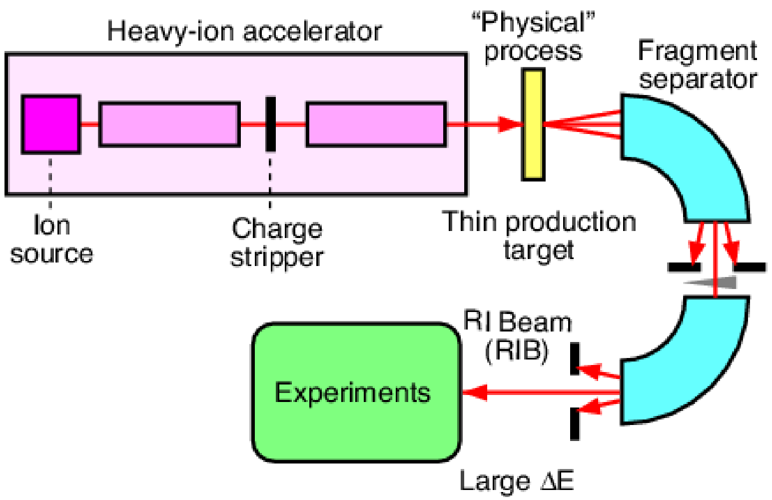


O. Kamigaito

B. Sherrill

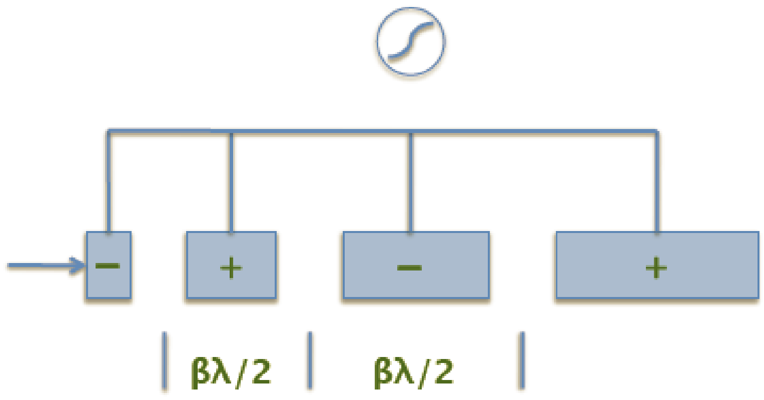
Production Techniques

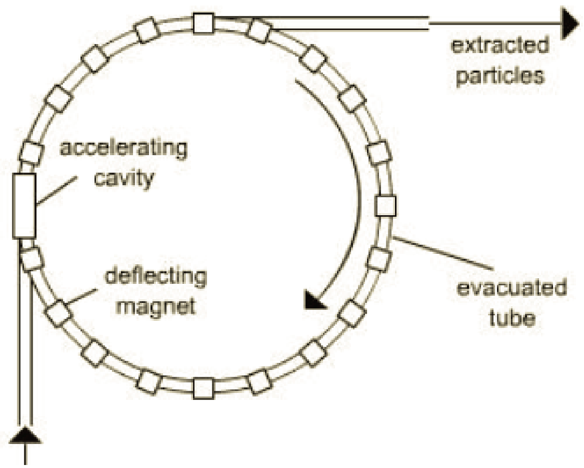




O. Kamigaito

Heavy ion accelerators for in-flight facilities



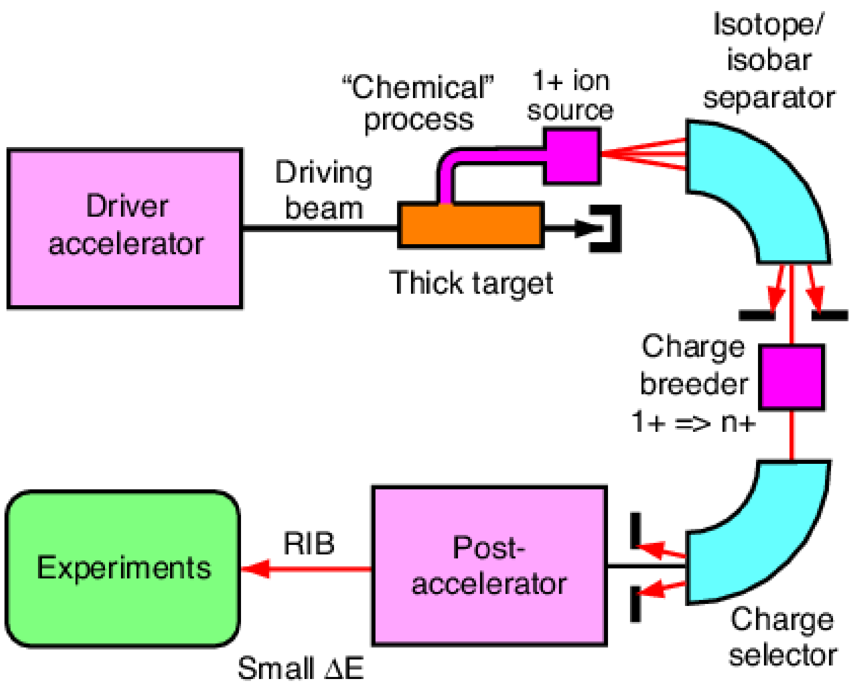


B. Sherrill

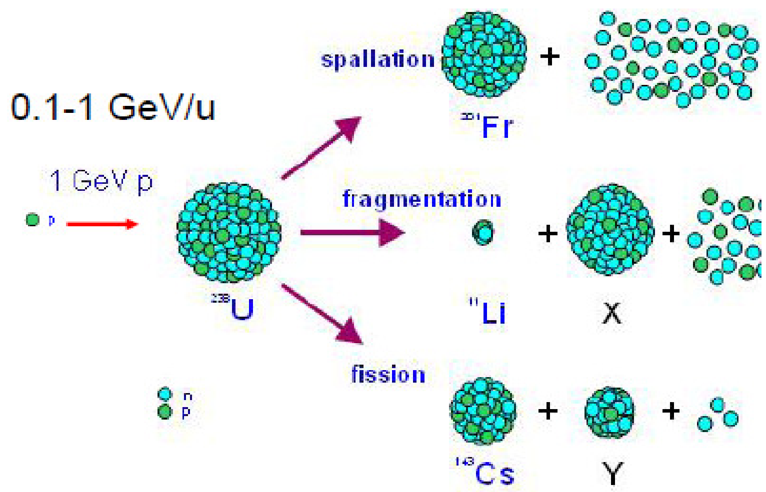
Production Techniques

ISotope On-Line (ISOL)-technique: Needs light ion driver/neutrons/photons. RIs are produced in a thick target, evaporated, and singly ionized separated. Not all elements are possible (no refractory elements).

High intensity, good beam quality, low energy (traps)

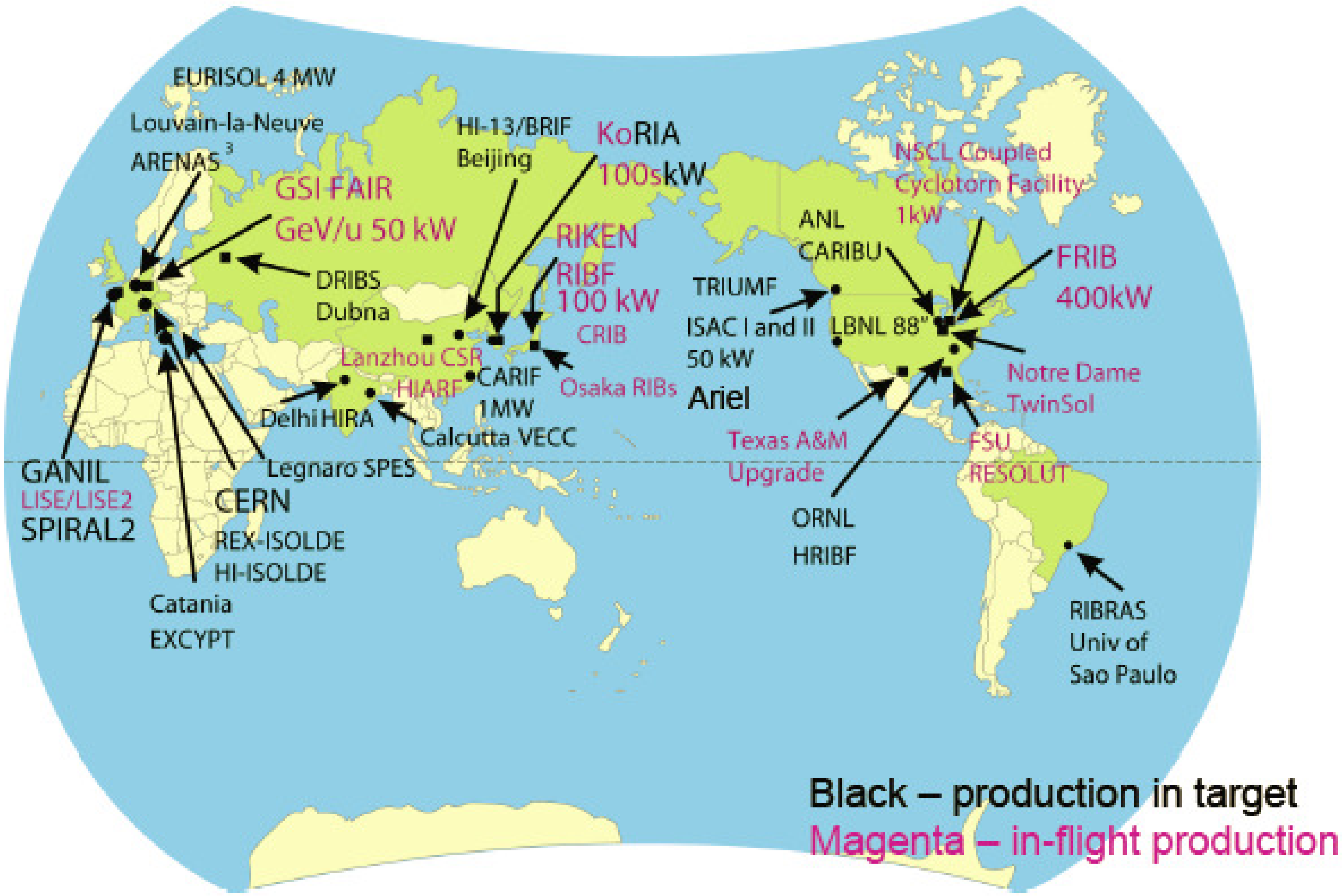


O. Kamigaito



P. Butler

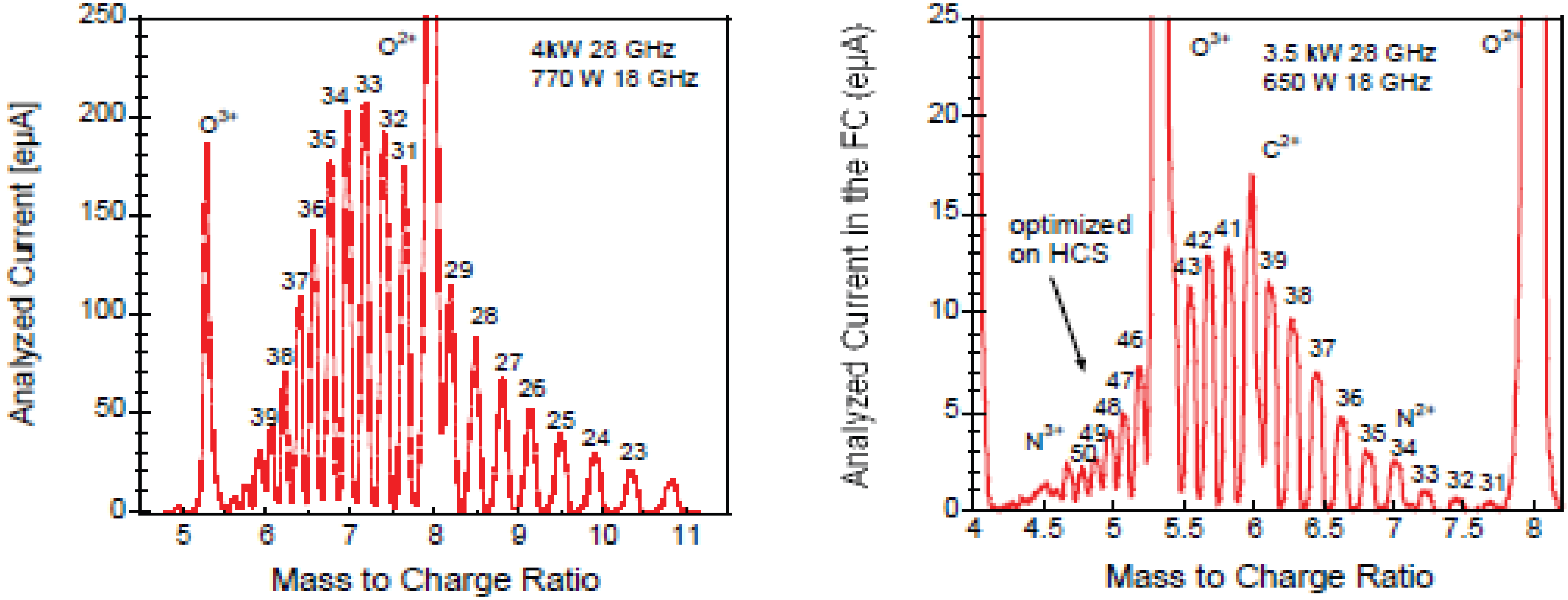
World view of radioactive ion factories
Largest effort in the field of ion accelerators in history



B. Sherrill, 2011

Special issues of heavy ion drivers for in-flight facilities

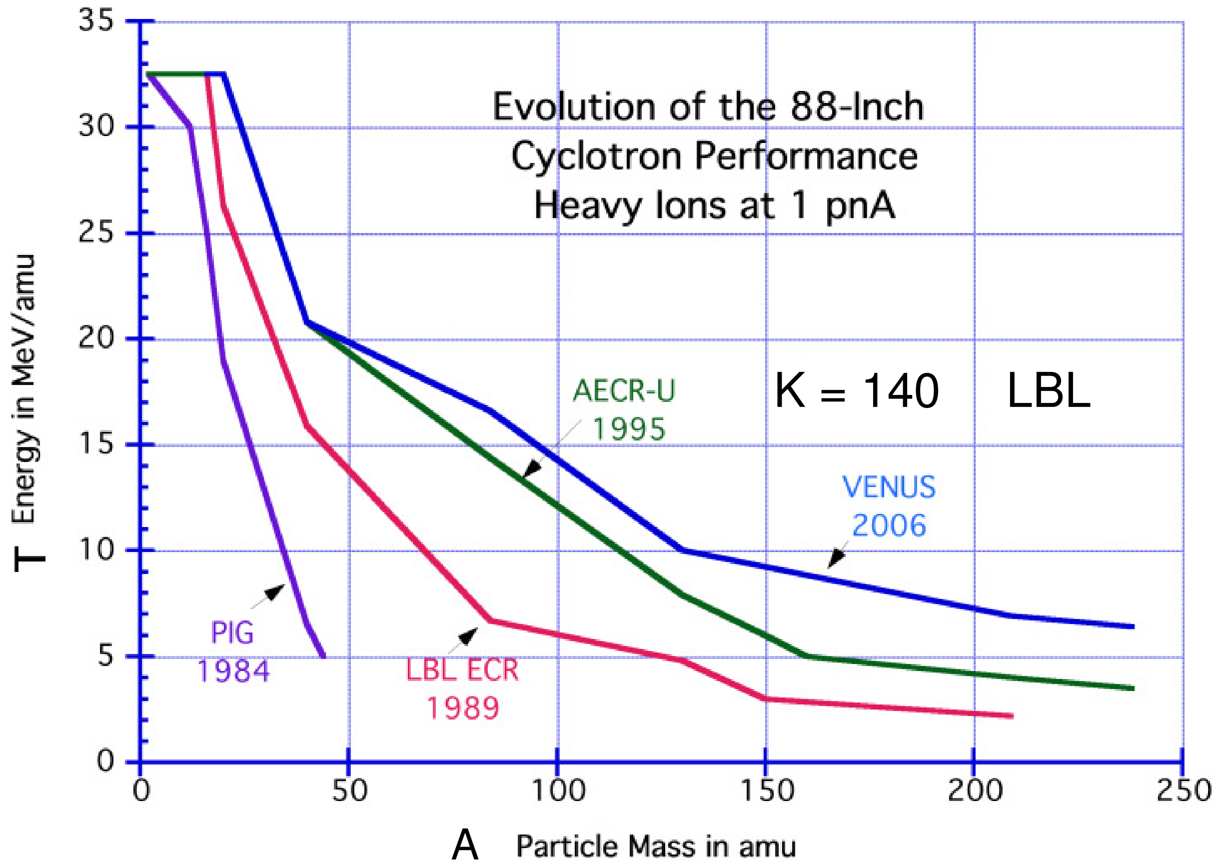
Ion Sources: From PIG- to ECR ion source: x3 in charge state



Spectra of uranium charge states from the LBL VENUS (Electron Cyclotron Resonance Ion Source, s. O. Kester) in the high-current mode (left) and the high-charge-state mode (right)

D. Leitner

Special issues of heavy ion drivers for in-flight facilities



C. Lyneis

New S.C. ECR-ion sources provide access to heavy ion nuclear physics for many existing cyclotrons

Cyclotron: $T(MeV/u)=K \cdot (q/A)^2$
T= kinetic energy
K=cyclotron parameter
q=charge state

Linac: $T(MeV/u)=q/A \cdot Eav (MV/m) \cdot L(m)$
Eav= average acceleration field
L= length
Rf-power ~ **$(A/q)^2$**

Special issues of heavy ion drivers for in-flight facilities

Equilibrium charge states of fast heavy ions after passage of matter

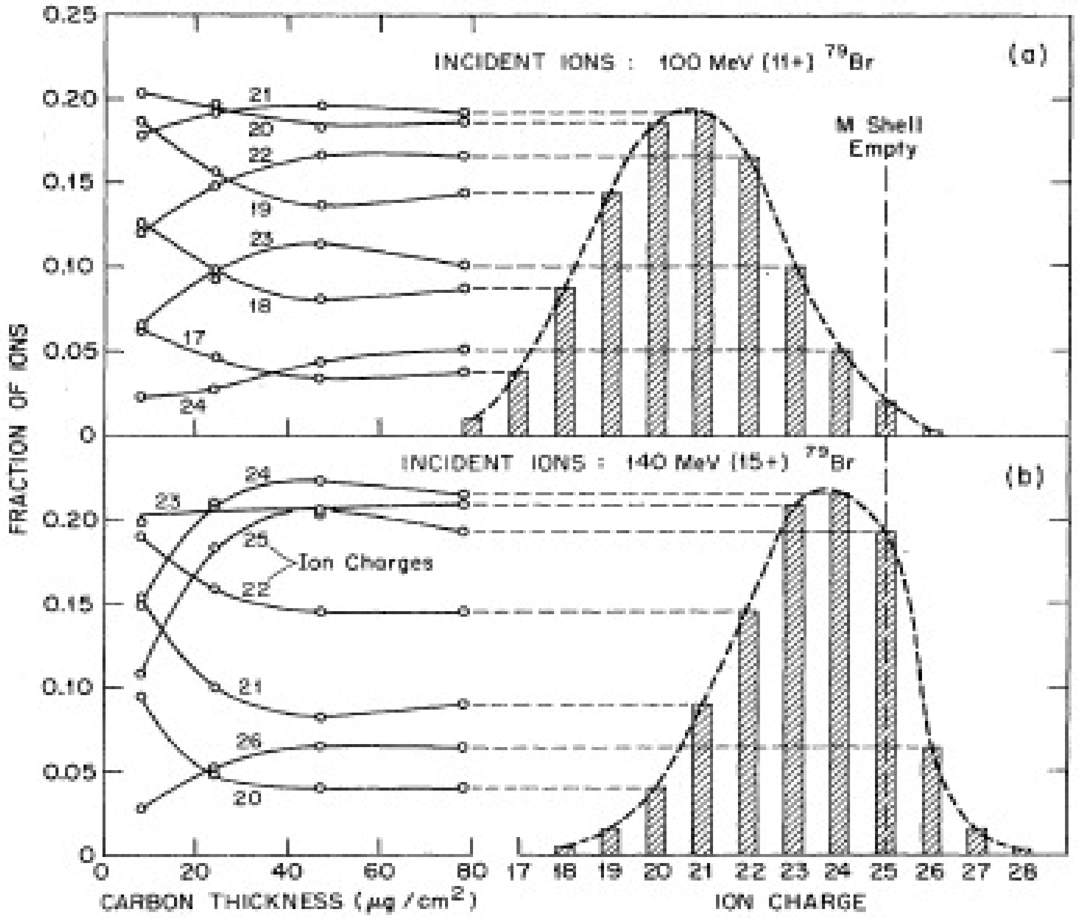
- **Ion charge state can be increased by stripping off electrons at sufficiently high energy in foil or gas targets**

- **$q = Z_p (1 – C • \exp (- Z_p^{-\gamma} •137•\beta)$**
- q = average equilibrium charge state — $C = C^* + 140/Z_p^2$, $C^* = 1.0285$
- Z_p = nuclear charge of the ion — γ = .56 for foils and .65 for the nitrogen jet used at the Unilac
  $\beta = v/c$

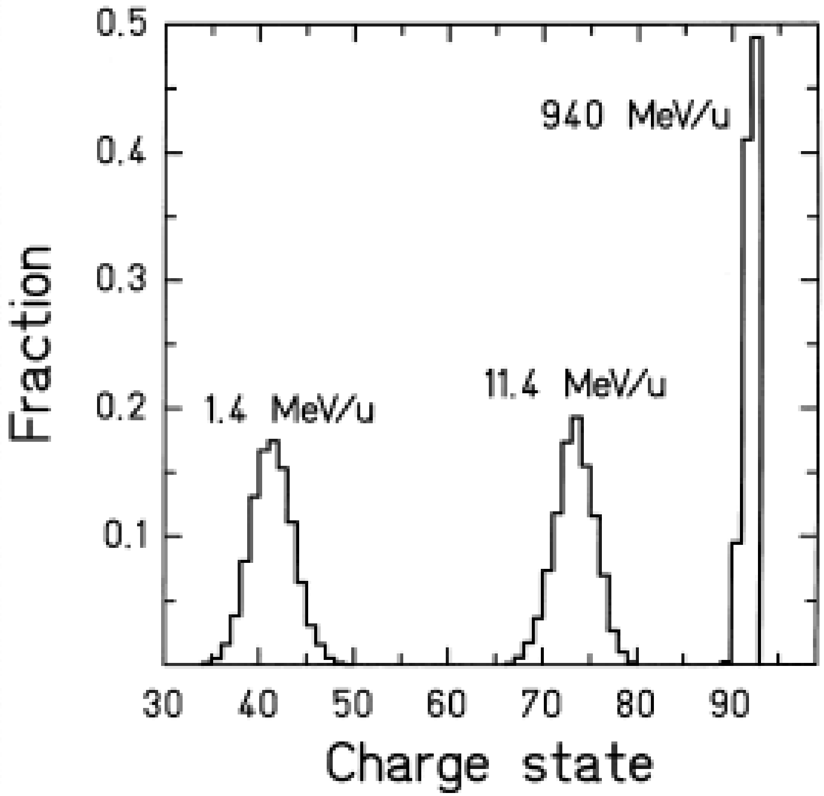
- Charge states produced in the ion source and charge states after stripper targets (gas or foil) are key figures for the layout and optimization of a heavy ion accelerator facility for a given output energy.
- For a linac the position of the stripper has to be optimized in order to minimize the total acceleration voltage, jumps in rf-frequency, choice of rf-power sources, ….
- That also holds for cyclotron stages, combinations of linacs with cyclotrons and synchrotrons
- **Thereby one can gain in acceleration efficiency, save money, but looses intensity**

Special issues of heavy ion drivers for in-flight facilities

Equilibrium charge state distributions of fast heavy ions after passing foil strippers; electron shell effects



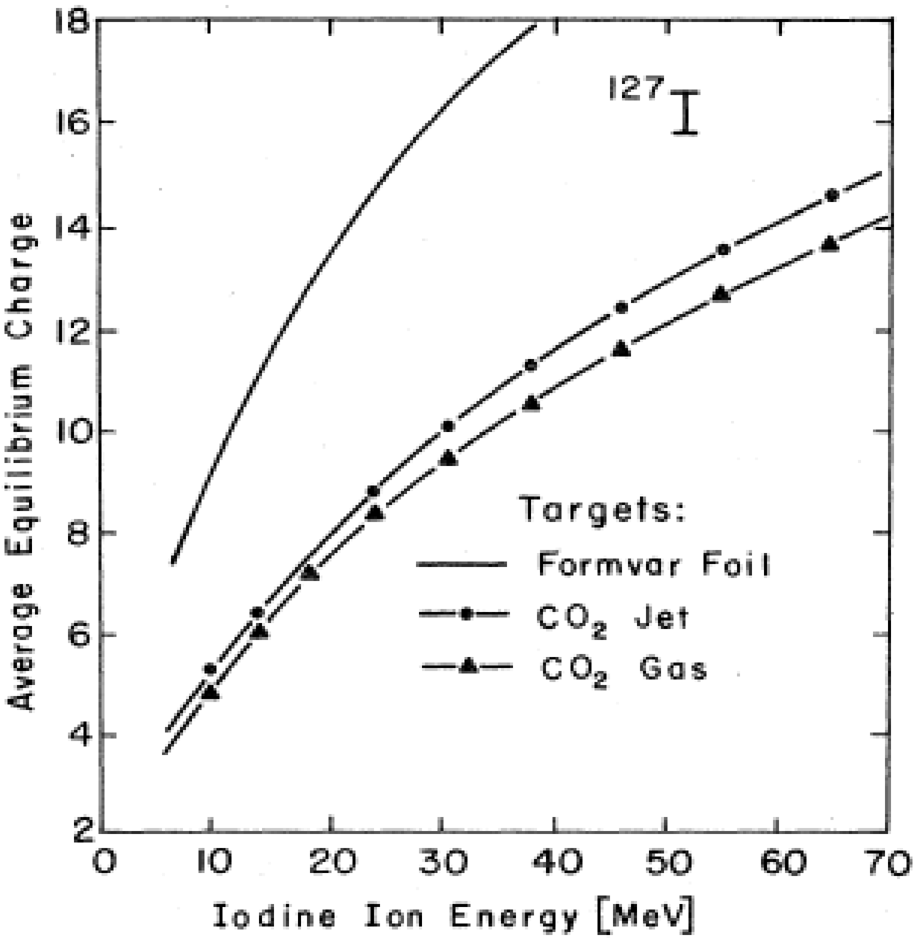
Oak Ridge 1967



Unilac/SIS

Special issues of heavy ion drivers for in-flight facilities

Average equilibrium charge states of fast heavy ions, stripper density effects



N. Bohr, Kgl. Danske. Videnskab. Selskab. Mat.- Fys. Medd. 18 no. 8 (1948).
H.-D. Betz, Rev. Mod. Phys. 44 (1972) 465 ! (comprehensive review)

B. Franzke
1971

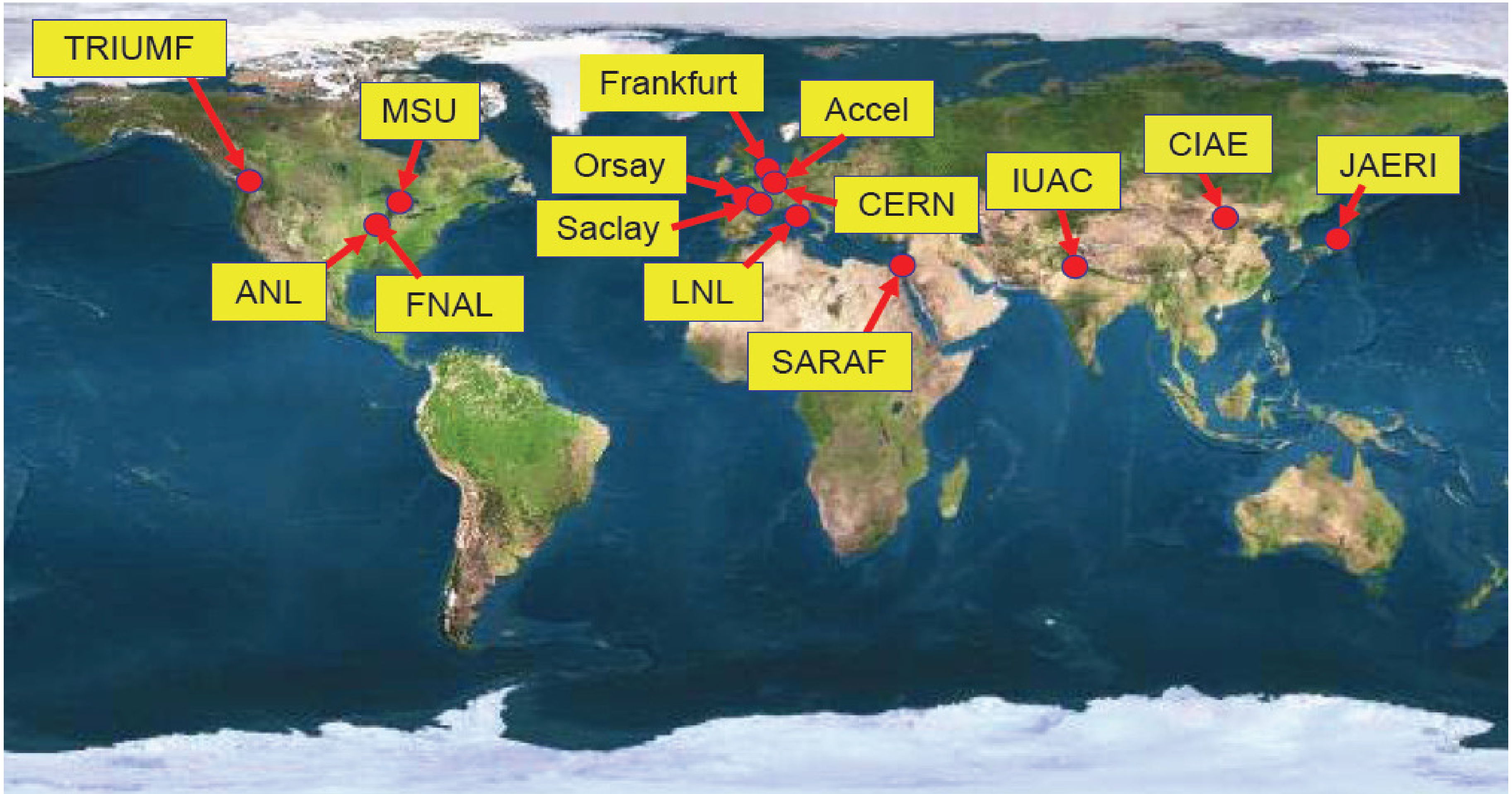
In addition, there are energy-dependant effects from the nuclear charge of the target,
Low-Z gas targets produce higher q at high energies.
Be-foils are best at low energies, but not at high energies.

Special issues of heavy ion linacs

Heavy ion linacs for drivers and ISOL post-accelerators:

- Low-β: Mass-to-charge ratio A/q out of source » 1 (uranium 238/30 ≈ 8), even after stripping the mass-to-charge ratio is > 1
- Heavy ion accelerators require flexibility for a broad range of mass-to-charge ratios and specific energies. Super-conducting rf-structures with short cavities, independently phase controlled, provide these features: quarter wave (QWRs) or half wave resonators (HWRs), more in the talks of U. Ratzinger and H. Podlech.
- CW-beams: Advantageous for targets, coincidence experiments.
- High average gradients in cw-operation allow to build short linacs for driver- and post-accelerators
- Beam loss budget has to be considered (high power drivers)

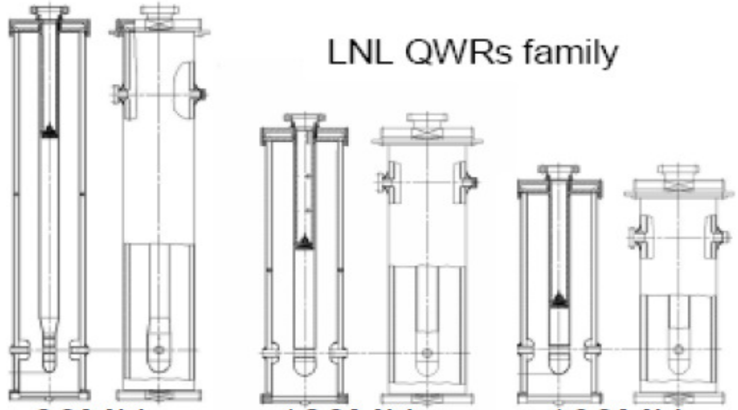
World view of super-conducting low-β linacs
for in-flight drivers and ISOL post-accelerators



R. Laxdal

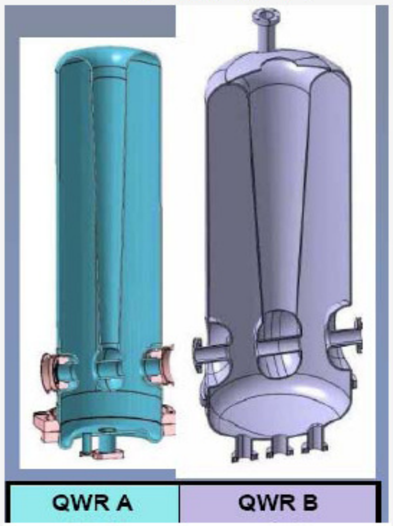
λ/4 resonators (QWR) for drivers and post-accelerators

- Many quarter wave prototypes have been built and tested world-wide over the last 15 years



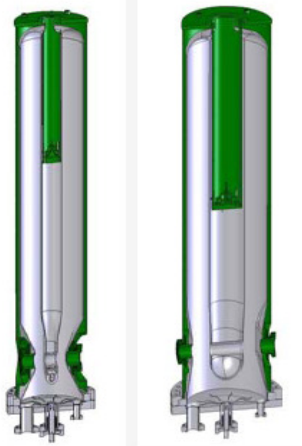
80MHz 4.7% | 120MHz 8% | 160MHz 11%

SPIRAL-2



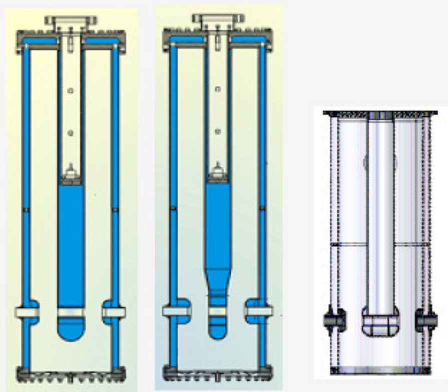
88MHz
7%, 12%

MSU



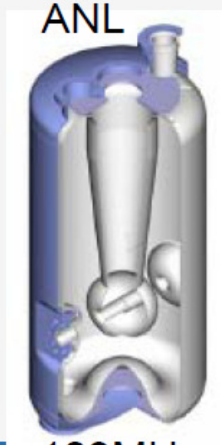
80.5MHz
4.1%, 8.5%

ISAC-II



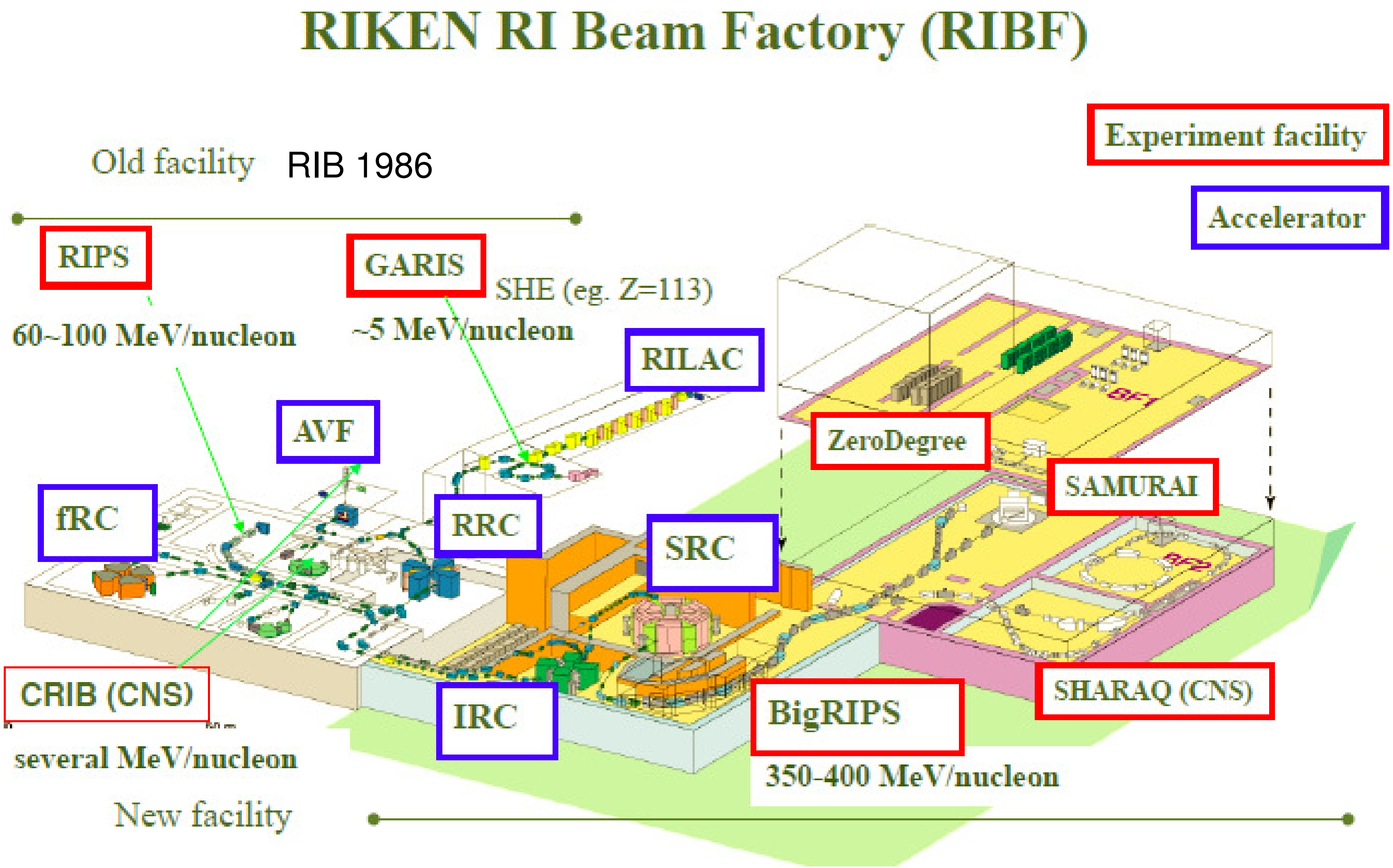
106MHz 7%, 5.7% | 141MHz 12%

ANL



109MHz
14.4%

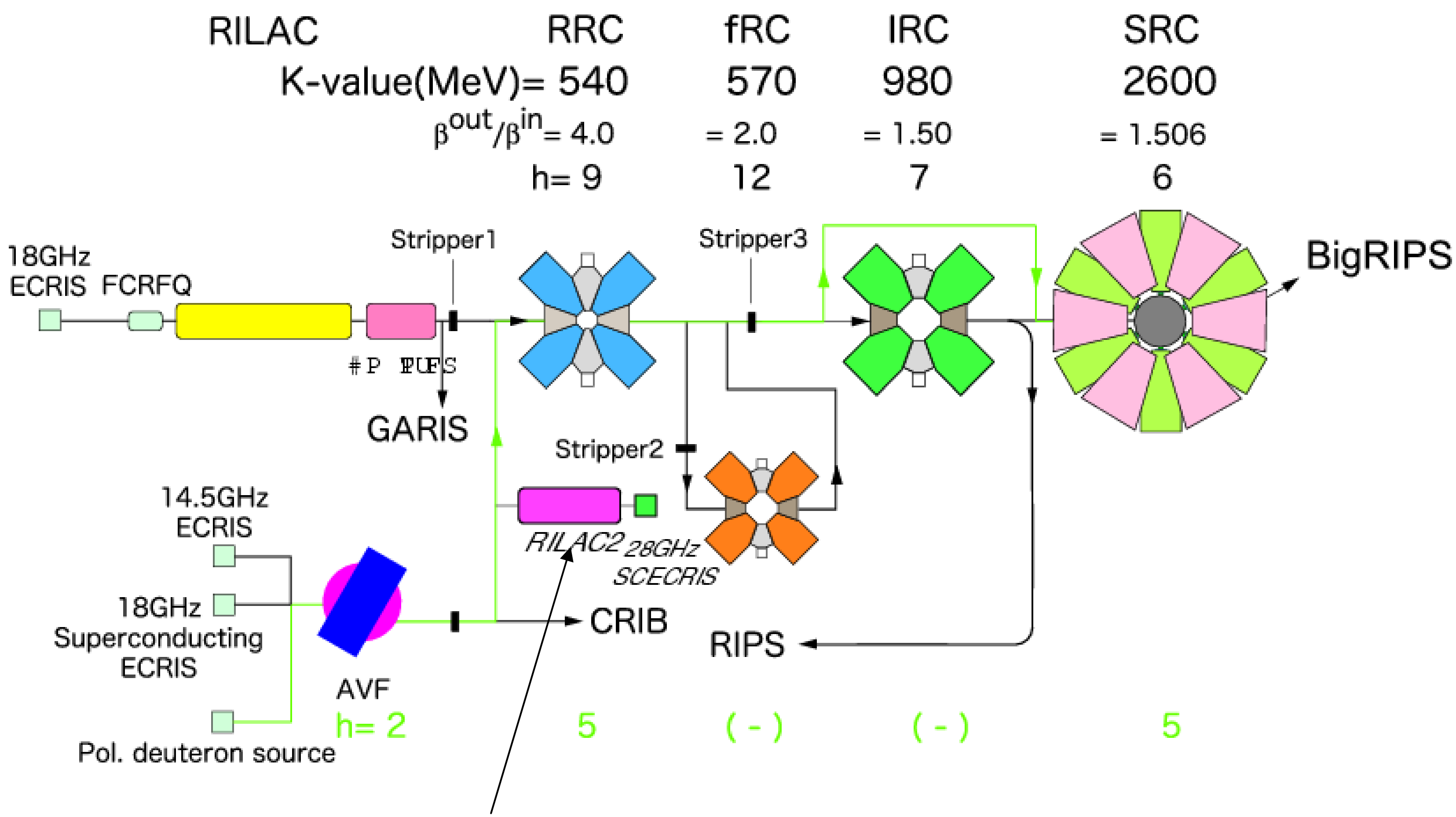
In-flight facilities



Uranium 345 MeV/u, since 2007

In-flight facilities

Schematic of the RIKEN Radioactive Ion Beam Factory (RIBF) for the in-flight production of radioactive beams (and superheavy elements)

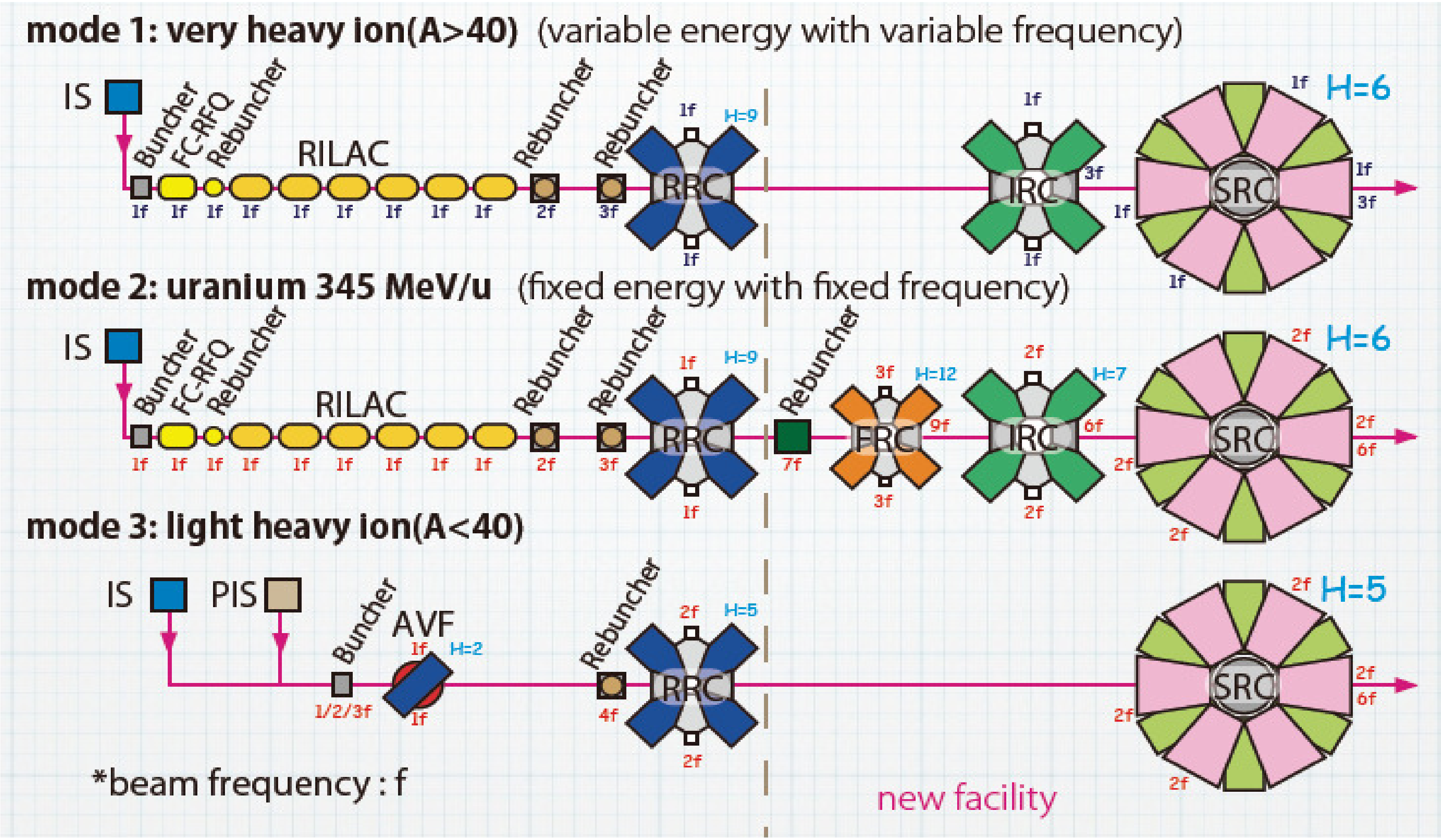


New linac for multi-ion operation and super-heavy element production

O. Kamigaito

In-flight facilities

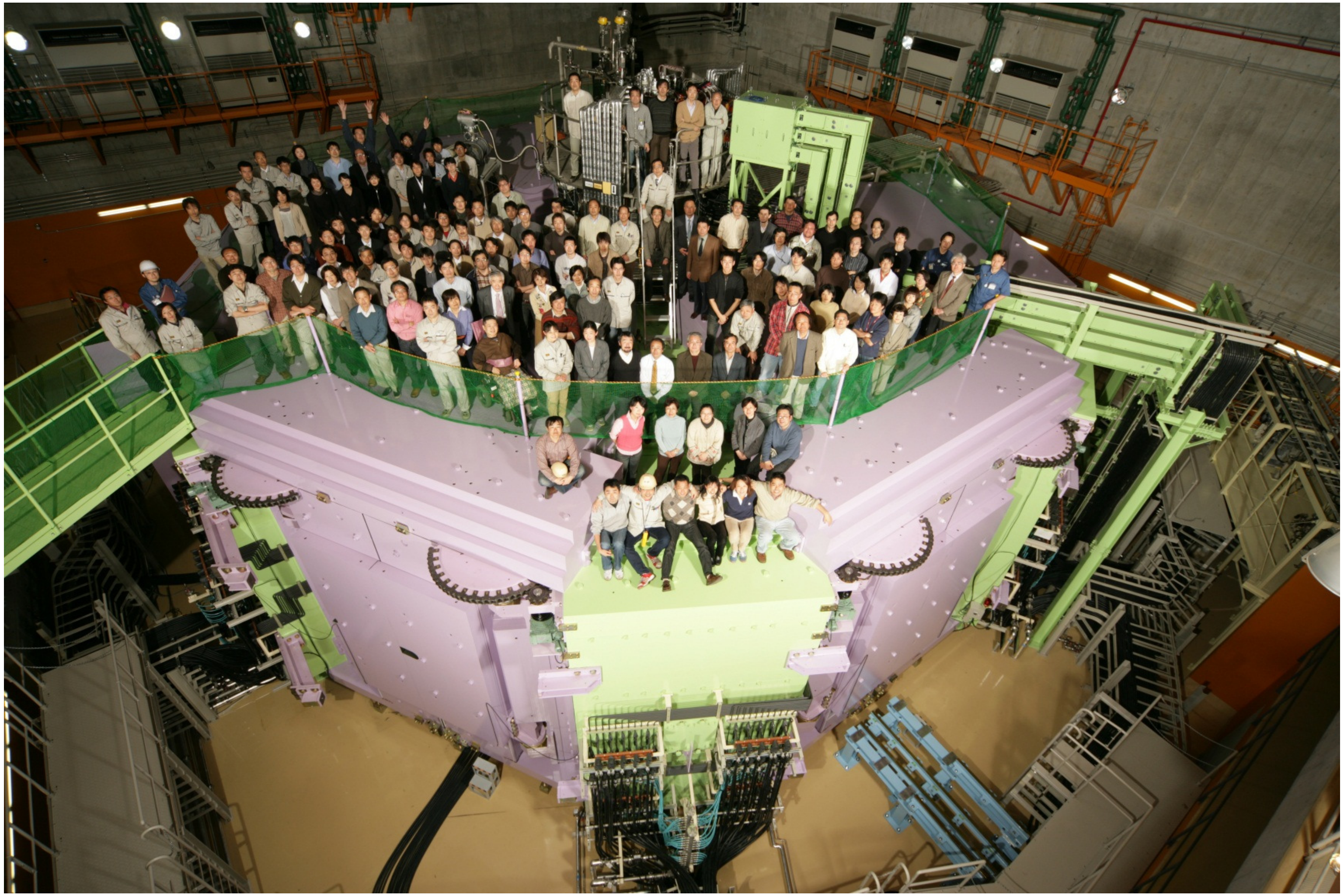
Operation modes of the RIKEN RIBF



O. Kamigaito

In-flight facilities

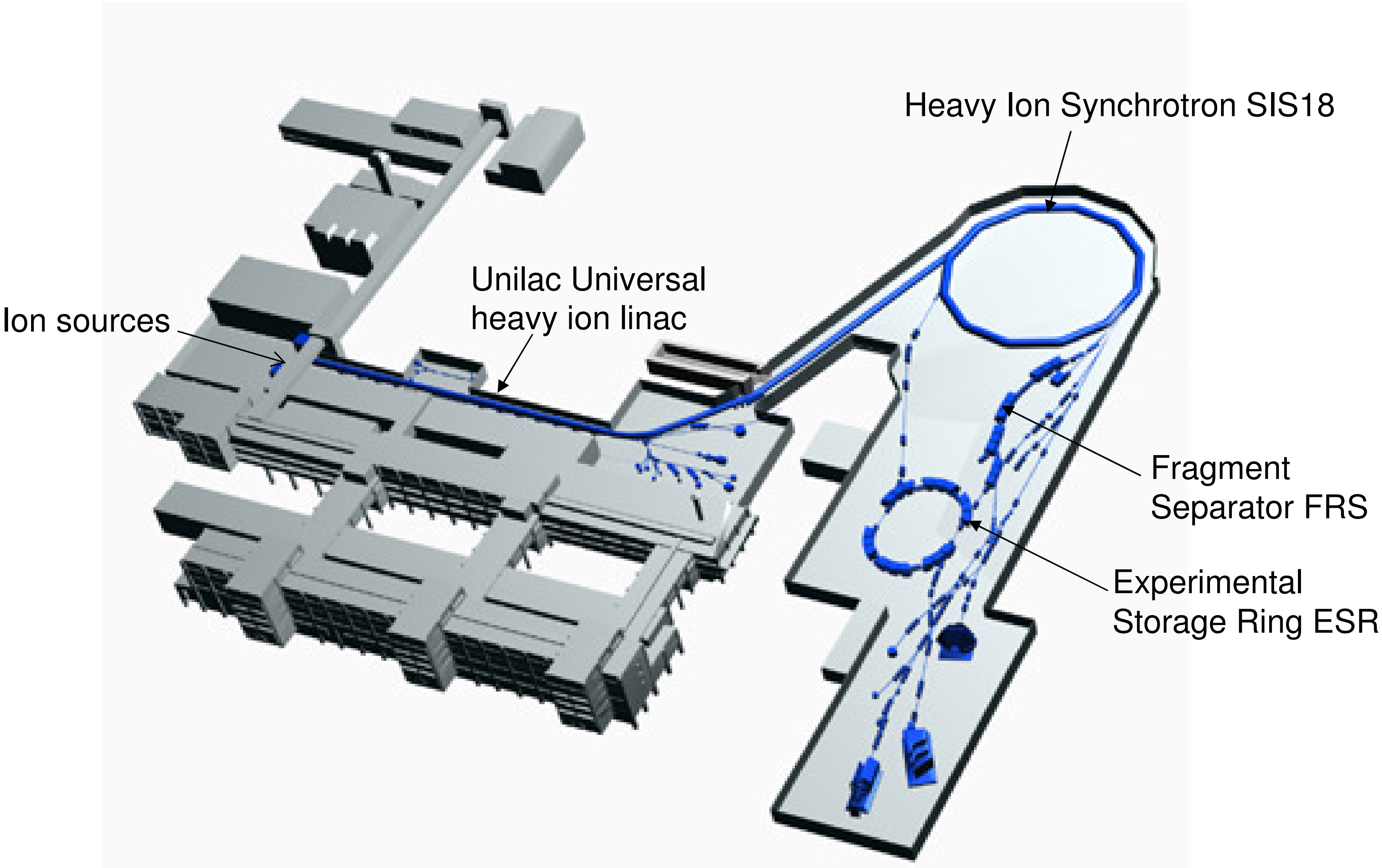
RIKEN super-conducting ring-cyclotron SRC



48Ca-345 MeV/u-400pnA; 238U-345 MeV/u-4pnA (1pμA)

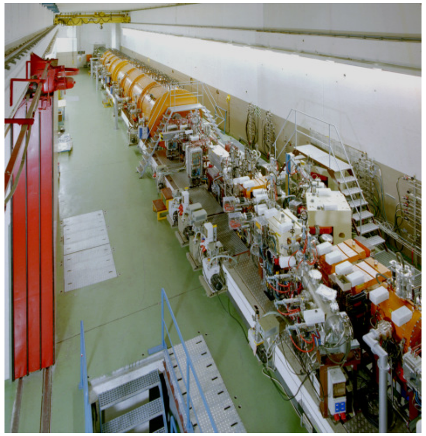
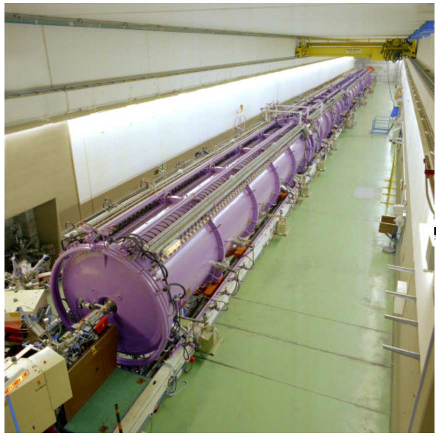
In-flight facilities

View of the existing GSI accelerator facility



In-flight facilities

View of the GSI accelerators Unilac and SIS

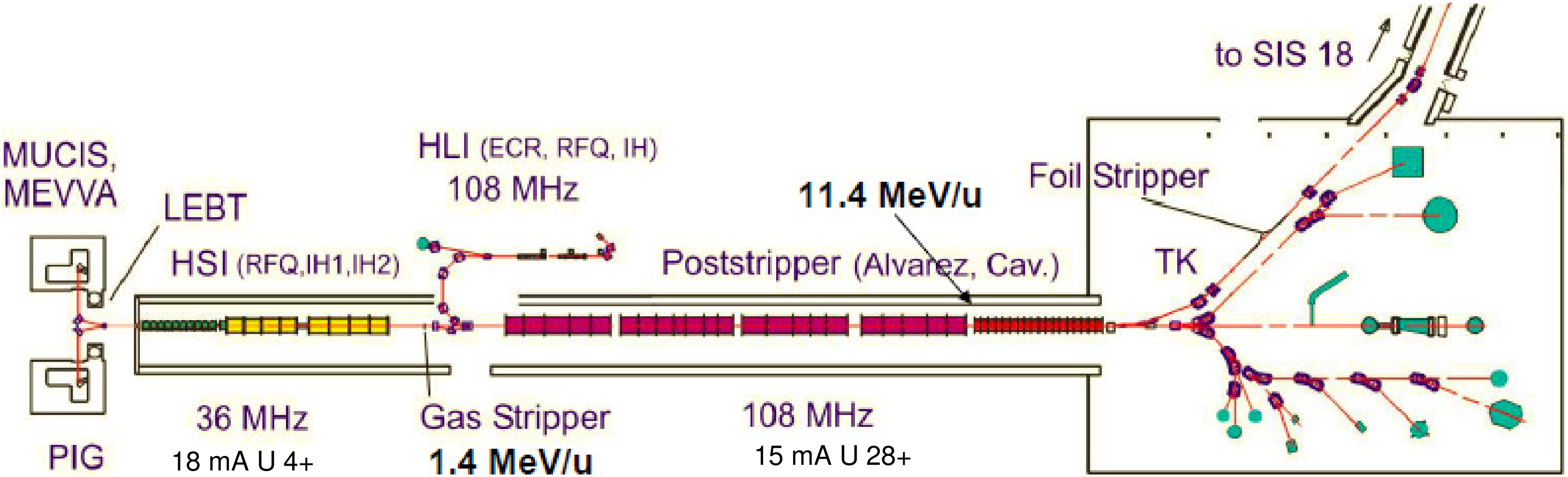




1 GeV/u

2•10E10
U73+

uranium 11.4 MeV/u

U 73+

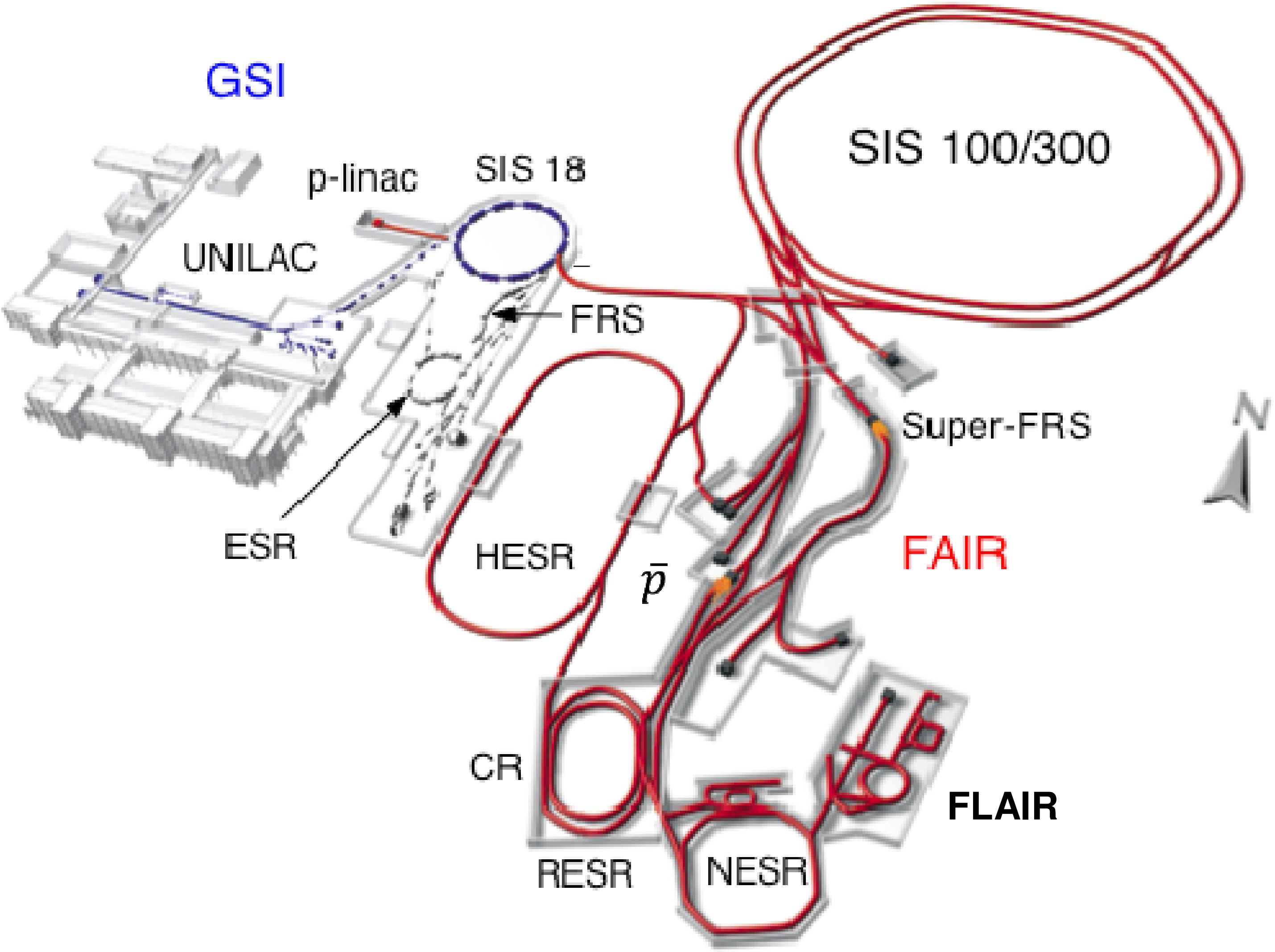


18 mA U 4+

15 mA U 28+

In-flight facilities

Existing **GSI** and **FAIR** Facility for Antiproton and Ion Research, construction started



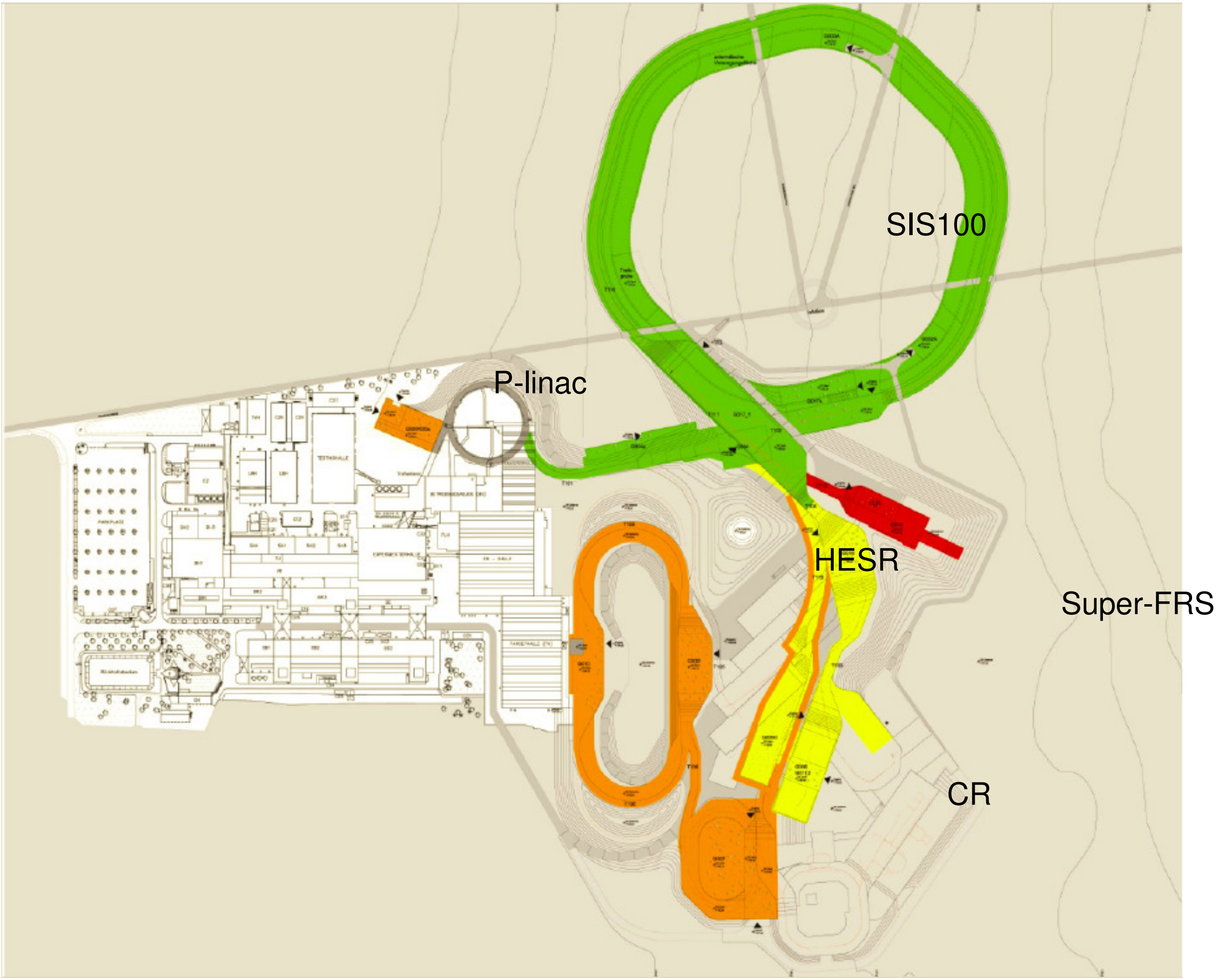
In-flight facilities

Key parameters of FAIR

Ring	**Circumference [m]**	**Beam rigidity [Tm]**	**Beam energy [GeV/u]**	**Specific Features**
Synchrotron SIS100 ☆	1083.6	100	2.7 for U^{28+} 29 for p	**Fast pulsed superferric magnets up to B=2 T, dB/dt=4 T/s, bunch compression to ~60 ns of $5\cdot10^{11}$ U ions, fast and slow extraction, $5\cdot10^{-12}$ mbar operating vacuum**
Synchrotron SIS300	1083.6	300	34 GeV/u for U^{92+}	**Pulsed superconducting cosθ-magnets up to B=6 T, dB/dt=1 T/s, slow extraction of ~ $3\cdot10^{11}$ U-ions per sec. with high duty cycle, $5\cdot10^{-12}$ mbar operating vacuum**
Collector Ring CR ☆	212	13	0.740 for A/q=2.7 3 for antiprotons	**Acceptance for antiprotons: 240 x 240 mm mrad, $\Delta p/p=\pm3\times10^{-2}$, fast stochastic cooling of radioactive ions and antiprotons, isochronous mass spectrometer for short-lived nuclei**
Accumulator Ring RESR	245	13	0.740 for A/q=2.7 3 for antiprotons	**Accumulation of antiprotons after pre-cooling in the CR, fast deceleration of short-lived nuclei, ramp rate 1T/s**
New Experi-mental Storage Ring NESR	222	13	0.740 for A/q=2.7 3 for antiprotons	**Electron cooling of radioactive ions and antiprotons with up to 450 keV electron-beam energy, precision mass spectrometer, internal target experiments with atoms and electrons, electron-nucleus scattering facility, deceleration of ions and antiprotons, ramp rate 1 T/s**
High-Energy Storage Ring HESR ☆	574	50	14	**Stochastic cooling of antiprotons up to 14 GeV, electron cooling of antiprotons up to 9 GeV; internal gas jet or pellet target**

☆ Modules of the start version

In-flight facilities

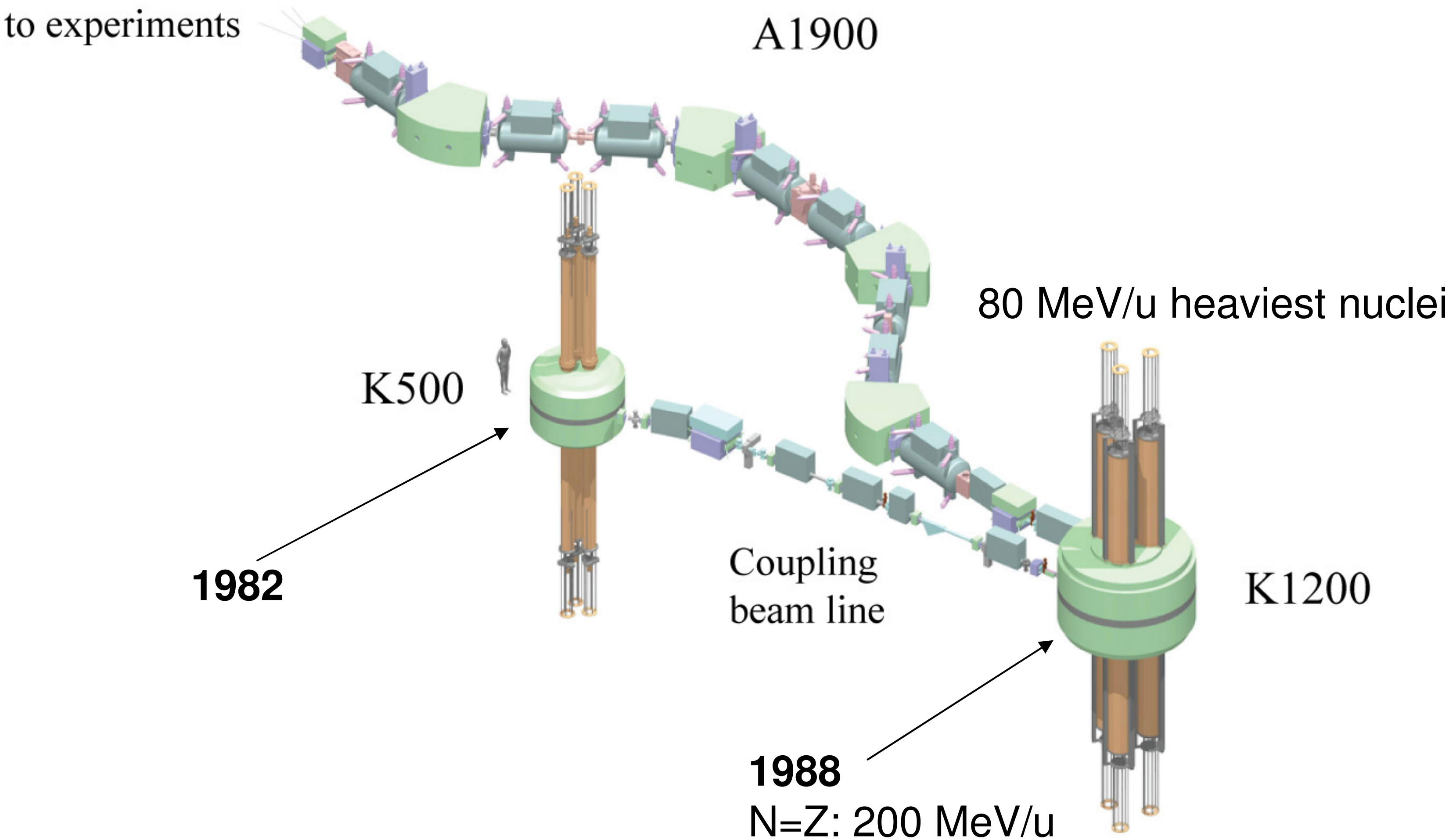


Trees for 1 to 3 have been cut. For SIS100 that will follow soon. Super-ferric dipoles for SIS100 have been ordered.

The FAIR modularized start version. Colouring of modules:0 – green; 1 – red; 2 – yellow; 3 – orange. Modules 4 and 5 are not marked. Start version costs about 1 B€.

In-flight facilities

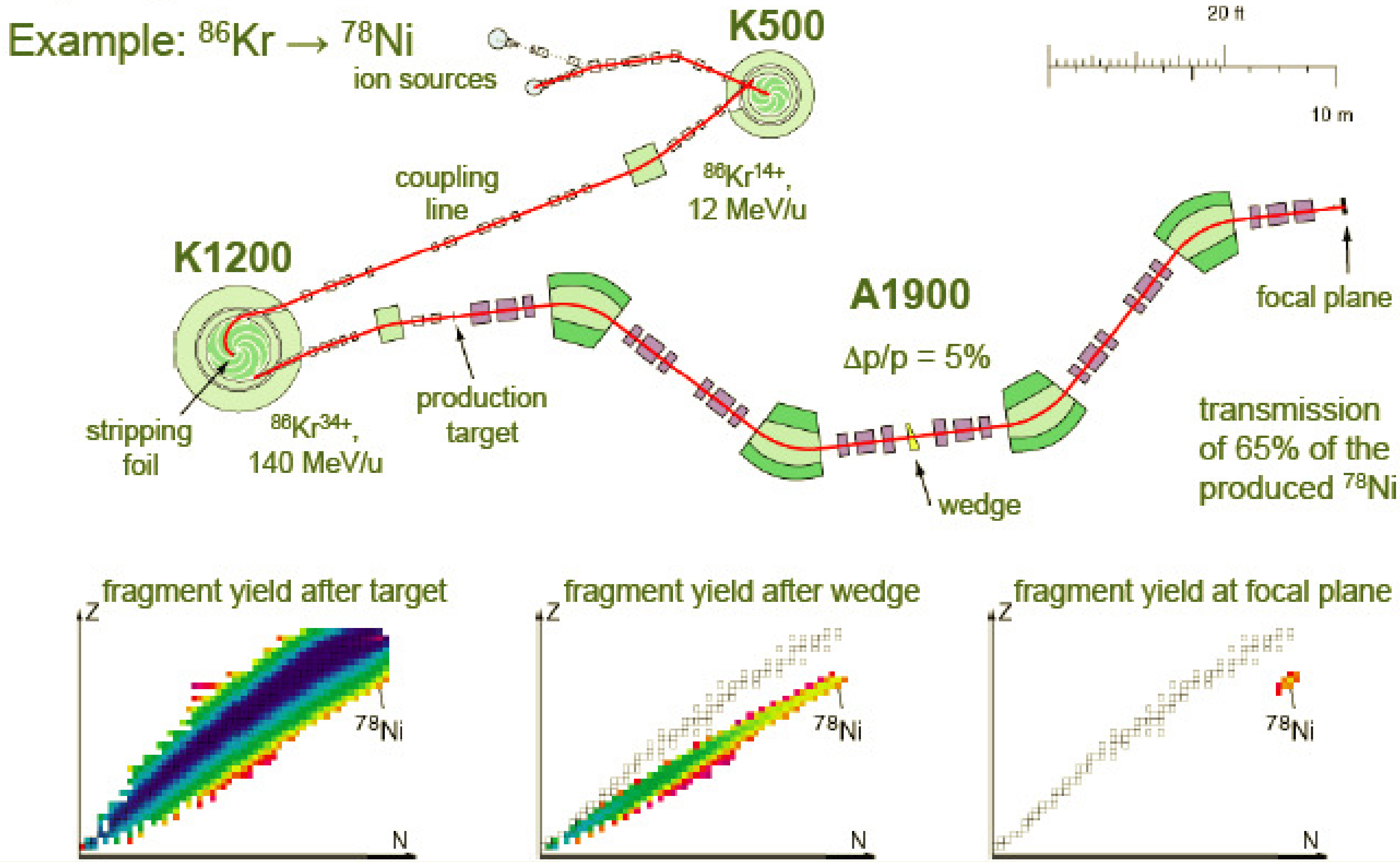
Coupled cyclotron facility (National Superconducting Cyclotron Laboratory, NSCL) at Michigan State University (MSU)



In-flight facilities

Coupled cyclotron facility (National Superconducting Cyclotron Laboratory, NSCL) at Michigan State University (MSU)

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



In-flight facilities

MSU post-accelerator for for in-flight produced radioactive isotopes: ReA3

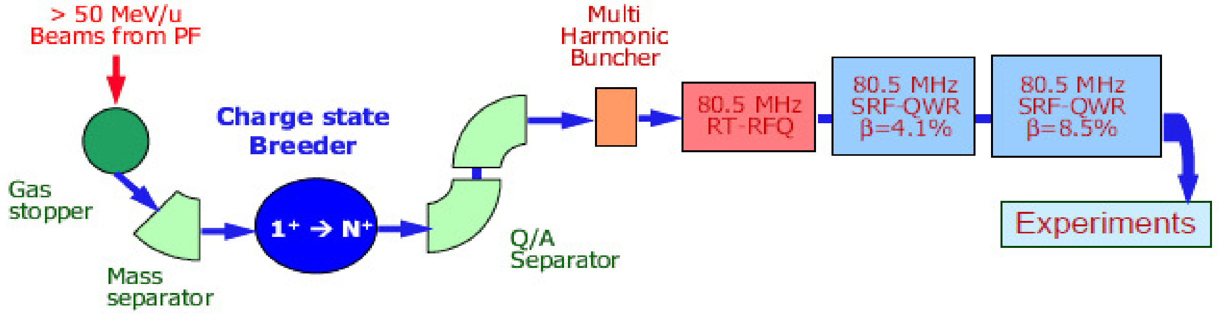
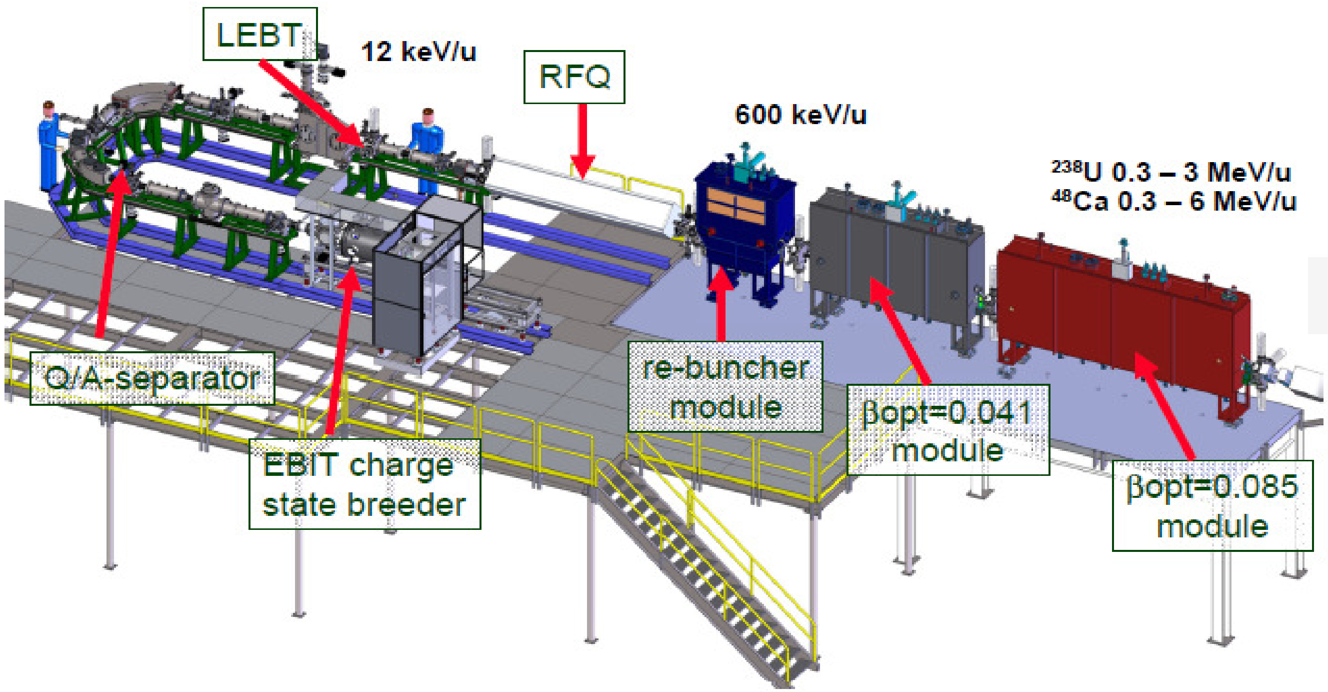
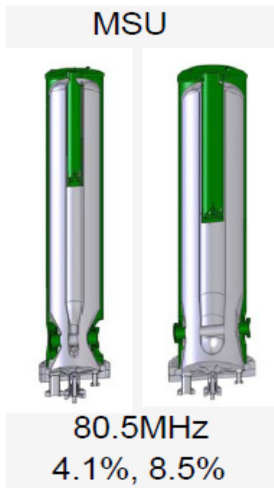


Figure 1: Reacceleration concept for ReA3.

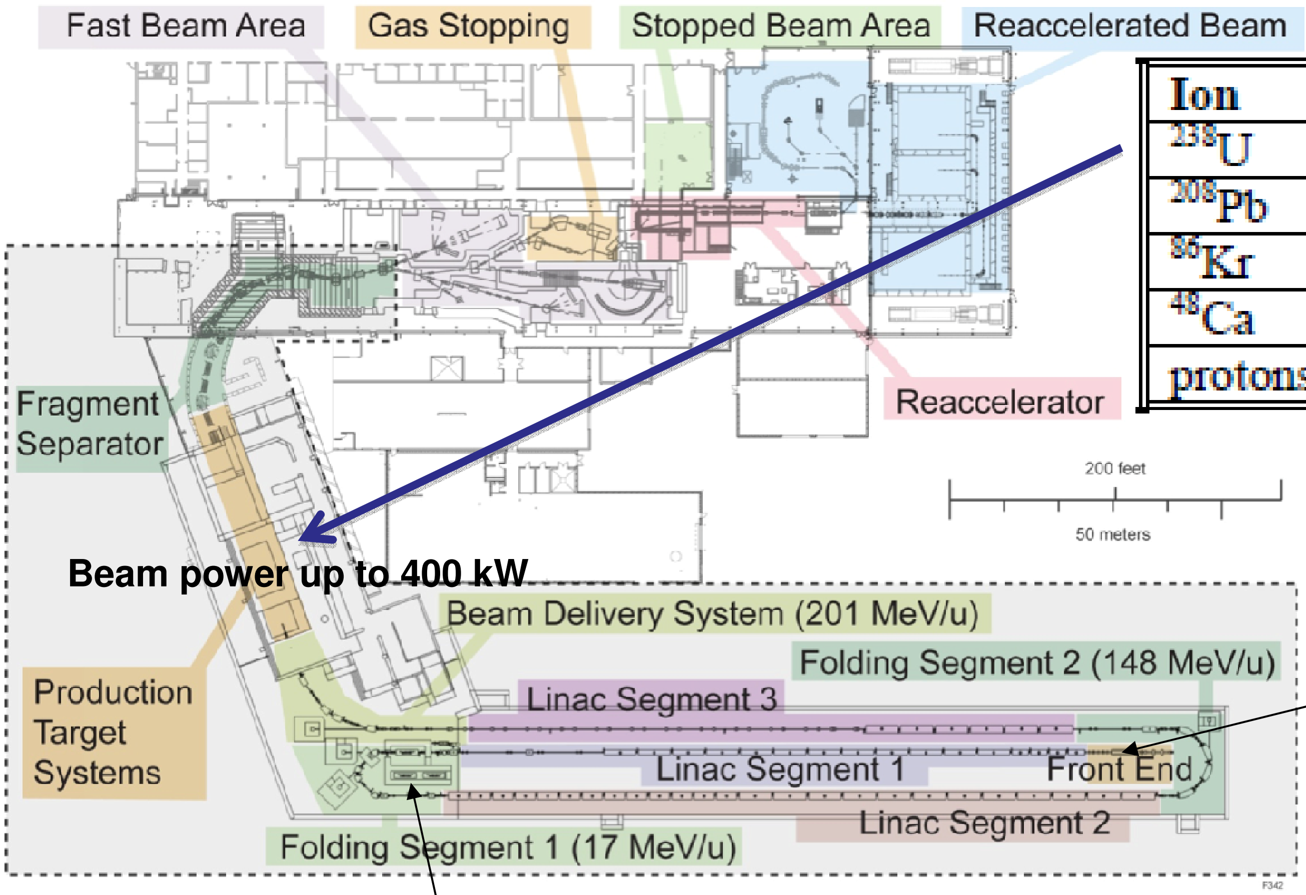




Expansion from now 3 to 15 MeV/u uranium:ReA15

In-flight facilities

MSU Facility for Rare Isotope Beams (FRIB), construction start in 2013



Ion	Energy (MeV/u)
^{238}U	210
^{208}Pb	210
^{86}Kr	265
^{48}Ca	270
protons	610

ECR ion source:
U33+/34+

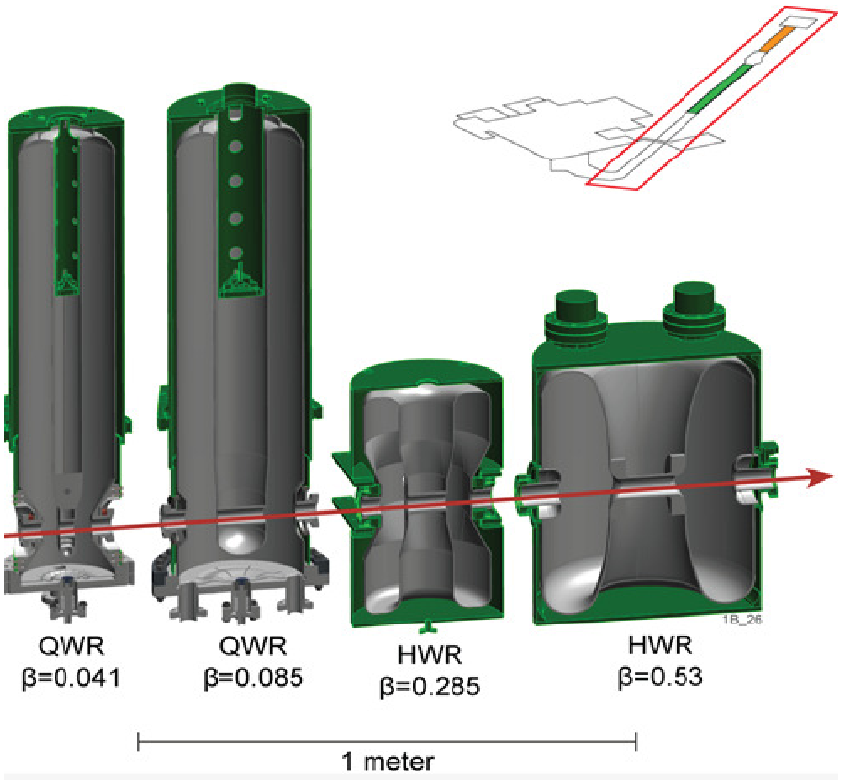
stripper-section
U77+ to U81+ for linac sections 2/3

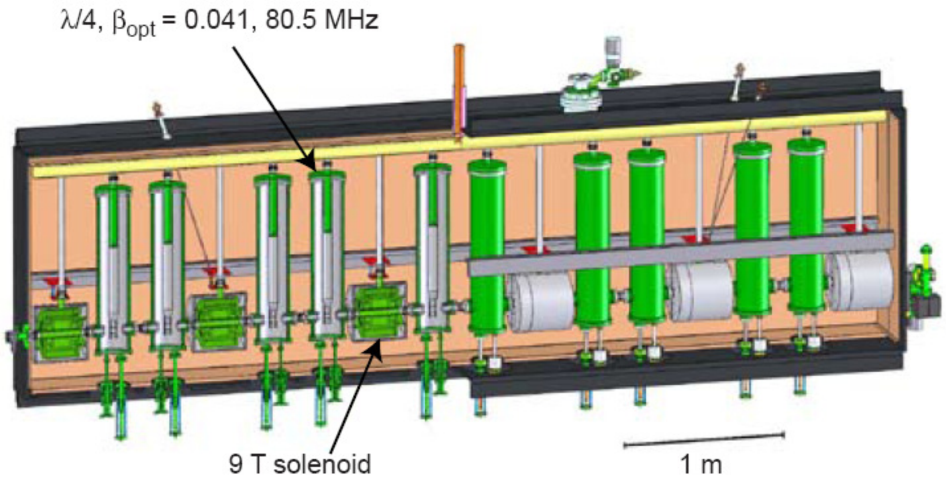
In-flight facilities

Super-conducting rf-cavities for the MSU project

Four types of cavities
for the whole energy range:

2 QWR and
2 HWR for the FRIB linac
2 QWR for the post-accelerator





In-flight facilities

Other facilities/projects

- IMP-HIRFL Lanzhou, China, 2005

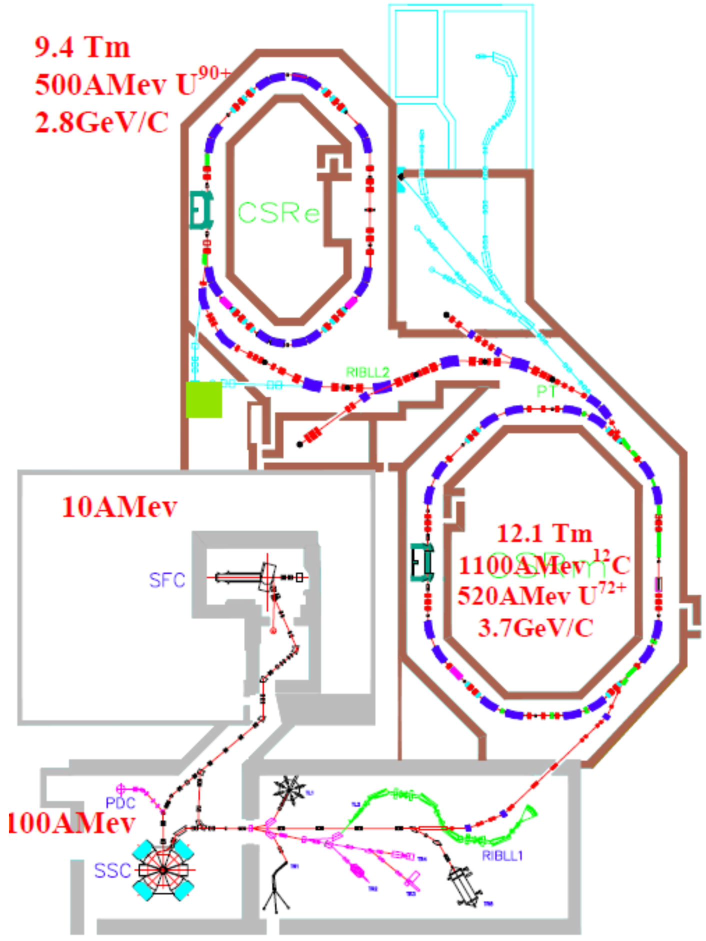
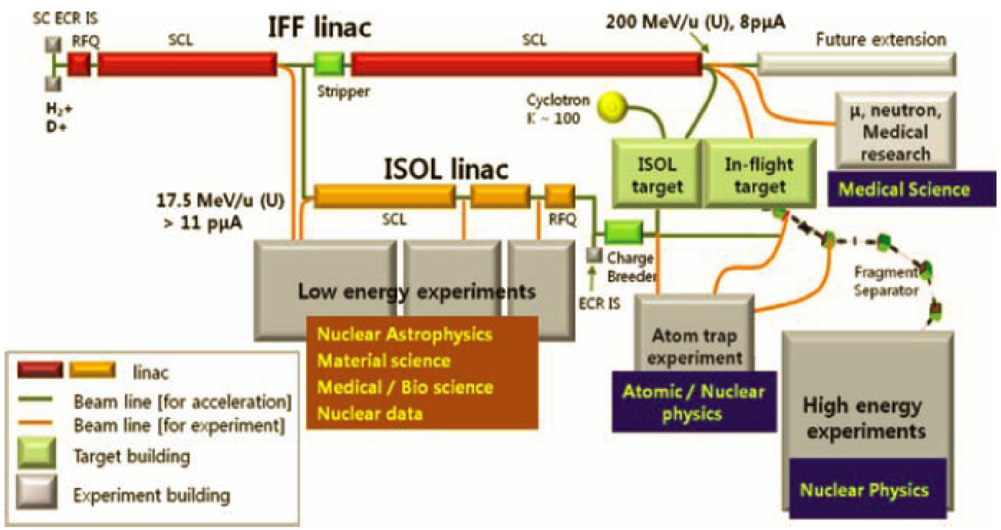


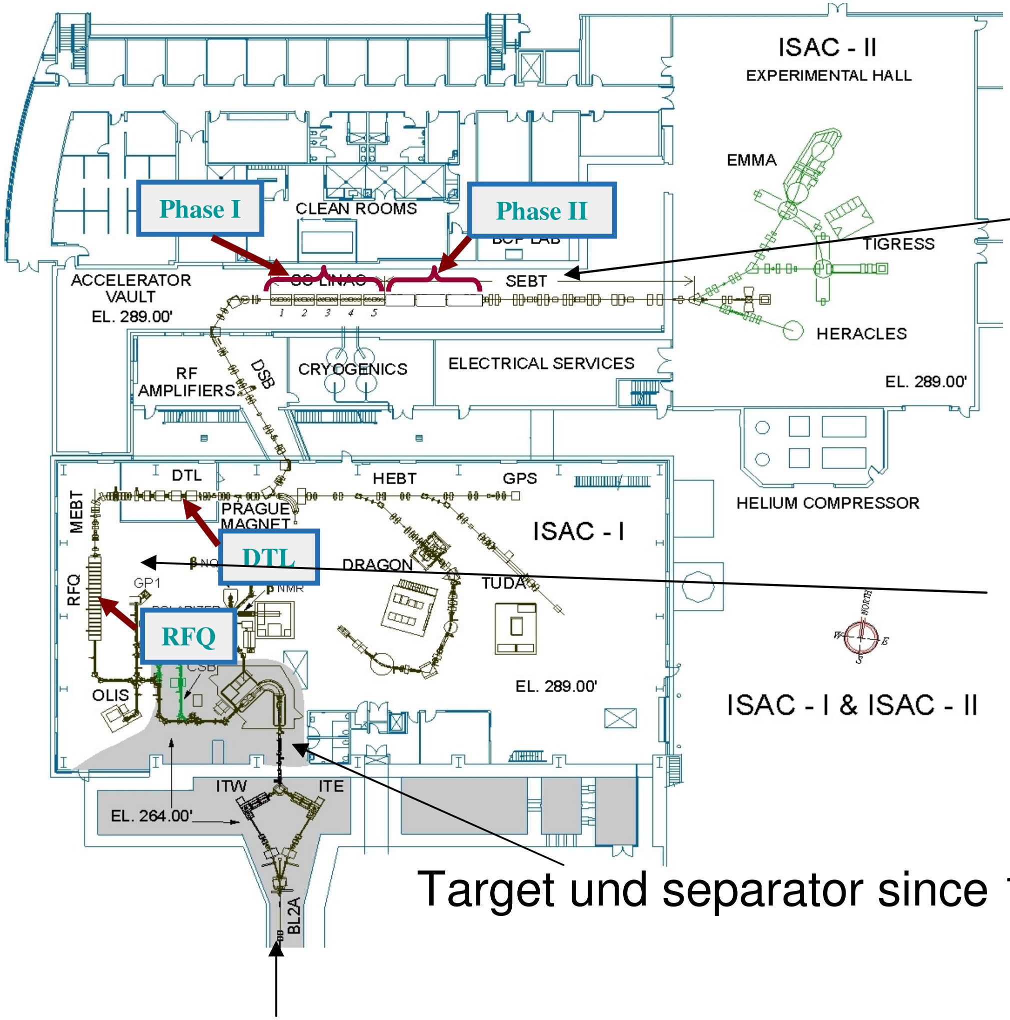
Figure1: Layout of HIRFL System

- Korea Rare Isotope Accelerator Project: In-flight plus ISOL



ISOL-facilities

ISAC at TRIUMF, Vancouver, facility for the production and acceleration of radioactive isotopes since 1998 with the ISOL-method



Super-conducting rf- linac for ISAC-II
2 x 20 MV, 20 QWRs
7 MV/m acc. gradient
106/141,4 MHz
β = 5,7 – 11 %
(since 2006 Phase I, commissioning phase II 2010, ECR charge booster)

RFQ and 5 x DTL(IH) for ISAC-I
RIBs ≤ 1,5 MeV/u (2≤A/q≤6)
(2001)

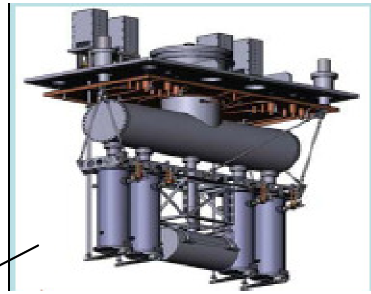
Target und separator since 1998

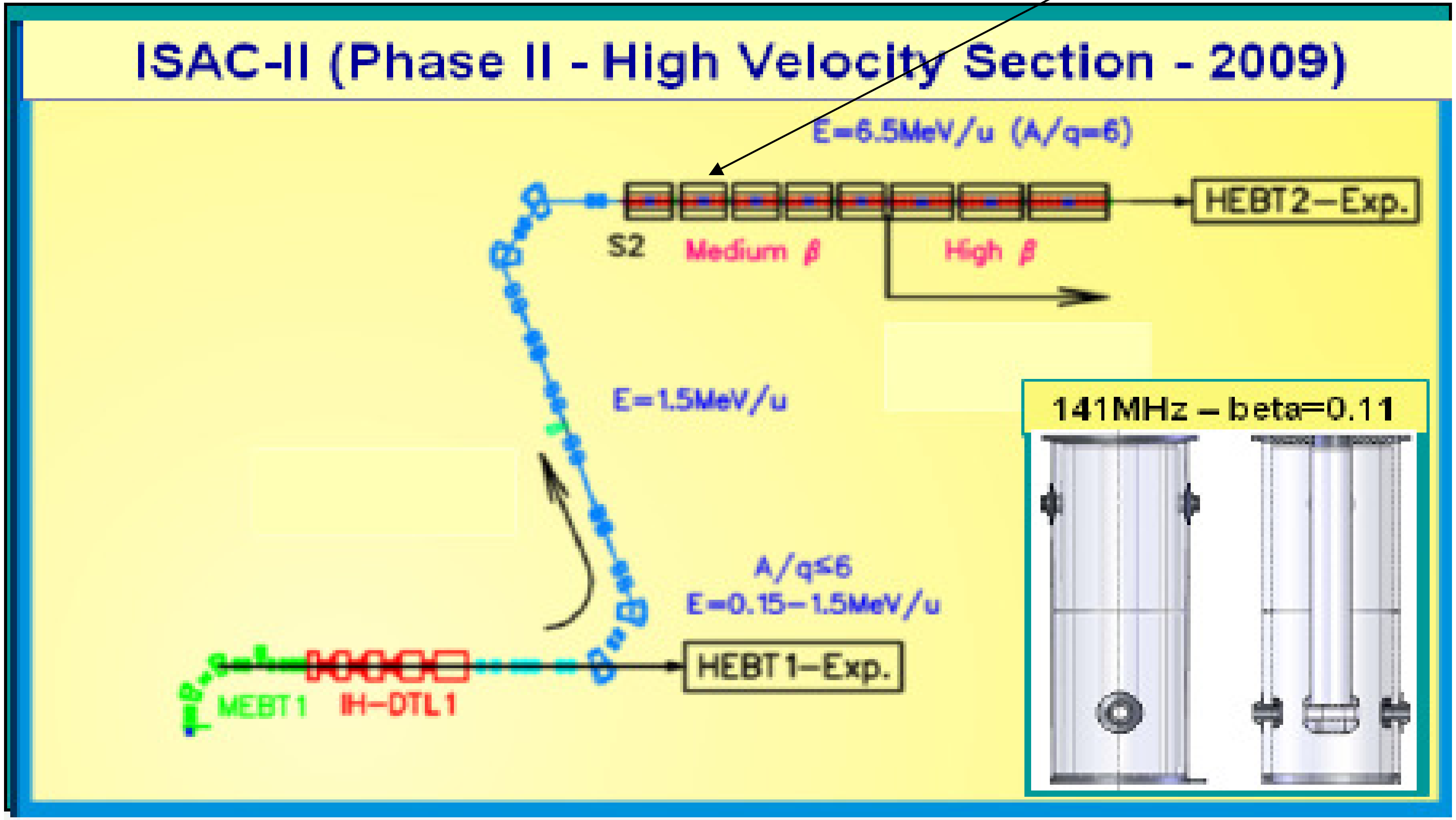
Next step:
e-driver , 50 MeV/10 mA,
photon induced fission,
two ion operation

500 MeV/100 µA protons, from cyclotron (50 kW)

ISOL-facilities

ISAC – II

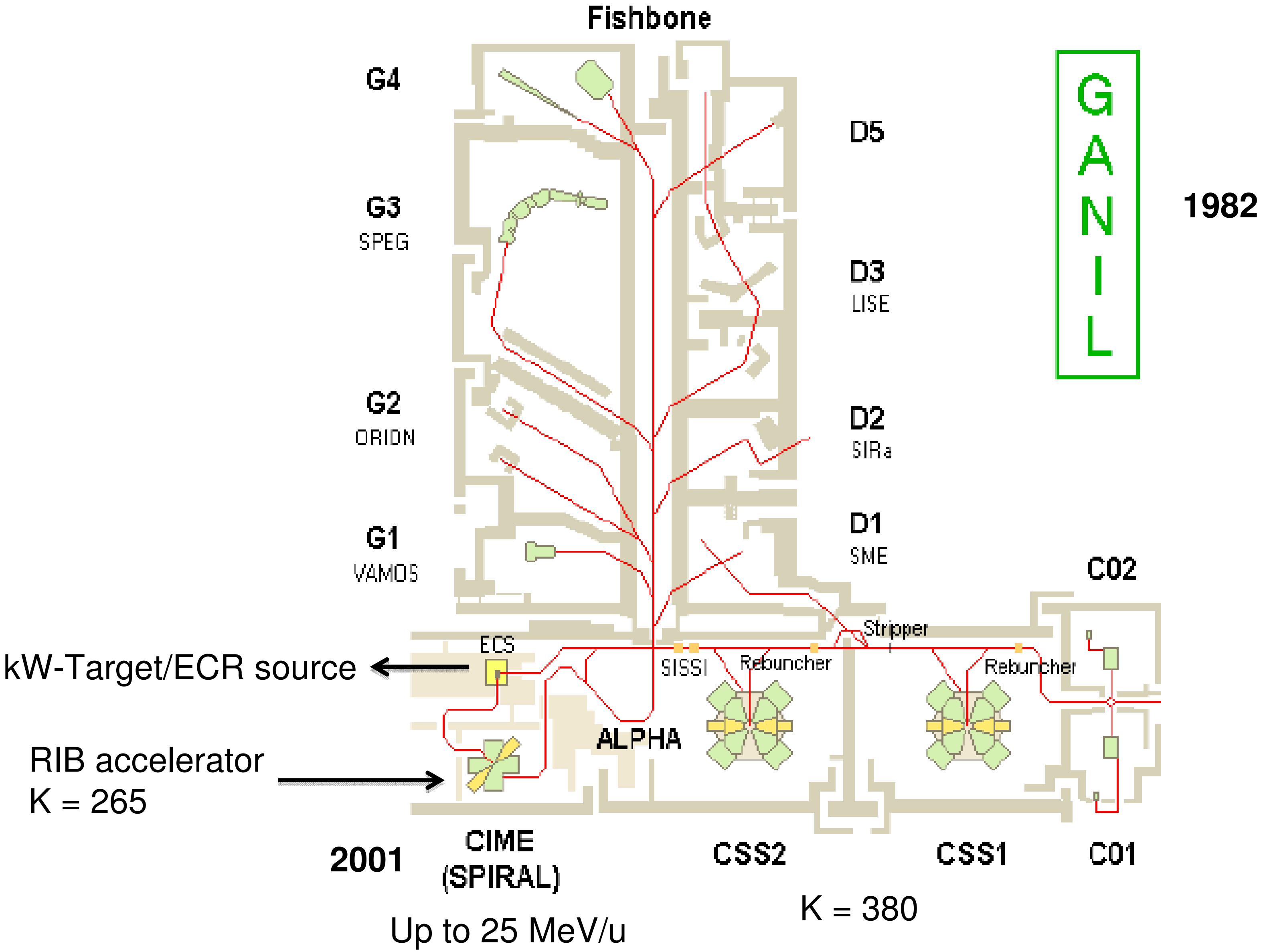




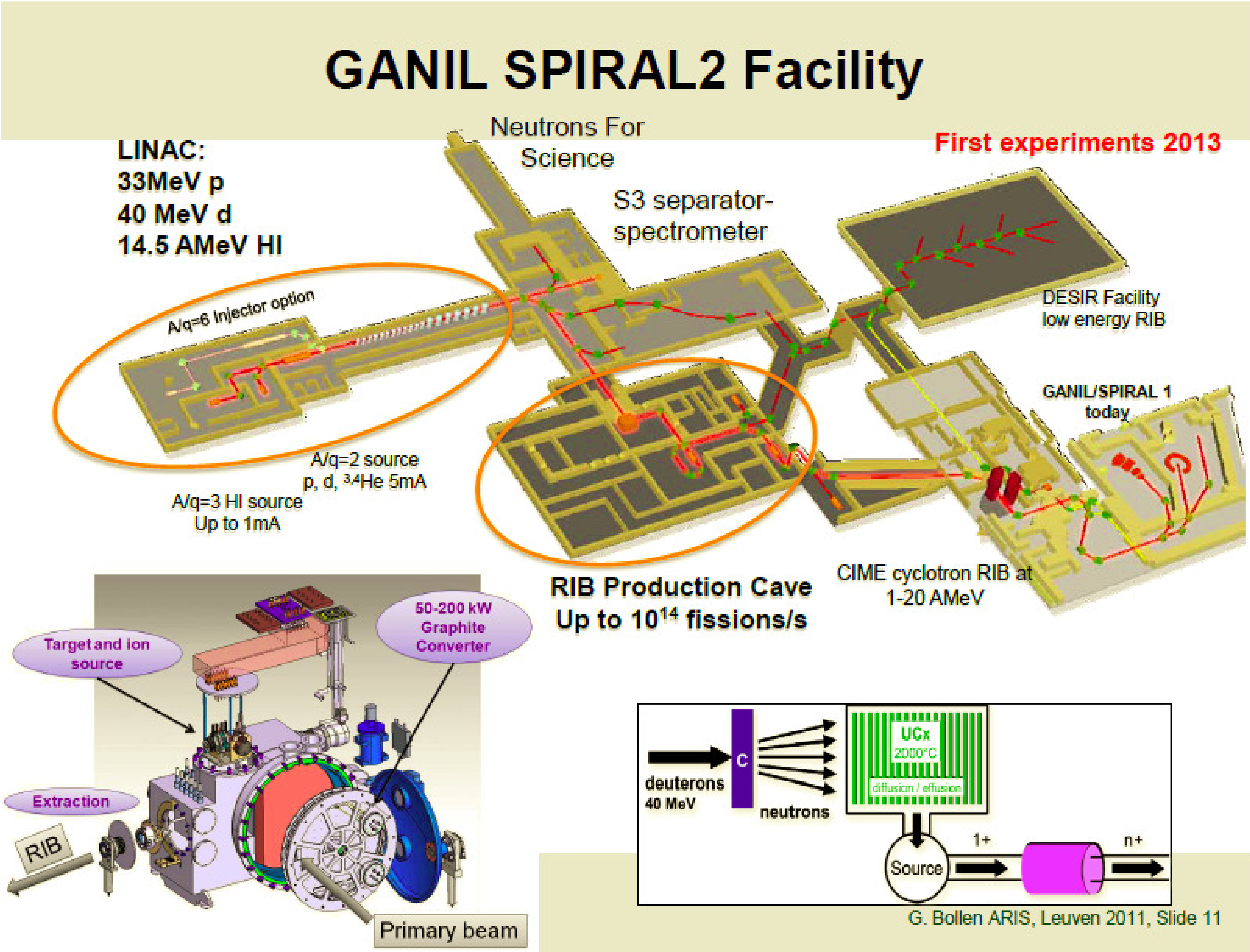
ISOL-facilities

View of the super-conducting linac of TRIUMF ISAC-II

ISOL facilities



ISOL-facilities

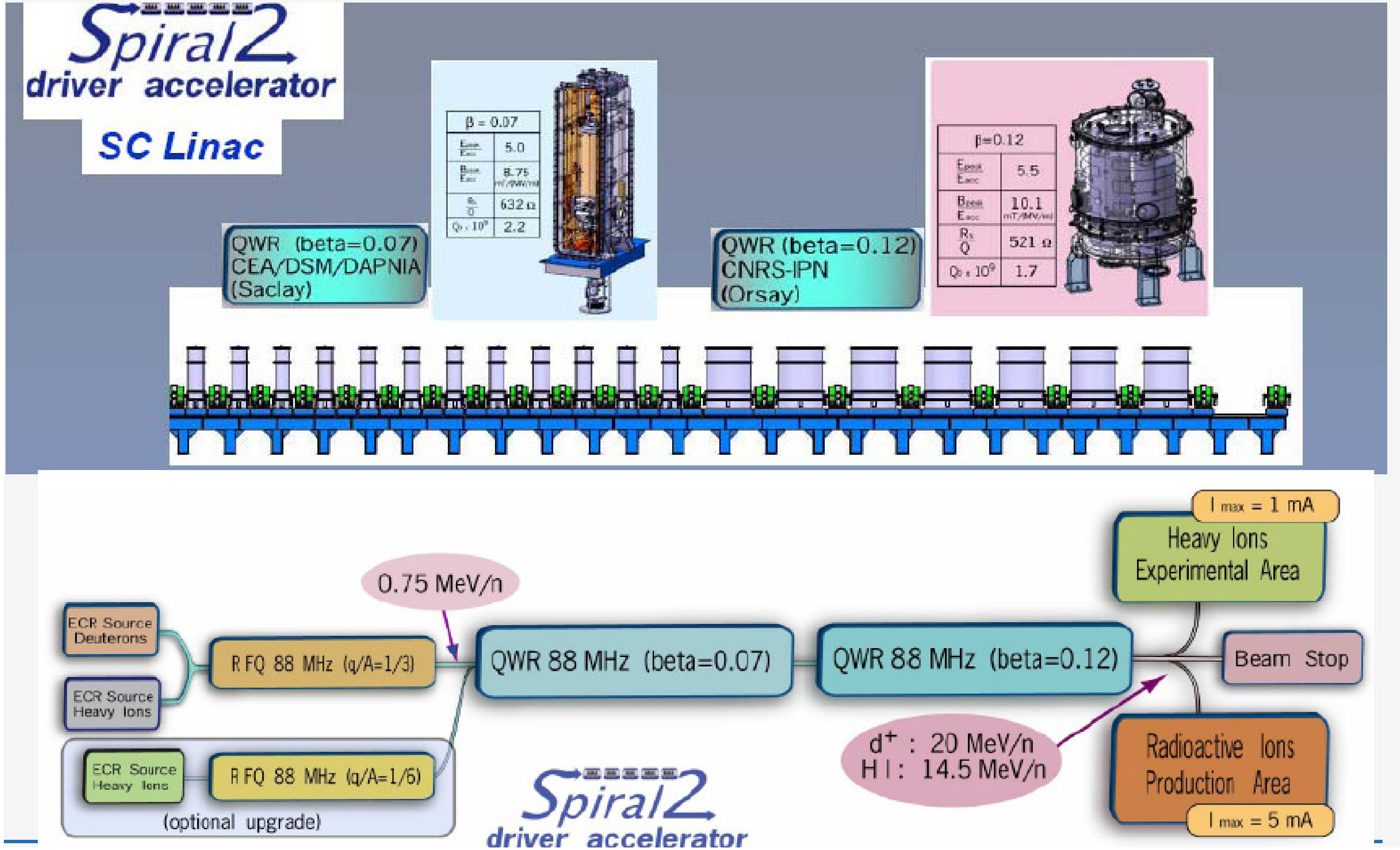


ISOL-facilities

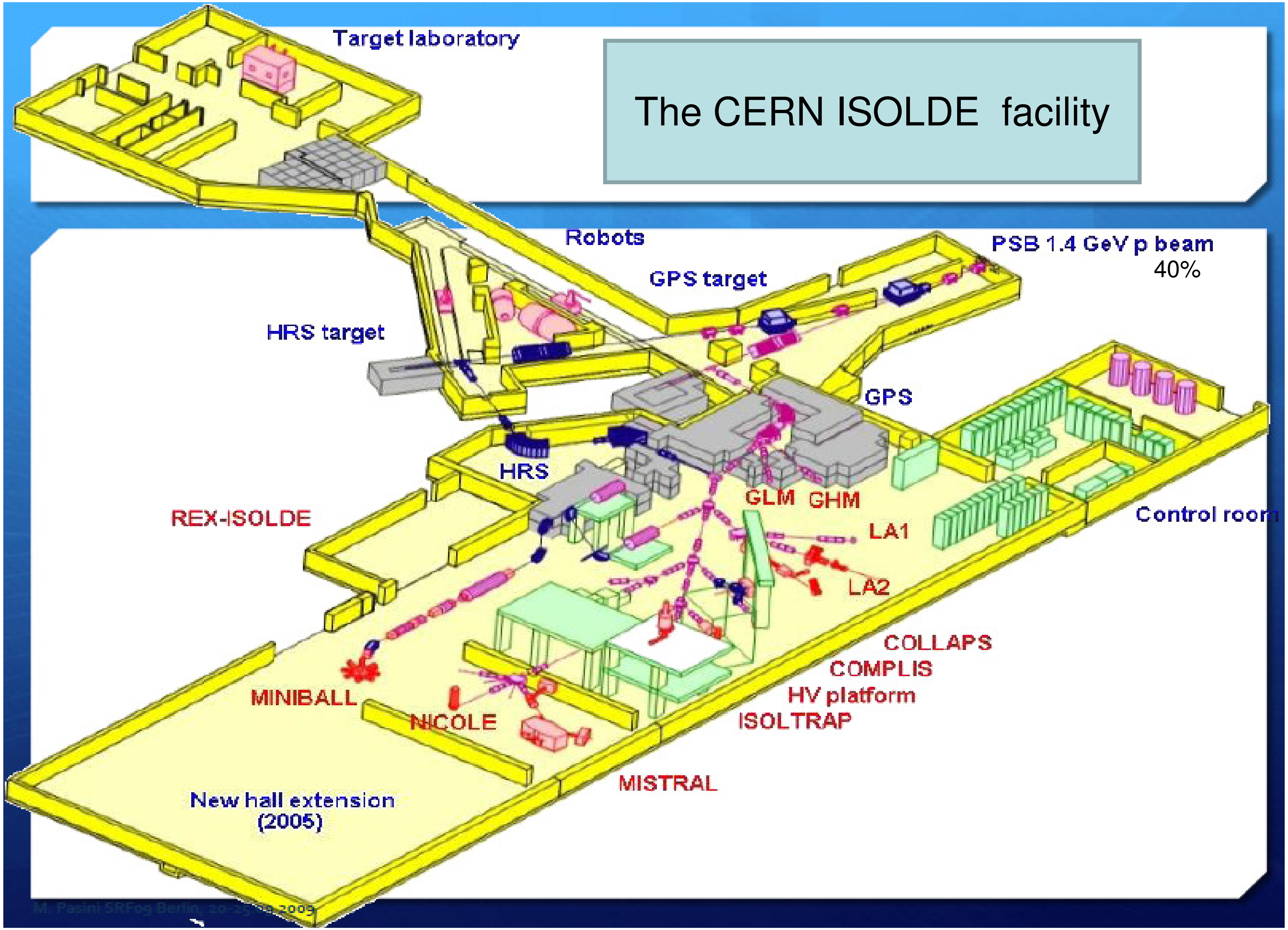
SPIRAL2 Linac

SPIRAL-II GANIL (20MeV/u d+, 5mA)

The main process being the fission in uranium carbide targets via fast neutrons

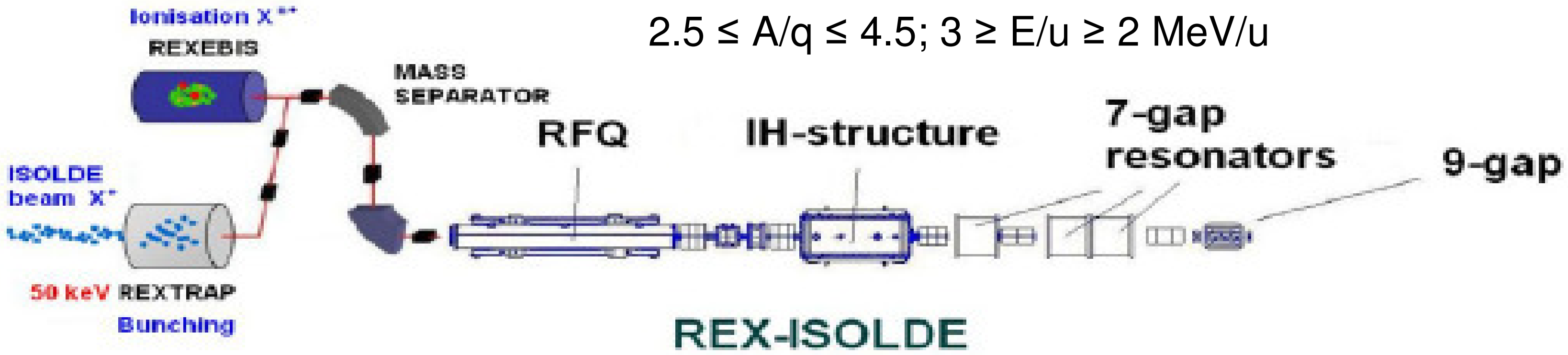


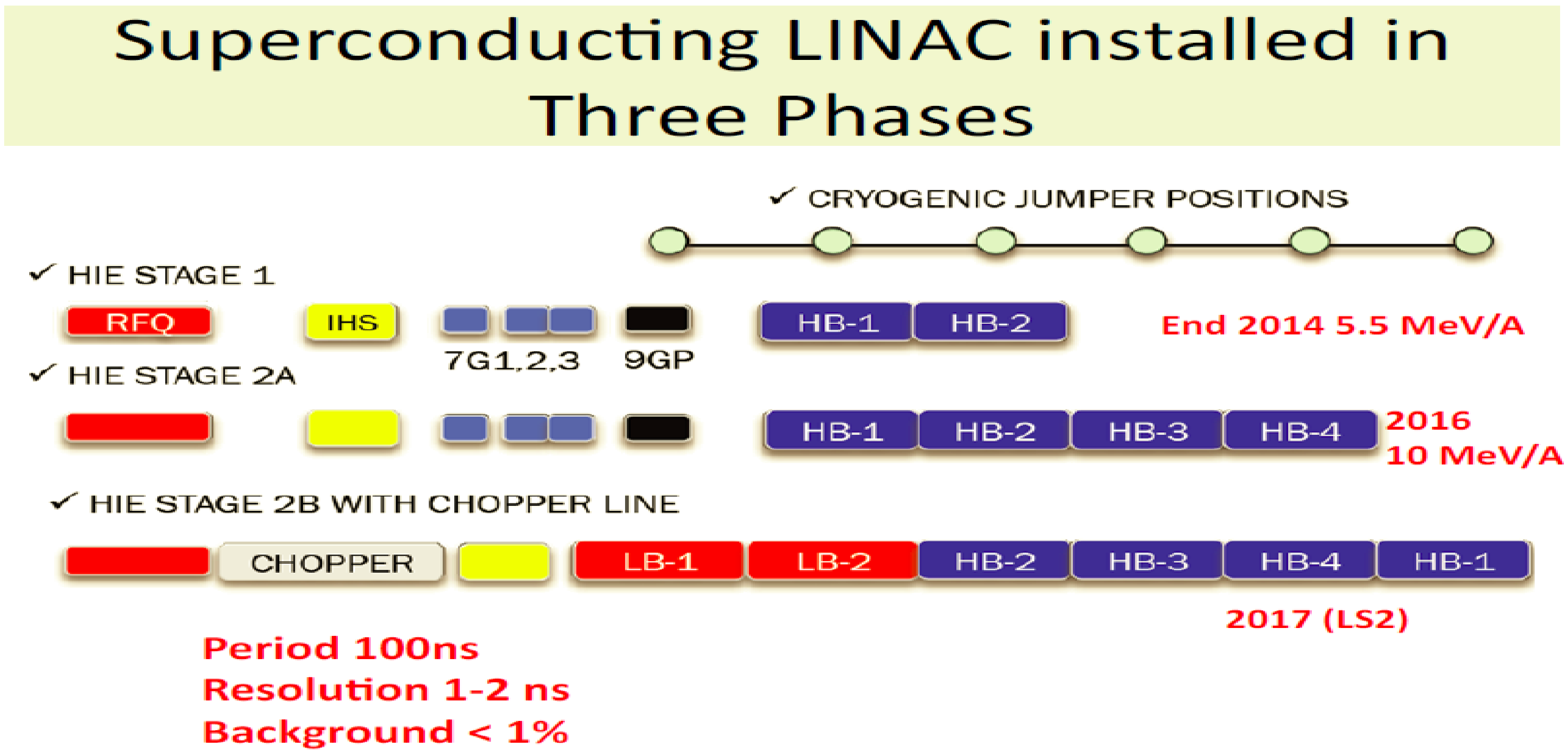
ISOL-facilities



ISOL-facilities

2.5 ≤ A/q ≤ 4.5; 3 ≥ E/u ≥ 2 MeV/u

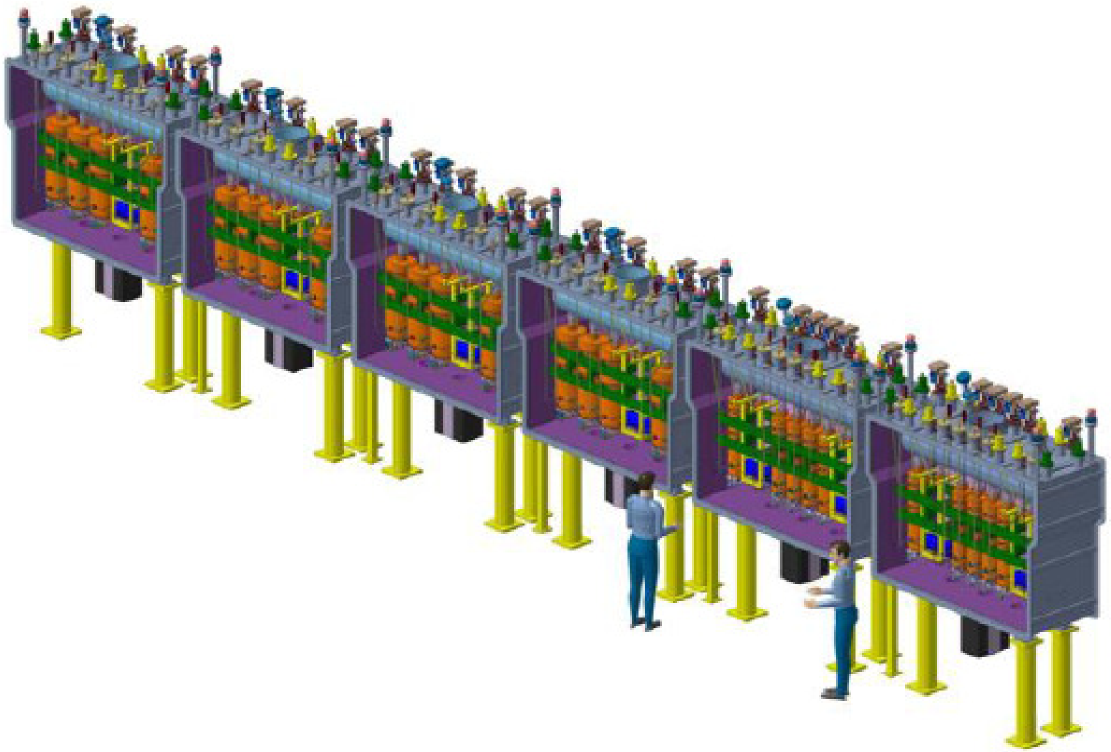




ISOL-facilities

The HIE-ISOLDE SC linac

Ligne Cryomodules



On the way to EURISOLs